# Doctoral Thesis

# STUDY ON THE INDOOR THERMAL ENVIRONMENT AND ENERGY CONSUMPTION OF MULTI-UNIT RESIDENCES IN CHINA

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# STUDY ON THE INDOOR THERMAL ENVIRONMENT AND ENERGY CONSUMPTION OF MULTI-UNIT RESIDENCES IN CHINA

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# CHAPTER 1 INTRODUCTION

## 1.1 Background of Research

### 1.1.1 The problems facing China

(1) Global climate change

Today tackling the risk of global climate change is the most significant and serious environmental problem. Currently, the global average temperature increased and a large range of snow and ice melted. In 2007, the Intergovernmental Panel on Climate Change (IPCC) released the assessment report and pointed out that the global average temperature has raised 0.13ºC every decade over the past 50 years. However, the climate warming is mainly caused by greenhouse gas emissions. With the rapid increase of global energy consumption, the emissions of environmental pollutants such as carbon dioxide, nitrogen oxides and dust particles also increased year by year. Meanwhile the impact of fossil energy on environmental pollution and global climate is becoming increasingly serious.

According to the data from global carbon planning organization showed in Figure 1-1 [(1)], the total emission of carbon dioxide in China in 2013 has exceeded the combined emissions of the US and Europe, accounting for 29% of the total emission all over the world and ranking the 1st in the world. However, the emission control in the construction field is critical among all major fields of carbon emission reduction, and building energy consumption must be reduced to control emissions in the construction field.

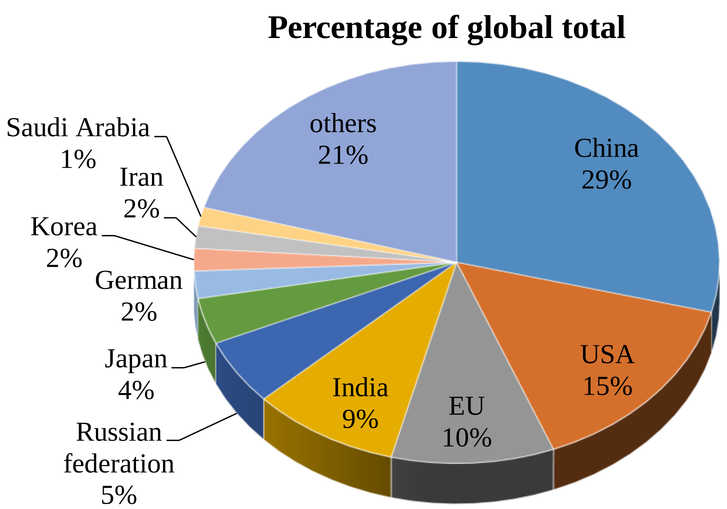



Figure 1-1 Global carbon emissions ranking in 2013

(2) Energy shortages

In addition, energy shortages have also become one of the most complex challenges facing China. With the increasing of energy consumption all over the world, building energy consumption of developed and developing countries both accounts for a sizeable proportion among the total energy consumption of a country. Table 1-1 shows that building energy consumption of some developed countries in the world accounted for about 30~40% of total energy consumption; while building energy consumption of China also accounted for 27.6% of total energy consumption(2).

Table 1-1 The proportion of building energy consumption in total energy consumption (%)

| **Nation** | **USA** | **UK** | **Germany** | **Sweden** | **Dutch** | **Canada** | **Japan** | **China** |
|---|---|---|---|---|---|---|---|---|
| **Proportion** | 33.3 | 34.3 | 32.8 | 33.9 | 33.9 | 31.8 | 20.3 | 27.6 |

At the same time, the energy consumption of urban residential buildings takes bigger share than that of rural and urban non-residential building in the building sector(3), as shown in Figure 1-1. Recent economic growth and improvements in living standards have led to greater demands for comfortable and healthy living environments. The heating range is gradually moving southward, also increasingly for use of air conditioning. However, it will inevitably be accompanied by an increase in energy consumption. The urban residential buildings should reduce the energy consumption to be duty-bound as energy-hungry.

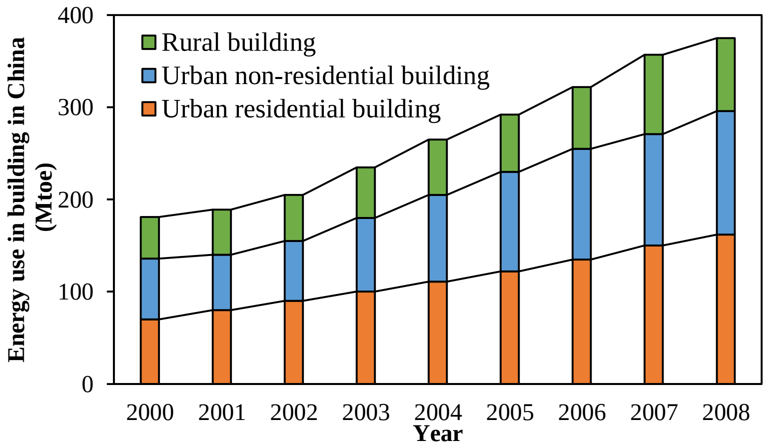



Figure 1-2 Energy use in buildings in China

(Note: Mtoe refers million tons of oil equivalents)

Therefore, energy conservation of unban residential building is the inevitable requirement to decrease energy consumption, reduce carbon emissions and achieve social sustainable development.

### 1.1.2 Energy consumption status of urban multi-unit residence in China

The demand for energy in China is rising fast with the rapid development of economic construction, the total energy consumption has been ranked 2nd in the world, the second-biggest customer after the United States, the energy supply is confronting the tremendous pressure. In recent years, the building energy consumption in China has been ranked the first among all kinds of energy consumption. According to statistics, the proportion of building energy consumption in total energy consumption increased from 10% in the late 1970s to 27.6% in recent years, the research of China National Construction Ministry of Science and Technology Company showed that the proportion of building energy consumption in China will further rise to about 35% (2). At the same time, energy consumption of urban multi-unit residence takes bigger share than that of rural and public in the building sector. The construction area of many new established multi-unit residence annually in China is up to 1.6 billion to 2 billion square meters, much more than all the developed countries 'established construction area combined, of which more than 95% of new multi-unit residences are high energy-consuming building. Therefore, reducing the energy consumption of urban multi-unit residence to alleviate the energy shortage and achieve the sustainable development strategy in China has an important role. And the obvious characteristics of energy consumption status of urban multi-unit residence in China are as follows:

1) The thermal insulation performance of external envelope of urban multi-unit residence has obvious difference with that of developed countries, Table 1-2 compared the energy-saving building technology index of different countries (4~7).

Table 1-2 Comparison of energy saving building technology index(U-value)

| Nation | | Exterior wall ($W/m^2k$) | Exterior window ($W/m^2k$) | Roof ($W/m^2k$) |
|---|---|---|---|---|
| China | Beijing | 1.16 | 4.0 | 0.8 |
| | Harbin | 0.52 | 2.5 | 0.5 |
| USA (Similar to Beijing ) | | 0.32(Internal insulation) /0.45(External insulation) | 2.04 | 0.19 |
| Canada | Similar to Beijing | 0.38 | 2.86 | 0.23 |
| | Similar to Harbin | 0.27 | 2.22 | 0.17 |
| Russia | Similar to Beijing | 0.8 | 2.75 | 0.57 |
| | Similar to Harbin | 0.55 | 2.35 | 0.4 |
| Germany | Berlin | 0.50 | 1.5 | 0.22 |
| Britain | | 0.45 | Double glazing | 0.45 |
| Sweden | | 0.17 | 2.0 | 0.12 |
| Denmark | | 0.30 | 2.9 | 0.15 |
| Japan | Hokkaido | 0.46* | | |
| | Tokyo | 0.87* | | |

*Average U-value of exterior envelope.

It can be seen that the average thermal insulation level of multi-unit residence exterior wall in China is just one-third of European developed countries on the same latitude; accordingly the building energy consumption will become 2-3 times higher.

2) In northern China, large district heating area and long heating period with no household heat metering and moderating system, continuous heating 24 hours a day, and residents pay by heating area that not to measure heat metering and not to regulate the heat; along with the heavily use of low-efficiency small boilers, those make the energy consumption of heating in winter of northern area large and thus causes great waste.

3) With the improvement of living standard, the popularity rate of air conditioning is becoming higher and higher, and the proportion of air-conditioning energy consumption of residential buildings in summer rapidly increases along with it. According to the National Bureau of Statistics [(3)], by the end of 2012, the number of urban residential air conditioners owned per 100 households grew to about 127 units as shown in the Figure 1-3. This number has quadrupled since 2001. Because of the large power consumption and the centralized use of air conditioning, the air conditioning load of some cities in summer even accounted for more than 50% of the peak load. Since 2010, although the annual power generation amount in China increased by 8%, there exists power shortage phenomenon in many cities such as Shanghai, Guangzhou and others in summer.

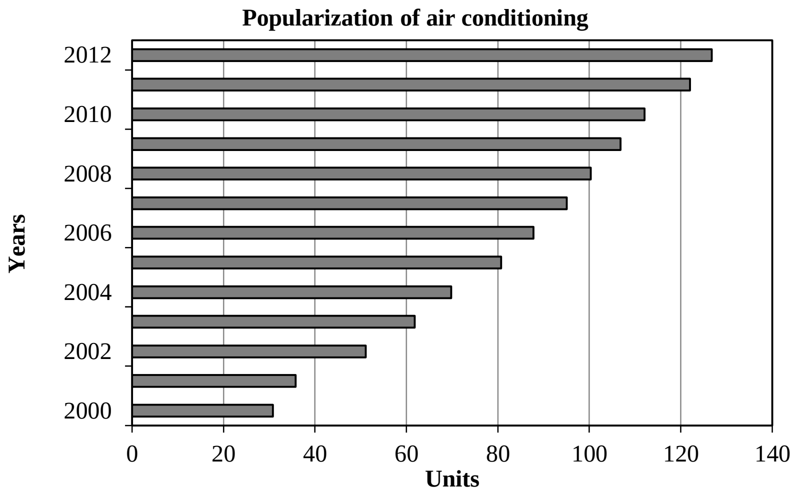



Figure 1-3 Popularization of air conditioning

4) In addition to heating and energy consumption of air conditioning, urban multi-unit residential energy consumption in China including lighting, cooking, household appliances, hot water supply and other aspects is also increasing gradually.

According to the analysis of urban multi-unit residential energy consumption status, energy saving of urban multi-unit residence has become an inevitable requirement of economy, social sustainable development and ecological environment construction in China.

### 1.1.3 The process of energy saving of urban multi-unit residence in China

The building energy conservation work of China began in 1980s, started late than developed countries. Considering that the energy saving of residential building, economic development and people's living standard are closely interconnected, China government has taken a series of relevant measures in recent years. Table 1-3 shows the energy saving specification standard of residential building in China. Since 1986, energy saving of multi-unit residence has been raised to a new height of national implementation resources and sustainable development strategy as understanding and fixed position at the national macro level. At the same time, the government also constantly perfect the energy saving regulations and develop the national and regional energy saving design standards, scale up efforts to the development and application of building energy-saving technology work. Since 2001, the multi-unit residence energy saving design standards of different climatic zones have been promulgated and implemented. A new energy saving objective of multi-unit residence was developed in 2005: the building energy consumption would reduce by 25% than that of traditional multi-unit residence through the envelope structure, and then achieved the 50% decrement of total energy consumption of multi-unit residence combined with the equipment energy saving method. Beijing, Shanghai and northern cold-weather cities have also developed local standards and expanded building energy saving work combined their actual condition. Although China continued to make further steady efforts to the residential building energy saving, there are still a lot of problems. For example, the relevant standards cannot cover all over the country and different types construction; specifications and standards do not have strong implementation; the key energy-saving technologies and products are in urgent need of development; most of new established multi-unit residence do not adopt energy-saving materials; the existing buildings have almost not ever been energy-saving reformed; energy-saving awareness of residents is relatively weak and so on.

Table 1-3 Energy saving specification standard of residential building in China

| | 1986 / 1987 / 1988 / 1989 / 1990 / 1991 / 1992 / 1993 / 1994 / 1995 / 1996 / 1997 / 1998 / 1999 / 2000 / 2001 / 2002 / 2003 / 2004 / 2005 / 2006 / 2007 / 2008 / 2009 / 2010 / 2011 / 2012 / 2013 / 2014 |
|---|---|
| National codes and standards | ● Energy conservation design standard for heating residential buildings(JGJ26-86) |
| | ● Thermal design code for civil building(GBT50176-1993) |
| | ● Energy conservation design standard for heating residential buildings (JGJ26-95) |
| | ● Energy Conservation Law of the People's Republic of China ● Revision |
| | Provisions on the Administration of Energy Conservation for Civil Buildings ● ● Revision |
| | Technical Specification for Energy Conservation Renovation of Existing Heating Residential Building (JGJ129-2000) ● |
| | ● Standard for Energy Efficiency Inspection of Heating Residential Buildings (JGJ132-2001) |
| | ● Design standard for energy efficiency of residential buildings in Hot Summer and Cold Winter Zone (JGJ134-2001) ● Revision |
| | ● Design standard for energy efficiency of residential buildings in Hot Summer and Warm Winter Zone (JGJ75-2003) ● Revision |
| | Design standard for energy efficiency of residential buildings in Severe Cold and Cold Zones (JGJ26-2010) ● |
| | Green building evaluation criteria (GB/T 50378-2014) ● |
| Regional codes and standards | ● Energy Detailed rules for application conservation design standard for new heating residential buildings in Heilongjiang Province(DB23/T120-2001) |
| | Design Standard for Energy Efficiency of Residential Buildings in Zhejiang Province(DB33/1015-2003) ● |
| | Design Standard for Energy Efficiency of Residential Buildings in Beijing (DBJ11/602-2006) ● ● Revision |
| | Design Standard for Energy Efficiency of Residential Buildings in Jilin Province (DB22/T450-2007) ● |
| | Design Standard for Energy Efficiency of Residential Buildings in Sichuan Province (DB51/5027-2008) ● |
| | Design Standard for Energy Efficiency of Residential Buildings in Hebei Province (DB13/63-2011) ● |
| | Design Standard for Energy Efficiency of Residential Buildings in Shanghai (DGJ08-2011) ● |
| | Design Standard for Energy Efficiency of Residential Buildings in Shandong Province (DBJ14/037-2012) ● |
| | Design Standard for Energy Efficiency of Residential Buildings in Shanxi Province(DBJ04/242-2012) ● |

## 1.2 Literature review

With the proportion of building energy consumption in total energy consumption has increased year by year, building energy conservation has been widely attached more importance in China. At the same time, because of improvement of people's living standard, the requirements to indoor thermal comfort of residence were also improved to a certain extent, so some researchers started the related study. For the multi-unit residences of typical cities, the energy consumption statistics, optimization design of envelope insulation structure, the use pattern of air conditioning as well as the measurement and analysis of indoor thermal environment were conducted, which can establish the foundation for the promotion of energy saving technology and improvement of indoor thermal environment.

### 1.2.1 Energy consumption statistics

The energy consumption survey in China started in 1980s. "Building Energy Efficiency Economic and Technological Policy Research Group of China" composed by Tu and others has investigated and researched the actual condition of work progress of China's building energy consumption, building thermal environment and building energy efficiency for the first time in 1989(8). In 1998~1999, sampling survey of more than 200 residences in Hubei area was carried out by Hu (9). The results showed that the thermal comfort problems of residence in summer was more serious than that in winter, the total power consumption and air-conditioning power consumption of investigated residences were 9.0~36.9kWh/($m^2$·a) and 1.0~9.8 kWh/($m^2$·a), respectively. In 2001, the survey analysis of air conditioning power condition of 780 residences was carried out by Long(10), the average monthly electricity consumption of each residence in air conditioning season and transition season were 191kwh and 98kwh respectively, and the growth trend of air conditioning power consumption of residence in the future was also predicted. In 2003, the field measurement and questionnaire of energy use situation in winter of 100 residences in Changsha city was carried out by Li (11) from Hunan University, which analyzed the relationships among the formation of energy use structure and the basic condition of the residential building, the requirement to thermal comfort of human-being, the living habits, the household income level, the local climate characteristics, the regional energy policy and other factors. From 2004 to 2006, Yu etc. surveyed the residential energy consumption in five different cities and compared with the energy consumption in Japan(12). Results showed that the energy consumption gap is quite large in different regions. The annual energy consumption in Pangyang which located in Severe Cold Zone was the largest, and that in Changsha which located in Hot Summer and Cold Winter Zone was the least. Compared with that in Japan, the average annual energy consumption in five cities was about 9GJ/ household larger in China. In 2006, Wan measured the energy of air conditioning in six residences in Shanghai(13). Results showed that the daily consumption of air conditioning fluctuated at random, and the peak air load occurs at 19~ 22, the daily energy consumption of air-conditioning is 11.4kWh. In 2007, the energy measurement was also conducted in two residences in Beijing by Wan(14). The results showed that the energy consumption of air conditioning accounted the largest part in the total in the whole year, followed by cooking and hot water. The energy consumption of air conditioning heating and refrigerator had higher correlation with outdoor temperature, while less correlation for cooking and hot water energy consumption. In order to understand the behavior and energy consumption characteristics of air conditioning in multi-unit residences, Li(15) investigated the operation status and energy consumption of 69 households in Beijing by setting one power meter for each air conditioning in the summer of 2011. The results show that the air conditioning energy consumption of households varies from 6kWh to 596kWh with the average of 161kWh.The average full-load runtime for each air conditioning is about 0.61h per day. Average energy consumption intensity of air conditioning per floor area is 2.0kWh/m$^2$. The differences of energy consumption of air conditioning in different households are very large. The air conditioning operating pattern is the most important influencing factor of the energy consumption. In 2012, the influencing factors of annual energy consumption in Shanghai were analyzed by SHI(16). The results show that the quantity of air conditioning, floor area, residential age, energy saving consciousness and so on had great influence on the total energy consumption of residential building.

As mentioned above, the energy consumption survey in China started relatively late, the development scope was limited to some southern large and medium-sized cities such as Shanghai. Energy consumption survey mainly depended on the two ways of questionnaire and measurement revolved the energy consumption of air conditioning. The energy consumption gap was quite large in different regions. And the energy consumption of air conditioning accounted the largest part in the total in the whole year especially in southern cities. The air conditioning operating pattern was the most important influencing factor of the energy consumption. The total annual energy consumption in northern cities was greater than that in southern cities in China.

### 1.2.2 Optimization design of envelope structure

Regarding the energy saving technology aspects of envelope structure, many researchers have carried on the related research with the aid of simulation software.

In 2005, based on the thermal calculation of software-TRNSYS, H. Yoshino (et al) simulated the annual energy consumption of urban residential buildings in Beijing and Shanghai (17), and the influence of wall insulation was also studied. It demonstrated that the thermal insulation properties of an exterior wall are better for developing an effective improvement in Beijing. The annual load decreases to 26% when the thermal insulation property of exterior wall is improved to the Canadian R2000 standard level. However, the effect of wall thermal insulation was not so significant in Shanghai in comparison with that of Beijing. Improving the thermal insulation properties moderately, achieving the appropriate ventilation and solar shading would be the effective energy conservation solutions in Shanghai. In the same year, Pu (18) simulated and calculated the air conditioning load and energy consumption in Shenzhen. The results showed that the shading coefficient of glass had the greatest impact on the air conditioning load and annual energy consumption in Shenzhen. Compared with ordinary 3mm dummy glass, the air conditioning load of Low-e insulated glazing can be reduced by about 20%. In 2007, Wei(19) revealed that composite wall materials such as 200mm aerated concrete wall and polystyrene board thermal insulation had a significant role in reducing residential building energy consumption in Hot Summer and Cold Winter Zone. Aiming at the problem of energy saving reconstruction of existing multi-unit residences in Xi'an city, Wang (20) carried out the simulation and calculation of energy consumption in 2007. The calculation and analysis results showed that the prioritized energy saving measures of the existing buildings should be promoted as follows: increasing sun visor to the south, adopting the double glazing window and increasing the thermal insulation layer of polystyrene board for the wall. In 2008, Geng studied the influence of shading condition on the energy consumption of air conditioning in Shanghai(21). Results showed that the shading effect using the shading blinds with reflecting plate was more significant than the traditional shading effect；The best daylighting point occurred when the shading coefficient was 0.7, the ratio of upper reflecting plate was 75% namely. In 2010, the energy simulation was conducted by Cai to analyze the envelope performance of residential building on the annual air-conditioning heating energy consumption in Shanghai(22). Results showed that in residential buildings, the energy consumption used for cooling and heating accounts for 60%~70% of the total energy consumption. Increasing the thickness of insulation layer of exterior wall can effectively reduce the heating energy consumption, but it was not significant to reduce the cooling energy consumption. Using the movable shading can effectively reduce the cooling energy consumption. In 2011, Fu researched the influence of external window on low energy resident building consumption in Nanjing by the DeST(23).

Results showed that he influence of heat transfer coefficient of exterior window on heating energy consumption in winter was larger than energy consumption of air conditioning in summer. On the basis of 50% energy-saving design, the 30% energy saving can be achieved when the shading coefficient of exterior window in summer was reduced to 0.15 and the heat transfer coefficient was reduced to 0.97W/$m^2$k. In 2012, Li (24) studied the comprehensive effect of the window-wall ratio and type of window glass on heating energy consumption in Lhasa, and drew the conclusion that compared with single glass, a larger south window-wall ratio resulted in a better heating energy saving effect for double and low-e glass.

On the basis of above literatures, it can be summarized that the most of the previous studies on optimization design of envelope structure were focused on the C zone and HSCW zone and based on previous national energy conservation standards which have been implemented since 2001 and the energy saving target was set as 50%. Researchers mainly focused on the influence of external envelope structures including the external walls, windows and shading condition on residential energy consumption. The influence of exterior wall insulation on heating energy consumption was significant, but had little influence on energy consumption of air conditioning. The influence of parameters in different areas was different.

### 1.2.3 Air conditioning usage pattern

The use pattern of air conditioning has a direct impact on energy consumption of residential buildings. The use pattern of air conditioning is controlled by the random behavior of indoor occupants; the air conditioning behavior of occupants depends on the occupants' energy saving awareness.

In 2006, Zhu Guangjun (25) used the building energy consumption simulation software DeST to simulate a residential building in Shanghai area; the impacts of various factors of the air-conditioning operation pattern on the air conditioning energy consumption for residential heating were analyzed. The simulation results showed that each 1ºC reduction of the setting temperature of air conditioning in winter could reduce by about 10% energy consumption, and each 1ºC increase of the control temperature of air conditioning in summer could reduce by about 5% energy consumption. In 2007, Li(26) from Tsinghua University tested the air conditioning energy consumption of a residential building in summer in Beijing. The results showed that indoor air conditioning temperature had a greater impact on the energy consumption of air conditioning, the air conditioning setting temperature increased from 25 to 26ºC, the air-conditioning energy consumption decreased by 23%, the close of inner door during the operation of air conditioning can decrease 40% air conditioning energy consumption. In 2011, Li(27) analyzed the behavior patterns of people and energy consumption condition in residential building of Hot Summer and Cold Winter Zone in detail by the collected more than and 900 questionnaires from large sample of household survey. The results showed that in the residential building of Hot Summer and Cold Winter Zone, the significant effect level of opening time of air conditioning, the setting temperature of air conditioning, switching behavior of air conditioning, open window for ventilation at night, floor area on the building energy consumption in summer decreased in turn, which illustrated that the use pattern of air conditioning and occupant behavior are the important factors affecting the energy consumption of residential buildings in this region. In 2015, Cheng took the residential building in Shanghai as research object, the occupant behavior on the residential air handing unit was investigated with real electricity consumption and energy simulation (28). The results showed that the occupant behavior affected the residential energy of AHU, the energy consumption mainly distributed at night; environmental uncertainty led to deviation between reality and simulation. Questionnaire of occupant behavior also impacted the energy simulation.

At present, the research on air conditioning usage pattern is less. And the research mainly focused on the influence of setting temperature of air conditioning, switching behavior of occupant on the energy consumption. Especially, the setting temperature of air conditioning can directly affect the indoor thermal environment quality and residential energy consumption.

### 1.2.4 Indoor thermal environment

The indoor temperature of residences can directly affect the human body's thermal sensation, and also indirectly reflects the residential heating and use condition of air conditioning equipment. Therefore, the grasp of residential indoor thermal environment can not only improve the thermal comfort condition of residents, but also can promote the implementation of energy-saving measures of residential buildings to a certain extent.

Under the support of the government, the experts and scholars in Japan carried out the measurement analysis and survey research on a variety of residential forms under the different climatic conditions. For example, in 2001, Yoshino Hiroshi investigated and measured on the residential indoor environment characteristics and occupants' health condition in high insulation and high airtight buildings (29). At the same time, the indoor thermal environment of residential buildings of some cities in China were also investigated and measured, which played an important role to grasp the residential building indoor thermal environment situations in different zones.

The survey on residential indoor thermal environment in China started in 1990s. Xia (30) from Tsinghua University carried out the indoor physical parameters' measurement and questionnaire investigation of 88 typical multi-unit residences in Beijing in 1998. The results showed the measured thermal sensation TSV value was lower than PMV value, which indicated that the people that are investigated has a higher ability to withstand heat.

In 2002, Wang (31) from carried out the field survey of the indoor thermal environment and thermal sensation of residents in winter for 66 residences in Harbin. The thermal sensation questionnaires filled by 120 residents were collected. The results showed that, in accordance with the ISO7730 and ASHRAE55-1992 comfort standard, the thermal environment of nearly 77.5% residents was in the comfort range, but the acceptance rate of thermal environment was up to 91.7%. The acceptable operation temperature of 80% residents was 18~25.5ºC. In 2003, the results of field study on thermal comfort in Harbin were analyzed and summarized ulteriorly by Wang(32). The results showed that the thermal neutral temperature of residents in Harbin was 21.5ºC. The temperature sensitivity of male is lower than female. Thermal neutral temperature of male was lower than female by 1ºC, and female relatively prefer warmer thermal environment.

Li ever conducted the questionnaire survey and the field measurement about indoor thermal environment in urban multi-unit residences in August 2002 and January 2003 in Changsha, respectively (33). The questionnaire mainly investigated the building characteristic, occupants' life style, energy consumption of residences and the subjective prediction of indoor thermal environment. The influence of residential height, house plans, occupants' living habits as well as consumption concept on indoor thermal environment were analyzed. The indoor thermal environment was evaluated as well. Results showed that the comfort zone of indoor thermal environment in winter and summer in Changsha is 16.8~20.ET* and 24.7~27.7ET*, respectively (Icl=1.5clo in winter and 0.25clo in summer, M=58W/$m^2$).

In 2003, Zhong(34) measured the winter indoor environment parameters of non-heating residential buildings in Hot Summer and Cold Winter Zone. The results showed that about 80% of the time of the indoor temperature in winter was not up to the human health requirements of the temperature 12$^o$ C. It was concluded that the room tightness is the main basis for selecting heating mode and equipment in winter in this area.

Investigations of indoor thermal environment in winter were carried out in Harbin, Beijing, Xi’an, Shanghai and Hong Kong of China by Yoshino from 2003(35). The results showed that the indoor thermal condition in heating usage zone is good, such as Harbin, Beijing and Xi’an. Since the district heating system are used in these cities, the indoor average temperatures were 19.8ºC in Harbin, 20.4ºC in Beijing and 20.4ºC in Xi’an, respectively. The differences between living room and bedroom are very small. However, the indoor thermal comfort is strongly affected by the outdoor climate in non-heating usage zone, occupants use heating individually to warm their houses such as Shanghai and Hong Kong. It is expected that the poor indoor environment will be improved in near future by growth of the economy and increase of the demand for comfortable thermal environment. Therefore, the performance of the residential buildings, with better thermal insulation and air tightness must be more important for energy conservation.

From 2004, with the investigation scale expansion, Yoshino conducted the field measurement and questionnaire survey in the urban areas of nine major cities (36). The measurement showed that winter indoor temperatures in Harbin, Urumqi, Beijing and Xi’an remain at a relatively stable level near 20.8ºC due to the central heating system installed. However in the other cities lacking central heating systems, indoor temperatures fluctuated as a function of the change of outdoor temperature. On the other hand, summer indoor evening temperatures in Shanghai, Changsha, Chongqing and Hong Kong were higher than the comfort zone of ASHRAE. Therefore it is expected that energy use for space heating and cooling in the southern China will increase in the near future because of occupants’ requirement for comfortable indoor environment. Based on the results yielded by this study, in Beijing the calculation of space heating and cooling loads indicated that the energy used to heat indoor spaces can be halved by installing thermal insulation and properly sealing the building.

Ding conducted the field study about thermal comfort of residential buildings in summer in Dongguan (37) in 2006. It was suggested that the setting temperature of air conditioning that was set as 26~27ºC could satisfy more than 70% occupants' thermal comfort. From the comparison of investigation, it was suggested that having lived long in the high humid-hot climate zone, the thermal expectation and thermal adaptability had an important influence on the subjective value of indoor thermal environment. Taking into account the energy saving, increasing the indoor design temperature and humidity properly also would fulfill the need of thermal comfort.

Zhu carried out the field investigations from 2011 to 2012 year to study the indoor thermal environment, thermal sensation and adaptation measures of Dalian apartment’s residents in winter (38). Different Thermal comfort apparatuses were used to test the environment parameters, subjective questionnaires about thermal sensation from 102 residents of 36 residences were collected at the same time. The results showed that acceptability to the thermal environment was 93.2%. The neutral and expected temperature was 20.44ºC and 20.81ºC, respectively. The 80% acceptable temperature range was 17.38~24.28ºC, of which 57% subjects thought that humidification measures should be taken because of the dryness in the room.

In 2013, Gao researched the indoor thermal environment in old industrial regions of Harbin(39). Results showed that although there was district heating system, the indoor thermal environment was not optimistic in the old residences especially the residences used more than 30 years. The indoor temperature was low, with an average of 17.2 ºC. Frost appears due to the aging and its own performance issues of windows. Even some residential indoor appear phenomenon of moldy and condensation.

With the improvement of people's living standard, researchers paid more and more attention to the thermal environment in multi-unit residential buildings, especially in the Cold Zone and Hot Summer and Cold Winter Zone. Because of the different heating methods, compared the colder zones where had district heating system, the indoor thermal comfort urgent need to improve improved in the southern cities where occupants use heating individually to warm their houses. In addition, although there was district heating system in Severe Cold Zone and Cold Zone, the indoor thermal environment should also be improved in the old residences.

## 1.3 Limitation of Existing Research

As mentioned above, it can be seen that the related research on multi-unit residences in China has made great progress, especially in the pursuit of energy saving of residential building and evaluation of indoor thermal environment. However, under the research background that the legal framework and scope for energy saving is in the early stage, so the previous research has some limitations and needs further more in-depth study:

1) Narrow research scope

The development scope was limited to some single climate zones and large cities, few researches that simultaneously compared and considered the difference in requirements of different climate zones in China.

2) Single research target

The previous research usually only focused on a single aspect, but there was few researches that simultaneously considered the comprehensive improvement of indoor thermal environment and energy saving.

3) Under the conditions of old standard

Most simulation studies have been conducted based on previous national standards of 2001 (energy saving target -50%), less discussion of new current standards after 2011 (energy saving targets -65%).

4) Lack of some influencing factors evaluation

Most simulation studies focused on the influence of external envelope structures including the external walls, windows and shading condition, few studies on the setting temperatures and the air tightness.

5) Less comparative analysis

There was almost no simulation study that simultaneously compared the thermal performance of residential buildings of actual conditions, national standard and improvement cases.

## 1.4 Research Objectives

### 1.4.1 Research purpose and content

The purpose of this study is to grasp the status of indoor thermal environments and identify the actual energy demand of multi-unit residences as well as the influence of building performance parameters on the energy consumption and comfortable indoor thermal environment in different climate zones in China. And then the feasible solutions are sought to improve the indoor thermal environment and reduce energy consumption. Finally, a good balance between the environmental quality and the energy saving in multi-unit residences is attempted to achieve. The main contents include three parts as follows:

(1) The related articles of residential buildings published in China over the past 15 years have been classified and analyzed through literature review. The current research status of multi-unit residences in different climate zones was summarized.

(2) A field investigation was conducted in different climate zones in China, including field measurements and questionnaires survey. The excellent technical measures in multi-unit residences in different zones were compared and analyzed. At the same time, the current weak links of multi-unit residences' energy consumption and the indoor thermal environment have been also identified.

(3) Building envelope is the key point of residential building energy conservation, and is also a necessary condition to determine indoor thermal comfort. This research compiled different parameters and performed dynamic building energy simulations to study annual energy demand and indoor thermal environment in five climate zones of China. The effects of building design parameters on energy performance and indoor thermal environment were estimated.

On such basis, rational improvement proposals and measures have been put forward to improve the comfort of indoor thermal environments and energy conservation in multi-unit residences in China. It is expected to have a guiding significance for reducing energy consumption and improving indoor thermal comfort for Chinese multi-unit residences in the future.

### 1.4.2 Innovation of this research

The innovations of this research are mainly as follows:

1) The multi-unit residences in multiple climate zones was studied simultaneously on the basis of considering the difference in requirements to the indoor environment and energy saving in five climate zones in China.

2) The requirement of both indoor thermal comfort and energy saving was considered in this research.

3) This research discussed on the basis of new standard which was implemented after 2011 and the energy saving targets was set as 65%.

4) The influence of two less studied parameters –air tightness and setting temperature on the energy demand and indoor thermal comfort were researched in this thesis.

5) This research simulated and compared the thermal performance of residential buildings of actual conditions, national standard and improvement cases simultaneously.

## 1.5 Structure of This Thesis

This paper is mainly divided into seven chapters, and structure frame of full thesis was shown in Figure 1-4.

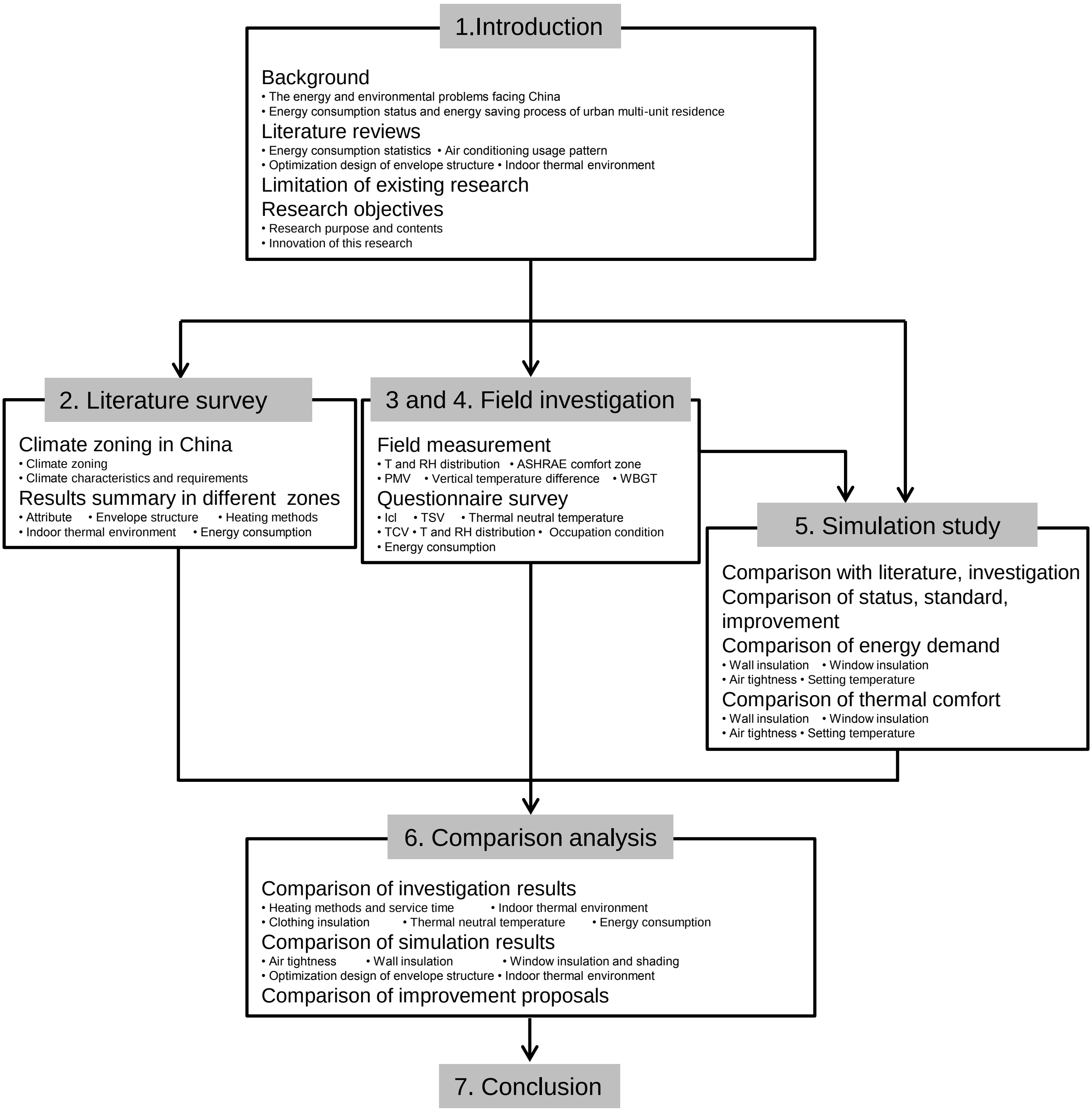



Figure 1-4 Structure frame of thesis

The specific ideas and chapters were shown as follows:

**Chapter 1** described the background, previous research status, the purpose and the significance as well as the major research approach of this study.

**Chapter 2** summarized the results of relevant literature published in the past 15 years based on different climate zones. Through reviewing about 99 articles, the data recorded in each article was extracted and statistically analyzed.

**Chapter 3** researched the actual conditions of indoor thermal environments and energy consumption in winter in multi-unit residences in three colder climate zones in China via field measurement and questionnaire analysis. On the basis of survey results, rational improvement proposals and measures had been put forward to improve the comfort of indoor thermal environments and energy conservation in multi-unit residences in winter.

**Chapter 4** researched the actual conditions of indoor thermal environments and energy consumption in summer in multi-unit residences in three hotter climate zones in China. Then the rational improvement proposals and measures had been put forward to improve the comfort of indoor thermal environments and energy conservation in multi-unit residences in summer.

**Chapter 5** compiled four different parameters and performed simulations based on new energy saving standard. The energy saving potential of current conditions was analyzed. Meanwhile, the influential parameter on energy demand and indoor thermal comfort was clarified in all five climate zones.

**Chapter 6** compared the results of literature survey, field investigation and simulation study, and analyzed the reasons for different results in different climate zones.

**Chapter 7** summarized the conclusions of each chapter and put forward the direction of future research.

## References

(1)Josep G. Canadell, Robert Dickinson, et al: ESSP Report No.1, The Global Carbon Project, Sep 2013.

(2)Shanqing YU. Standardization of building energy efficiency, China Standardization, 2000(1):15~18

(3)National Bureau of Statistics of the People's Republic of China: China Statistical Yearbook, 2013.

(4)Junfu CAI, Residential Energy Efficiency Design, China Architecture & Building Press, 1991.

(5)Fengxiang TU, Zhanying DI, Zhenyu ZHANG. Recent progress in building energy efficiency standards in Britain, France and Germany, Building energy conservation, 2002(37):131~138

(6)Paul Waide, Benoit Lebot, Mark Hinnells. Appliance energy standards in Europe Buildings, 1997(26):45~67

(7)Alan K. Meier. Observed energy savings from appliance efficiency standards, Energy and Buildings, 1997(26):111~117

(8)Ministry of national construction. Outline of the fifteen energy plan of the Ministry of construction, Construction technique, 2002, Vol.31, No.8: 1~6.

(9)Pingfang Hu, Zhangning Jiang,Yuhan Leng. Investigation of thermal environment and energy consumption for Hubei residences, Journal of HV&AC, 2004, 34(6):21~22.

(10)W D Long, T Zhong,B H Zhang. Situation and trends of residential building environment services in Shanghai, Proceedings of the 2003-4th International Symposium on heating, Ventilating and Air conditioning. Beijing: Tsinghua University Press, pp493~498, 2003.

(11)Nianping Li. Investigation and analysis on summer energy structure of residential buildings in Changsha, Journal of HV&AC, pp14~17, Vol.34, No.5, 2004.

(12)Liang YU, Hiroshi YOSHINO, Research on energy consumption of urban apartment buildings in China, J. Environ. Eng., AIJ, pp.183-190, Vol73, No.624, 2008.

(13)Xudong WAN, Jingchao XIE,Yaohua ZHAO, Survey and measurement result analysis on the thermal environment and energy consumption of urban residential buildings, Energy Conservation Technology, 2008, 26(147):68~74.

(14)Xudong WAN, Investigation and numerical simulation of indoor thermal environment and energy consumption in residential buildings, Master Thesis of Beijing University of Technology, 2009.

(15)Li Zhaojian, Xie Deqiang, Jiang Hongbin, Wei Xing. Testing Study on Operating Behavior and Energy Consumption of Air Conditioners in Residential Buildings in Beijing, Journal of HV&AC, pp15~20,Vol.44, No.2,2014.

(16)Xiaofei SHI, Ying PEI, Investigation and analysis on the influence factors affecting residential energy consumption in Shanghai, Energy Saving Technology, Vol.40, No.251, 2012.

(17)Hiroshi Yoshino, Yasuko Yoshino, Qingyuan Zhang: Indoor thermal environment and energy saving for urban residential buildings in China, Energy and Buildings 38(2006), pp.1308-1319.

(18)Zengwen PU. Influence of Low-e glass on air conditioning load and building energy consumption, Journal of HV&AC, pp119~121, Vol.35, No.8, 2005.

(19)Caixin Wei: Energy consumption simulation and analysis on the technical economy of air conditioning schemes of residential buildings in Hot Summer and Cold Winter Zone, Master Thesis, Dong Hua University, 2007.

(20)Weihao WANG, Dongyang WANG, Xilian LUO, Energy Consumption Simulation and Energy Saving Analysis on Envelope of Existing Building, Building science. 2007, 23(2):22~26.

(21)Jianguo Geng, Research on the indoor daylighting environment and energy consumption of Shanghai shaded residential building, Master thesis of Tongji University of Technology,2008.

(22)Longjun CAI, Lingfeng YAO, Envelope Performance of Residential Building on the Annual Air-conditioning Heating Energy Consumption in Shanghai, Construction Conserves Energy, 2010, (2):19~23.

(23)Heng FU, Influence of external window on low energy resident building consumption, Master thesis of Nanjing University of Technology,2011.

(24)En LI, Yasunori AKASHI, Daisuke SUMIYOSHI, Passive design strategy on residential buildings for sustainable development of Lhasa, Journal of Environmental Engineering. AIJ, July 2013 pp.471-480.

(25)Guangjun Zhu, Xiaoliang Zhang. Effects of Operation Mode of Air Conditioning on Energy Consumption of Heating and Air Conditioning in Residential Buildings, Journal of Chongqing Jianzhu University,2006,128(5):119~121.

(26)Zhaojian LI, YiJiang, Qingfan Wei. Survey and analysis on influence of environment parameters and residents' behaviors on air conditioning energy consumption in a residential building, Journal of HV&AC, pp67~71,Vol.37, No.8,2007.

(27)Nan LI. Impacts of human behavior on energy consumption of residential buildings in China's Hot Summer and Cold Winter Zone, Doctor Thesis, Chongqing University, 2011.

(28)Xuan CHENG, Case study on influence of occupant behavior on residential air handing unit and energy consumption, Building Science,Vol.31,No.10,2015.

(29)Hiroshi Yoshino, Haihong Lou, Indoor Thermal Environment of Residential Buildings in Three Cities of China, Journal of Asian Architecture and Building Engineering,2002,1(1):01.

(30)Yizai Xia,Rongyi Zhao,Yi Jiang. Study on thermal comfort of residential environment in Beijing, Journal of HV&AC, pp1~5, Vol.29, No.2, 2000.

(31)Zhaojun WANG, Xiukui FANG, Leming LIAN. Field study on thermal comfort of winter residents in Harbin, Journal of Harbin Institute of Technology, 2002, 34(4):500~504.

(32)Zhaojun WANG, Analysis on the results of thermal comfort field study in residential buildings in Harbin, Building Energy & Environment, 2004, 23(3):5~8.

(33)Li Nianping, Pan Yougui, Hiroshi Yoshino. Field Measurement and Analysis of Indoor Thermal Environment of Changsha Urban Residential Buildings, Journal of Building Energy &Environment, 2004, 23(1):94~98.

(34)Ke ZHONG, Qi WANG, Selection of winter heating mode in Hot Summer and Cold Winter Zone, Journal of HV&AC, pp70~73, Vol.32, No.12, 2004.

(35)Hiroshi Yoshino, S. Guan, Y.F. Lun, Indoor thermal environment of urban residential buildings in China: winter investigation in five major cities, Energy and Buildings 36(2004), pp.1227-1233.

(36)Hiroshi Yoshino, Yasuko Yoshino, Qingyuan Zhang: Indoor thermal environment and energy saving for urban residential buildings in China, Energy and Buildings 38(2006), pp.1308-1319.

(37)Ding Xiujuan, Zheng Qinghong, Hu Qinghua, Li Kuishan. Investigation of Thermal Environment of Residential Buildings in Dong Guan, Journal of Building Energy & Environment, 2007, 26(5):82~85.

(38)Zhu Peisheng, Guo Fei, Zhu Tong, Liu Shuguo. Field Investigation of Dalian Apartment Thermal Environments and Thermal Adaptation in winter, Journal of Low Temperature Architecture Technology, 2013, 183(9):127~129.

(39)Feng GAO, The research of residence indoor thermal environment in old industrial regions of Harbin and it’s optimizational design, Master thesis of Xi'an University Of Architecture And Technology,2014.

# CHAPTER 2 LITERATURE SURVEY ON MULTI-UNIT RESIDENCES BASED ON DIFFERENT CLIMATE ZONES

## 2.1 Introduction

In order to fully understand the current status of research on the residential building in China, this chapter has compiled and analysed the related literature about residential building published in the past 15 years. These literatures survey was conducted based on the five different climate zones and different cities in China. Statistics include residential performance, the main heating cooling equipment, residential comfort and energy consumption and so on. Through reviewing about 99 articles, the data recorded in each article was extracted and statistically analyzed.

## 2.2 Thermal Design Zoning for Buildings in China

### 2.2.1 Climate zoning

Compared with public buildings, the internal heating power and building volume of residential buildings are relatively low, so the thermal performance of residential building is more dependent on the external meteorological environment. Compared with the regions at the same latitude all over the world, China is partial to hot in summer and cold in winter. Many regions in China need the heating in winter and cooling in summer, so the energy consumption problem is more serious.

China is within the middle and low latitudes of the northern hemisphere, the land area stretches between the latitudes of 18∘N and 53∘N. The maximum solar altitudes vary a great deal, and there is a large diversity in climates, especially for the temperature distributions during winter. Different climatic conditions also have different requirements on the design of residential buildings.

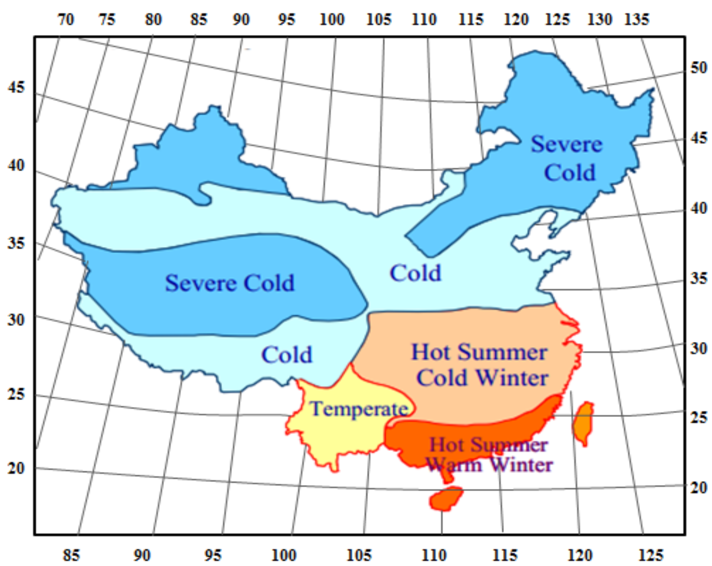



Figure 2-1 Building thermal design division (GB50176-93)

In order to make the civil building thermal design adapt to the regional climate, implement energy conservation and environmental protection policies, improve the residential building thermal environment and raise the heating and cooling energy efficiency, China adopted corresponding thermal design specification requirements《Code for thermal design of civil buildings-GB50176》[1]. According to this code, China was divided into five different climatic zones from north to south, which are Severe Cold (SC) Zone, Cold (C) Zone, Hot Summer and Cold Winter (HSCW) Zone, Hot Summer and Warm Winter (HSWW) Zone and Temperate (T) Zone, respectively. One of the most important characteristics of the Chinese climate is that winter and summer have long durations. Climate- responsive building strategies that are appropriate for each zone need to be implemented.

Building thermal zoning standards and design requirements have been showed in Table 2-1. The average temperature of the coldest month and the hottest month are taken as the key indicator of subzone, the number of days of Daily Mean Temperature (DMT) ≤5ºC and ≥25ºC are taken as an auxiliary criterion. Different climatic zones have different design requirements of heat preservation in winter and heat protection in summer.

Table 2-1 Building thermal zoning standards and design requirements

| **Zone Name** | **Zoning Standard** | | **Design requirements** |
|---|---|---|---|
| | **Main** | **Auxiliary** | |
| **Severe Cold** | Average temperature of the coldest month is ≤-10ºC | The number of days of DMT ≤5ºC is ≥145 | Must fully meet the requirements of heat preservation in winter;<br>Generally do not consider the heat protection in summer |
| **Cold** | Average temperature of the coldest month is 0~-10ºC | The number of days of DMT≤5ºC is 90~145 | Meet the requirements of heat preservation in winter;<br>Consider the heat protection in summer in some areas |
| **Hot Summer and Cold Winter** | Average temperature of the coldest month is 0~-10ºC<br>Average temperature of the hottest month is 25~30ºC | The number of days of DMT≤5ºC is 0~90;<br>The number of days of DMT≥25ºC is 40~100 | Must meet the requirements of heat protection in summer;<br>Consider the heat preservation in winter |
| **Hot Summer and Warm Winter** | Average temperature of the coldest month is >10ºC<br>Average temperature of the hottest month is 25~29ºC | The number of days of DMT≥25ºC is 100~200; | Must fully meet the requirements of heat protection in summer;<br>Generally do not consider the heat preservation in winter |
| **Temperate** | Average temperature of the coldest month is 0~-13ºC<br>Average temperature of the hottest month is 18~25ºC | The number of days of DMT≤5ºC is 0~90; | Consider heat preservation in winter in some areas;<br>Generally do not consider the heat protection in summer |

### 2.2.2 Climate characteristics and requirements for architectural design

In order to distinguish the influence otherness of climate conditions in different zones of China on the building, clarity the basic elements of building in each climate zone, and provide the climate parameters of building, China formulated the 《Standard of climatic regionalization for architecture- GB50178-93》 in 1993(2), this standard described the climate characteristics of each zone and basic requirements of building located in each climate zone.

1. Climate characteristics of each zone

(A) The Severe Cold Zone: very long and Severe Cold in winter, short and cool in summer, the average temperature in January is -31ºC ~-10ºC, the average temperature in July is below 25ºC, the annual range of outdoor air temperature is larger. The west is dry and the east is moist. The annual average relative humidity is 50%~70%, the annual precipitation is 200~800mm. The freeze-up period is long and the accumulated snow is thick.

(B) The Cold Zone: long, cold and dry in winter, hot and humid in summer, the precipitation is relatively concentrated. The average temperature in January is -10ºC ~0ºC, the average temperature in July is 18~28ºC. The annual average relative humidity is 50%~70%, the annual precipitation is 300~1000mm. Spring and autumn are short and dramatic changes in temperature. The sunshine is relatively abundant.

(C) The Hot Summer and Cold Winter Zone: sultry in summer, humid cold and small daily range of temperature in winter, the annual precipitation is large, the sunshine amount is less. The average temperature in January is 0ºC ~10ºC, the average temperature in July is 25ºC ~30ºC. The annual average relative humidity is 70%~80%, the annual precipitation is 1000~1800mm. It is the Meiyu Period in late spring and early summer, the overcast and rainy weather is much, there are frequently heavy rains and rainstorm.

(D) The Hot Summer and Warm Winter Zone: hot in summer, warm in winter and a high humidity all the year round. Both the annual range and daily range of outdoor air temperature are small, the annual precipitation is large. The average temperature in January is higher than 10ºC, the average temperature in July is 25ºC ~32ºC. The annual average relative humidity is over 80%, the annual precipitation is 1500~2000mm. There is frequently stormy weather because coastal areas suffered from many tropical storms and typhoons. The solar radiation is strong, the sunshine is abundant.

(E) The Temperate Zone: mild in winter, cool in summer, clear dry and wet seasons. The average temperature in January is 0ºC ~13ºC, the average temperature in July is 18ºC ~ 25ºC. The annual average relative humidity is 60%~80%, the annual precipitation is 600~2000mm. Foggy all around the year, the annual range of temperature is less, the daily range of temperature is larger, the sunshine is less.

2. The basic requirements of building in each climatic zone

(A) The Severe Cold Zone: The building located in the Severe Cold Zone must be fully meet the requirements of cold protection, heat preservation and freeze prevention in winter. It does not need to take into account the thermal protection in summer. The general plan, the monomer design and structural treatment should make the buildings meet the requirements of the sunshine and cold wind protection in winter. Buildings should take some energy-saving measures such as the reduction of exposed area, the improvement of the airtightness in winter, and the reasonable utilization of solar energy. The accumulated snow and freeze-thaw erosion and harm should be taken into consideration in roof construction.

(B) The Cold Zone: The buildings located in this zone must be meet the requirements of cold protection, heat preservation and freeze prevention in winter. The thermal protection of partial area should be taken into account in summer. The general plan, the monomer design and structural treatment should make the buildings meet the requirements of the sunshine and cold wind protection in winter. The main rooms should avoid the sunshine from the west. Buildings should take some energy-saving measures such as the reduction of exposed area, the improvement of the airtightness in winter and ventilation in summer, and the reasonable utilization of solar energy.

(C) The Hot Summer and Cold Winter Zone: The buildings located in this zone must meet the requirements of thermal protection in summer, ventilation and cooling, and appropriate cold protection in winter. The general plan, the monomer design and structural treatment should be conducive to good natural ventilation; the buildings should avoid the sunshine from the west, and meet the requirements of moisture-proof, rain-proof and flood control.

(D) The Hot Summer and Warm Winter Zone:

The buildings located in this zone must meet the requirements of thermal protection, ventilation and rain-proof in summer. The cold protection and heat preservation in winter need not be considered. The general plan, the monomer design and structural treatment should be clear and bright, full utilization of natural ventilation, the buildings should avoid the sunshine from the west and set the sunshade, and it should meet the requirements of moisture-proof, heavy rain-proof and flood control.

(E) The Temperate Zone: The buildings of partial area located in this zone must meet the requirements of cold protection and heat preservation in winter. The buildings should meet the requirements of rain-proof and ventilation in wet season, need not take the thermal protection into consideration. The general plan, the monomer design and structural treatment should be conducive to good natural ventilation in wet season. The main rooms should have good orientation; the buildings should pay attention to moisture-proof.

## 2.3 Comparison of literature survey in different climate zones

The objects of this literature survey are the ordinary multi-unit residences in use. The scopes are prior articles which were published after the 2000s, about 99 papers in China. These papers include master's thesis, academic journal and Seminar report, etc. The survey contents are shown in Table 2-2. Regarding the arrangement method, the data about residential attribute, envelope structures and heating conditions was directly extracted from the corresponding literature survey to make the proportion graphs based on residential number in five climate zones. Moreover, the data about indoor temperature and energy consumption of each residence was extracted from the average value of corresponding literature survey to make the box graphs.

Table 2-2 Contents of literature survey

| Survey items | Survey contents |
|---|---|
| Residential attribute | Construction age, structure, floor area, building layers |
| Envelope structures | External wall and window |
| Heating conditions | Heating methods, heating equipment |
| Field measurements | Indoor temperature, energy consumption |

### 2.3.1 Literature classification

Figure2-2 shows the proportion of literature in different climatic zones. There were 14 articles[(3)-(16)], 33 articles[(17)-(49)], 42 articles[(50)-(91)], 8 articles[(92)-(99)] and 2 articles[(100)(101)] in Severe Cold Zone, Cold Zone, Hot Summer Cold Winter Zone, Hot Summer Warm Winter Zone and Temperate Zone, respectively. It is worth noting that so far the related research mainly focused on the Cold Zone and Hot Summer and Cold Winter Zone, accounted for 34% and 40% respectively, what occupies the proportion to be least is the temperate. This is a result of less large and medium-sized cities and its unique geographical conditions.

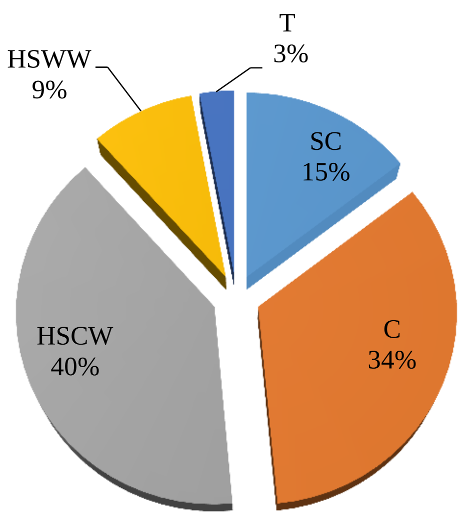



Figure 2-2 Climate zones classification

Figure2-3 shows the research contents of these classic literatures that we investigated (3)-(101). The research mainly focused on the measurement of indoor thermal environment, performance optimization of envelope structure, statistics and simulation of energy consumption and evaluation of thermal sensation. The research on indoor thermal environment have accounted for more than 30% in different climate zones. With the exception of the SC zone, the research on the evaluation of the thermal sensation of the indoor occupants is few. The research on economic comparison of air conditioning usage patterns only appeared in the C zone and HSCW zone. Moreover, as shown in Figure 2-3, the literatures about the HSWW and T climate zone are few in number. This means the attention of researchers was only paid to the influence of cold climate on multi-unit residences in winter. However, today it is also required to clarify the thermal environment of multi-unit residences in the regions where need cooling in summer or throughout the year.

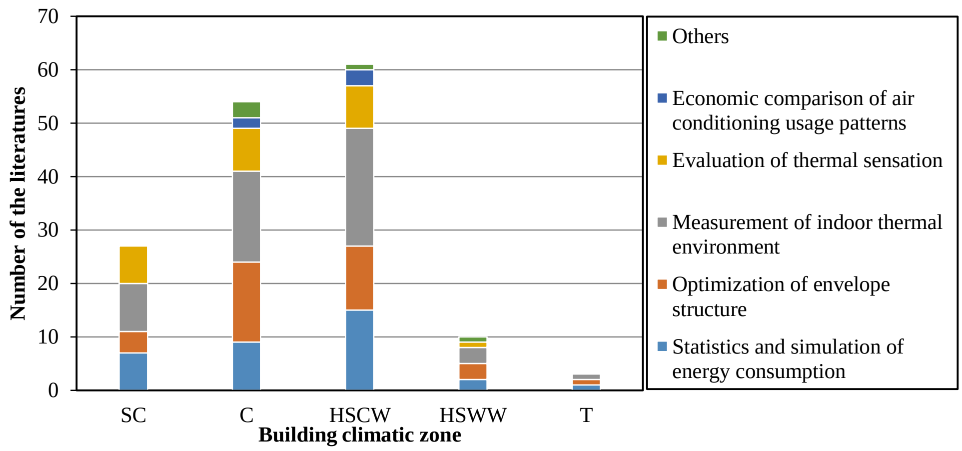



Figure 2-3 Research contents classification

### 2.3.2 Residential attribute

a) Completion year of residential building

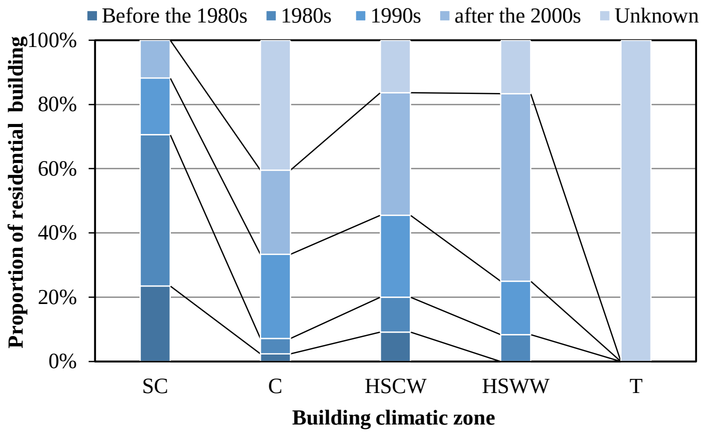



Figure 2-4 Completion year classification

Figure 2-4 shows the completed years by literature survey on the residential indoor thermal environment in different climate zones. These data derived from 35 articles and 144 residences(5)(9)-(14)(17)(18)(30)-(33)(37)(39)(41)-(44)(67)(68)-(71)(73)-(76)(91)(95)-(97)(101). It can be seen that there are some differences between different climate zones. For example, most residences reported by previous researches were built before the 1990s in the Severe Cold Zone, while after the 1990s in the other climate zones. Even to the extent that the residences which were built after the 2000s accounted for main sector in HSCW and HSWW zone. It means that attention of researchers in cold regions is mainly concentrated in the renovation of old buildings, while the improvement around the new building in the warm regions.

b) Construction structure of residential building

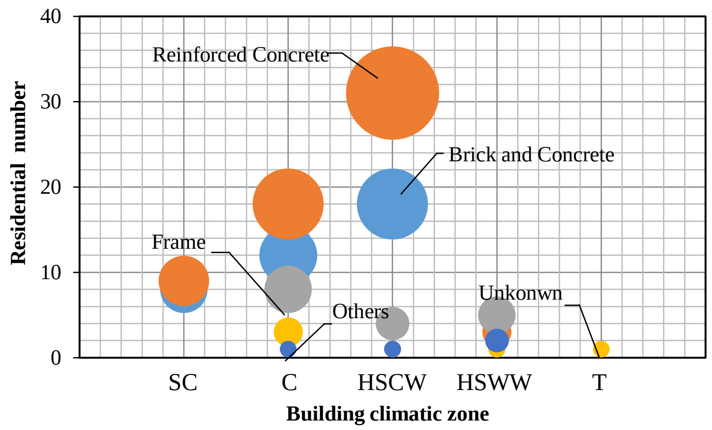



Figure 2-5 Construction structure classification

Figure 2-5 shows the construction structure classification of different climate zones. These data derived from 43 articles and 164 residences[(3)(5)(9)-(14)(17)(18)(32)-(39)(41)-(45)(52)(67)(68)-(81)(96)(97)(101)]. Without considering the unknown, reinforced concrete and brick concrete accounted for a larger proportion in areas where the weather was colder in winter. This is because the rise of frame structure is relatively late, but most residences reported by previous researches were built before the 2000s in the north. However, in the southern region, due to the large proportion of new residential, the frame structure gradually replaced of reinforced concrete and brick structure.

c) Floor area

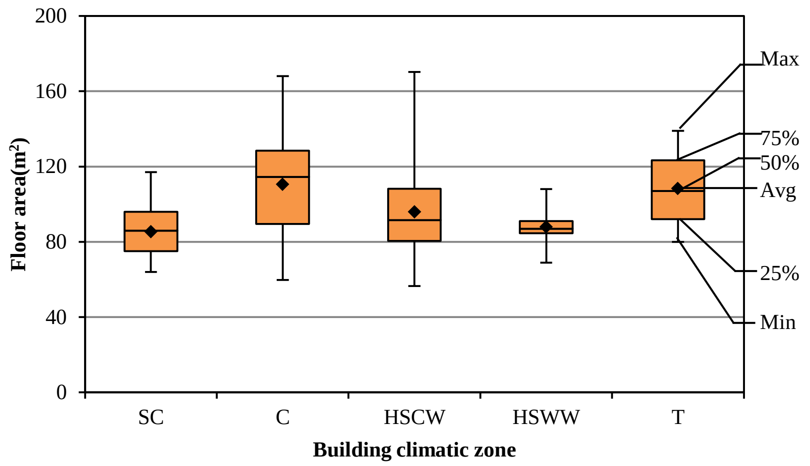



Figure 2-6 Floor area classification

Figure 2-6 shows the floor area classification of different climate zones. These data derived from 41 articles and 144 residences[(3)(5)(9)-(14)(17)(18)(30)-(33)(35)(37)-(39)(41)-(43)(45)(52)(67)(68)-(77)(79)-(80)(95)-(97)(101)]. The floor area is smaller in the Severe Cold and Hot Summer and Warm Winter Zone as a whole. Floor area less than 95m$^2$ accounted for 75% and the average floor area of 85.3m$^2$ in the Severe Cold Zone. Followed by the Hot Summer and Warm Winter Zone, that the average floor area of 87.8m$^2$. The influence of climate condition is one of the reasons, heating consumption in winter in the Severe Cold Zone and cooling consumption insummer in the Hot Summer and Warm Winter Zone make up a bigger component. The larger the floor area, energy consumption will also increase. Therefore, compared with other areas, the floor area of the two climate zones is smaller. While the floor area is relatively large in the other climatic zones, the proportion of households that the floor area is larger than 90m$^2$ is more than 50%. The average floor area in the Cold Zone is the largest, which is 110.5m$^2$. It is worth noting that there are households that floor area more than 160m$^2$ in both Cold Zone and Hot Summer and Cold Winter Zone.

d) Residential building layers

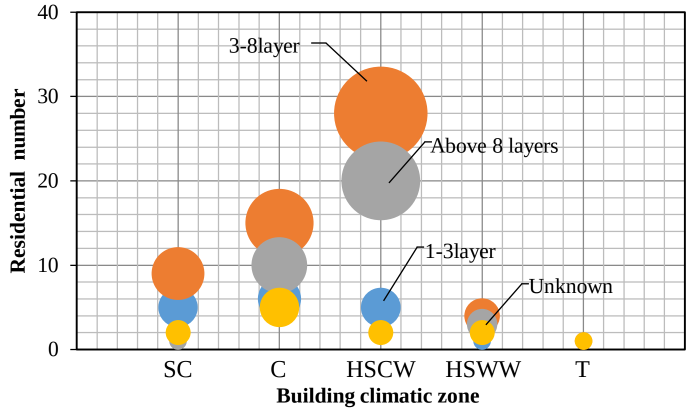



Figure 2-7 Residential building layers classification

Figure 2-7 shows the residential building layers. These data derived from 32 articles and 109 residences[(3)(9)-(14)(30)-(32)(34)(37)(41)-(45)(67)(71)(73)-(76)(78)-(81)(95)(96)(101)]. Residential buildings are mainly divided into low-rise residence, multi-storey residence and high-rise residence. It can be seen that most of the residential buildings are low-rise and multi-story building in the Severe Cold Zone and Hot Summer and Warm Winter Zone, and there are almost no high-rise residential buildings which more than 8 stories. This is because most of the high-rise residential buildings are facing the problem of natural light and ventilation resulted from several flats with one staircase. And the building shape coefficient of high-rise residential buildings is large, heat loss area of its enclosure structure is larger, then heat transfer through building envelope is bigger. This is not favourable to save energy. Therefore, in the area of high energy consumption of heating and air conditioning, the proportion of high-rise residential is less. However, multi-storey and high-rise residential buildings become two basic residential form of cold and Hot Summer and Cold Winter Zone.

Based on the above analysis and discussion of the residential attribute in the past literature, in accordance with the composition of residential building materials, as well as the age and building layers, residential buildings can be classified as follows:

(1) Before 1980, residential building is mainly low-rise and multi-storey residential which composed of brick and concrete structure, and the floor area is relatively small.

(2) Between 1980~2000, multi-storey residential dominated by brick and concrete structure accounted for main sector.

(3) Since 2000, reinforced concrete multi-storey and high-rise residential buildings become the era of signs, and the construction area has gradually increased.

### 2.3.3 Envelope structure

For the four major envelope components of building, including roof, wall, floor, doors and windows, the exterior wall, doors and windows are the main factors that affect the indoor thermal comfort and building energy saving. From the point of view of energy saving, the proportions of energy loss through the exterior wall and exterior window in the energy loss of entire building can be up to 27% and 19% [(102)], respectively. Therefore, it is an important link of building energy saving to find out the heat preservation and insulation condition of the exterior wall and exterior window of residential buildings.

a) External wall structure

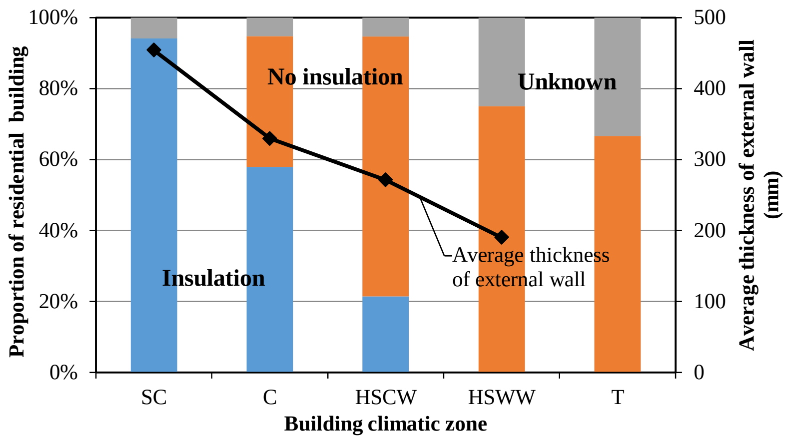



Figure 2-8 External wall structure classification

Figure 2-8 shows the condition of thermal insulation and the average thickness of external wall in different climate zones. These data derived from 43 articles and 169 residences[(3)(9)-(14)(17)-(18)(32)-(39)(41)-(45)(52)(67)-(79)(81)(91)(95)-(97)(101)]. Due to the outdoor temperature is extremely low in winter, without considering the unknown, all of the residential buildings in Severe Cold Zone have thermal insulation materials. The average thickness of external wall reached about 450mm, and the average thickness of thermal insulation material is about 60mm[(3)(9)-(14)]. The thermal performance of external walls is relatively better than other climate zones. In the Cold Zone, nearly 60% of residential buildings have insulation structure. Compared with the Severe Cold and Cold Zones, only about 20% of the residential buildings have insulation structure in Hot Summer and Cold Winter Zone. Even to the extent that the residential buildings have no insulation layer in the Hot Summer and Warm Winter Zone and temperate residential zone. And the average thickness of external wall is only about 200mm[(95)-(97)] in the Hot Summer and Warm Winter Zone. It is less than half the thickness of the external wall of the Severe Cold Zone. This is mainly due to the effect of improvement of the external wall thermal insulation performance on heating energy saving is obvious for cold regions in winter, but energy saving effect is little on air conditioning for hot summer hot regions in summer.

b) External window structure

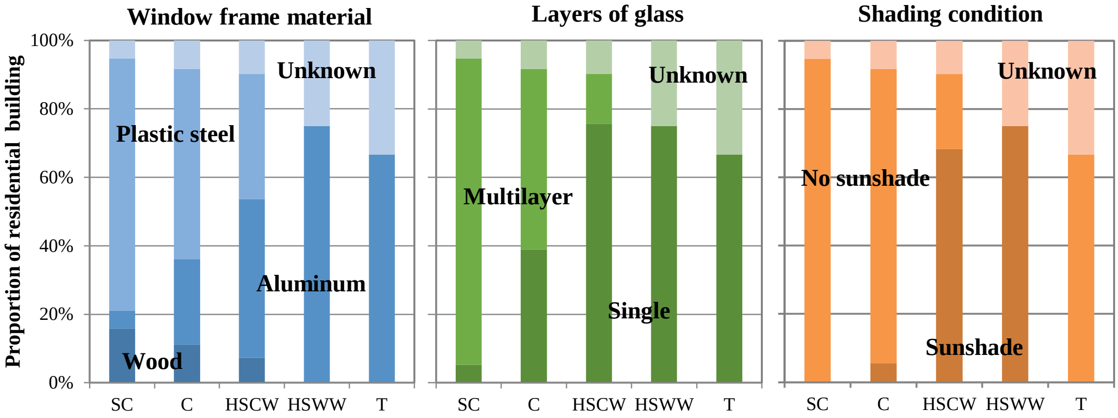



Figure 2-9 External window structure classification

Figure 2-9 shows the external window structure including window frame material, layers of glass and shading condition. These data derived from 40 articles and 163 residences[(3)(9)-(14)(17)-(18)(32)-(34)(36)-(39)(41)-(45)(67)(68)-(78)(80)(81)(91)(96)(97)(101)]. It can be seen that the residential buildings in southern region mainly adopts aluminum alloy window frame, it accounted for nearly 80% in Hot Summer and Warm Winter Zone. While the external window mainly use the plastic-steel window frame, less aluminum alloy and wooden window in northern regions. This may be due to thermal insulation performance of plastic-steel window frame is far better than the aluminum alloy window frame (The heat transfer coefficient of plastic-steel window frame is 2.0~2.8W/m$^2$k, while it is 4.2~4.8 W/m$^2$k of aluminum alloy and even bigger of wood frame [(37)]). Therefore, under the permission of condition, plastic-steel window frame have been selected for thermal insulation effect in the residential buildings of northern regions.

Regarding the glass material, more than 90% of residential buildings adopted double glazing in the Severe Cold Zone, followed by the Cold Zone is about 50%. However, more than 70% of the outer windows of residential buildings in southern China are single glazing. It is worth to explain that Low-e glass gradually popular in the southern residential buildings beyond the year 2000. Moreover, windows are usually equipped with the sunshade measures in hot summer regions, less shading measures in northern China.

## 2.3.4 Heating methods and equipment

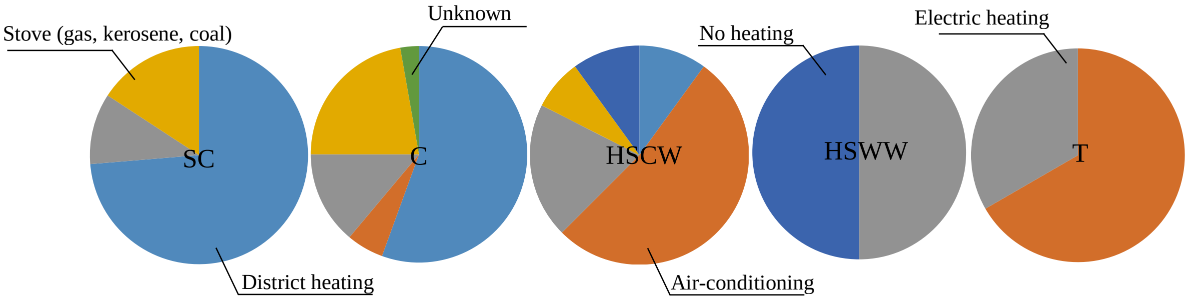



Figure 2-10 Heating methods and equipment

Figure 2-10 shows heating methods and equipment in different climate zones. These data derived from 42 articles and 148 residences[(3)(5)(9)-(14)(17)(18)(30)-(33)(35)-(39)(41)-(45)(67)(68)(81)(101)]. As the chart shows, in addition to the Hot Summer and Warm Winter Zone and a few residential buildings of Hot Summer and Cold Winter Zone, ownership rate of winter heating equipment in other areas has reached 100%. The proportion of district heating in Severe Cold Zone and Cold Zone was 74% and 56%, respectively. Figure 2-11 shows the diagram of district heating system.

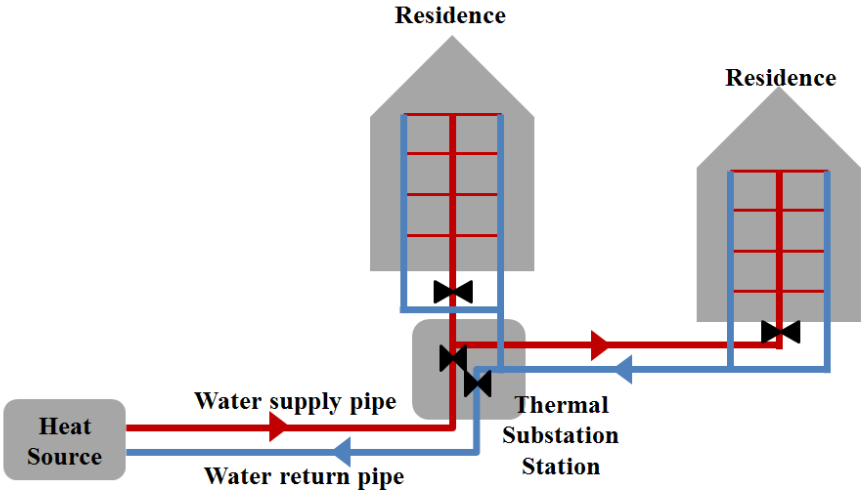



Figure 2-11 Diagram of district heating system

The frequently-used heat sources of district heating system are Combined Heat and Power (CHP) and Regional boiler room. Of which, Combined Heat and Power (CHP) refers to the mode of production which the power plant can not only produce electric energy, but also take advantage of the steam worked by the turbo generator to heat the users. The thermal medium of district heating system is generally hot water or steam. Because the energy efficiency of steam is low and the transportation distance is only 3~5km, while the heat loss of hot water medium is relatively less and the transportation distance can reach 15~20km, leading to be more common.

The supply and return water temperature of heating medium of district heating system is generally 80/60ºC, but the supply and return water temperature of low temperature floor radiant heating is relatively lower, 60/40ºC in general. The dedicated equipment room that connects the heat source and users, and is equipped with the heat exchange equipment (which can convert steam to hot water), distribution valves, measuring instruments and water pumps is called thermal substation station.

Figure 2-12 Heat source

Figure 2-13 Water supply and return pipe

There are also differences in radiator types adopted in the central heating residences. Among them, the ordinary cast iron radiator as shown in Figure 2-14 (a), which is mainly concentrated in the residential built in 70's ~90's, the proportion is about 32%. While the steel radiator as shown in Figure 2-14 (b), which is mainly concentrated in the residential built around 2000s, the proportion is 47%. Moreover, the radiant floor heating with low temperature, as shown in Figure 2-14 (c), is a new type of heating that was introduced and gradually rising after 2000 year.

(a) (b) (c)

Figure 2-14 Type of radiator in residences with district heating system

In addition, single household heating is a common heating system besides district heating, users can adjust according to demand. The stove heating is a relatively primitive heating way.

Use penetration rate of stove including gas, kerosene and coal is also higher in residential buildings that were built before 90s. Among them, coal stove as shown in the Figure 2-15(a) is more common. In Severe Cold and Cold Zones, the proportion of using air conditioning for heating is low. This is due to the limitations of heating area and larger heat capacity for matching floor area resulting from the larger temperature difference between indoor and outdoor, heating efficiency of air conditioning in winter is much lower than cooling in summer.

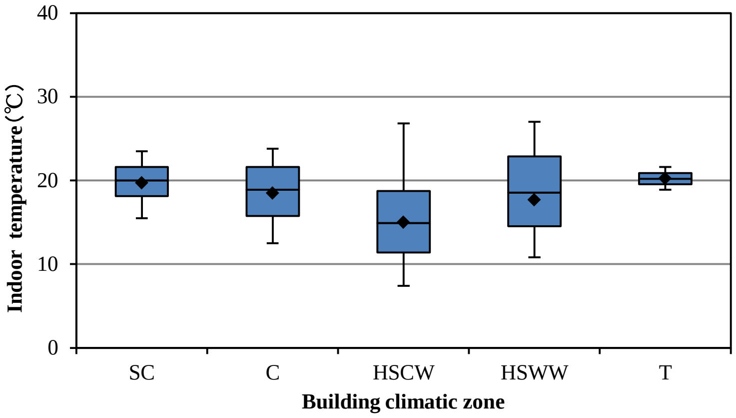
However, compared with the northern regions, the proportion of district heating in the Hot Summer and Cold Winter Zone is only 10%., Air conditioning has become the main heating equipment in the Hot Summer and Cold Winter Zone. About 53% of residences used air conditioning for heating. Moreover, there are 20% of residences that used electric heating in winter, now more popular is the oil filled electric heater as shown in the Figure 2-15(b). But the efficiency of dispersing heating is low, and there are also security risks. Especially the use of air conditioning and electric heating is not only high cost, but also a waste of resources. Some experts point out that, in the process of converting thermal energy into electrical energy, 50% of energy is lost [103]. The use of electric energy for heating, equivalent to the conversion from electrical energy to heat energy, energy efficiency is relatively low. Therefore, the heating mode in Hot Summer and Cold Winter Zone will become the research focus.

(a) (b)

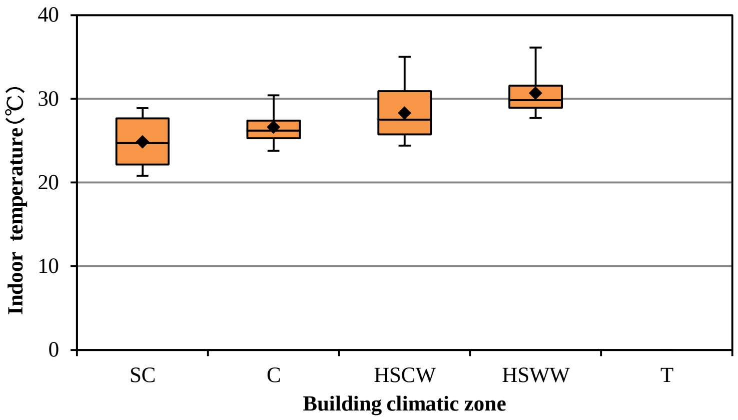
Figure 2-15 Household heating devices

Furthermore, due to the small number of researched residential buildings, there are 50% of the houses have no heating equipment in the Hot Summer and Warm Winter Zone, while the other 50% is using electric heating for heating.

### 2.3.5 Indoor thermal environment




(a)Indoor temperature in winter




(b)Indoor temperature in summer

Figure 2-16 Residential indoor thermal environments

Figure 2-16 shows the literature survey results of residential indoor thermal environment in different climate zones. These data derived from 47 articles and 196 residences[(9)-(14)(17)(18)(30)-(45)(49)(50)(67)-(77)(81)-(83)(91)(95)-(97)(101)]. As shown in (a), the indoor average temperature of the Severe Cold Zone and the Cold Zone in winter was more than 18ºC which is design temperature of district heating. It not only had a bearing on the good thermal insulation performance of residence but also on the demand for comfort of residents. This is because these two zones belongs to the district heating regions, and district heating penetration rate of current literature research was 74% in the Severe Cold Zone and 56% in the Cold Zone as above mentioned, the residential indoor temperature distribution is relatively narrow. In contrast, in non-district heating areas such as the Hot Summer and Cold Winter Zone, the average indoor temperature is lower than the Severe Cold Zone and the Cold Zone. The temperature range that is from 7.4ºC to 26.8ºC is more widely dispersed. The indoor thermal environment is poor in the case of non-air conditioning use. It cannot meet the requirements of the comfort of people. Compared with the Hot Summer and Cold Winter Zone, because the winter is short and the outdoor temperature is higher, the average indoor temperature of Hot Summer and Warm Winter Zone increased. And the temperature distribution is also widely than that of the district heating regions. In addition, because of the better climate conditions, and no district heating, the indoor thermal environment is more comfortable in the Temperate Zone.

Figure 2-16 (b) gives the indoor temperature of residence in summer. Compared with the data in winter, there was little difference in average indoor temperature of different zones. At the same time, the distribution ranges of temperature were relatively concentrated. The highest average temperature appeared in Hot Summer and Warm Winter Zone, which is about 30.6ºC. This temperature is much higher than the comfort temperature in summer. This also shows that the summer indoor thermal environment is relatively poor in this zone. This is mainly because the summer in this zone is intensely hot and air-conditioning was used intermittently. Air-conditioning coexists with natural ventilation mode in summer in these zones. In addition, heat insulation measures of residential envelope structures were poorer than that in Cold Zones. Therefore, heat gain through envelope was considerably much. Except for the Hot Summer and Warm Winter Zone, the highest indoor temperature reached 35ºC in the case of no using air conditioning equipment in Hot Summer and Cold Winter Zone. However, the average indoor temperature in this zone is still within the acceptable temperature range. In addition, it can be seen that the summer indoor thermal environment in the Severe Cold Zone and Cold Zone is relatively comfortable, which the average temperature are 24.84ºC and 26.6ºC respectively.

To sum up the above arguments, improving the indoor thermal environment in winter in Hot Summer and Cold Winter Zone and indoor thermal environment in summer in Hot Summer and Warm Winter Zone become the first priority of residential buildings. In addition, it can be seen that the survey on the humidity, the temperature difference between the upper and lower part, PMV values, WBGT and so on were very few.

### 2.3.6 Energy consumption

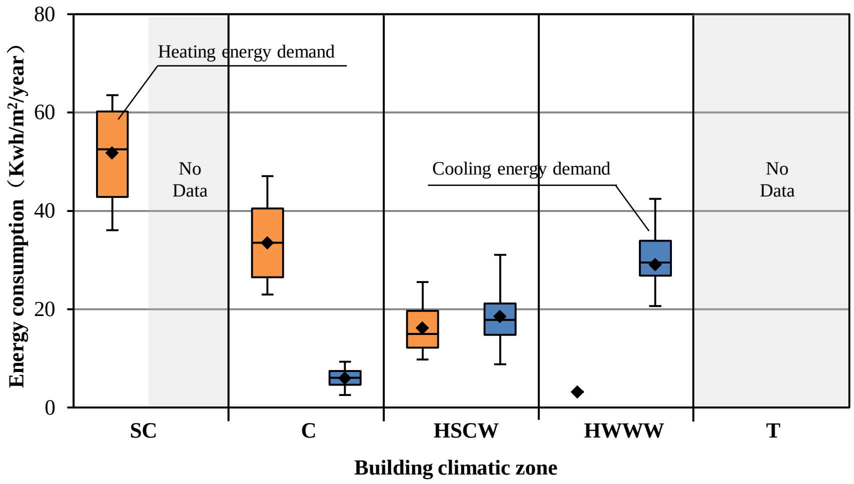



Figure 2-17 Annual energy consumption of heating and cooling

Figure 2-17 shows the literature survey results of residential annual energy consumption of heating and cooling in different climate zones. These data derived from 27 articles, among them, 19 articles obtained by actual investigation[(3)(5)(9)(11)(12)(18)(33)(35)-(37)(50)(68)(71)(72)(75)(76)(95)-(97)] and 8 articles[(4)(46)(53)(58)(59)(84)-(86)] obtained by large-scale questionnaire survey. As the chart shows, annual heating energy consumption of Severe Cold Zone is far more than other climate zones, mainly concentrated in 40~60Kwh/m$^2$. The Cold Zone is district heating area same as the Severe Cold Zone. Due to the current district heating charges by the floor area, there are different charges standards in different climatic zones and different cities. For example, the charge standard in Harbin which is located in the Severe Cold Zone is 34.32yuan/ m$^2$, while is 30.4 yuan/m$^2$ in Qingdao which is located in the Cold Zone. The charge standard in Cold Zone is less expensive than the Severe Cold Zone. And the annual heating energy consumption in Cold Zone is lower than that in Severe Cold Zone. The cooling energy consumption in Cold Zone is less, far less than the energy consumption for heating. Moreover, there is not much difference between annual heating and cooling energy consumption in the Hot Summer and Cold Winter Zone. The sum of cooling and heating energy consumption is almost the same as that in Cold Zone. The Hot Summer and Warm Winter Zone has the highest annual cooling energy consumption. But compared with the annual heating energy consumption in Severe Cold Zone and Cold Zone, the annual cooling energy consumption of these zones is less. This is due to the temperature difference between indoor and outdoor in winter is far greater than in summer, the load for cooling is lower than heating. Blessed with the unique climate, there is no statistics of annual energy consumption in Temperate Zone.

## 2.4 Conclusion

In this chapter, building climatic zoning, thermal design requirements and climate characteristics of five different climatic zones in China had been introduced. And then, this chapter summarized and analyzed the related research on the multi-unit residences in different climatic zones. Through reviewing the literature reference of 99 papers, the main conclusions were obtained as follows:

1) The previous studies about the multi-unit residences mainly concentrated in the Cold Zone and Hot Summer and Cold Winter Zone. And the research mainly focused on the measurement of indoor thermal environment, performance optimization of envelope structure, statistics and simulation of energy consumption and evaluation of thermal sensation.

2) Attention of researchers in cold regions was mainly concentrated in the renovation of old buildings, while the improvement around the new building in the warm regions. Reinforced concrete and brick concrete accounted for a larger proportion in northern regions, while the frame structure gradually replaced of reinforced concrete and brick structure in southern regions. Most of referred residences were low-rise and multi-story building and the floor area was smaller in the Severe Cold and Hot Summer and Warm Winter Zone. However, the multi-storey and high-rise residential buildings with larger floor area became two basic forms in the Cold and Hot Summer and Cold Winter Zone.

3) Compared with northern regions, there were few wall and window insulation measures; the thermal performance of envelope structures was poor in southern regions. However, the external windows were usually equipped with the sunshade measures in Hot Summer and Cold Winter Zone and Hot Summer and Warm Winter Zone.

4) About the heating methods and equipment, northern regions were mainly district heating and stove, while southern regions mainly relied on air conditioning.

5) Based on statistical analysis of the data in the previous studies, it is considered that improving the indoor environment in winter in Hot Summer and Cold Winter Zone and in summer in Hot Summer and Warm Winter Zone was the most important for multi-unit residences. In addition, the survey on the humidity, the temperature difference between the upper and lower part, PMV values, WBGT and so on were very few.

6) Compared with the annual cooling energy consumption in Hot Summer and Warm Winter Zone, the annual heating energy consumption of Severe Cold Zone was more serious.

Based on the above findings, it can be found that the research scope was limited to some large cities such as Beijing and Shanghai, and there was little research that simultaneously compared the different climate zones in China and that comprehensively considered the indoor thermal environment and energy consumption. Therefore, research focus of this study and oversight of all climatic zones are clarified.

## References

(1)China Academy of Building Research, Thermal design code for civil building (GB50196-93), China Planning Press, 1993.

(2)China Academy of Building Research, Standard of climate regionalization for architecture(GB50178-93), Ministry of Construction of the PRC,1993.

(3)Hai yan WANG, De xing SUN, Bin ZHANG, Test Result Analyses of Heating Energy Consumption for Energy Efficiency of Residential Building on Severe Cold Zone, Energy Conservation Technology, 2006, 24(1):42~45.

(4)Liang YU, Hiroshi YOSHINO, Research on energy consumption of urban apartment buildings in China, J. Environ. Eng., AIJ, pp.183-190, Vol73, No.624, 2008.

(5)Rui XING, A study of effective global warming countermeasures and marginal abatement cost for theChinese prefectural residential sector, J. Environ. Eng., AIJ, pp.899-907, Vol.77, No.681, 2012.

(6)Zhaohui CHEN, Dynamic simulation and analysis of residential building energy consumption in severe cold zone, Master Thesis of Xinjiang University, 2007.

(7)Peijie ZHOU, Energy saving design and solution of doors and windows in severe cold and cold zones, Door ＆ Windows, 2010, (12):30~38.

(8)Xingzhong GUO, A simulation study in the effect of thermal properties of doors and windows on building energy consumption, New Building Materials, 2014,(S1):54~57.

(9)Kaicheng LIU, Test and analysis of energy consumption of maintenance structure of existing brick concrete residence in severe cold zone, Testing&Research, 2013, (10):18~19.

(10)Yuelin MA, Thermal environment and energy saving analysis of urban housing in severe cold zone, Master thesis of Shenyang Jianzhu University,2013.

(11)Changquan XU,Jinling ZHAO,Field study of thermal and humidity environment of urban residences in Northeast China with severe cold climate,HV&AC, 2013, 43(11):75~80.

(12)Xudong WAN, Jingchao XIE,Yaohua ZHAO, Survey and measurement result analysis on the thermal environment and energy consumption of urban residential buildings, Energy Conservation Technology, 2008, 26(147):68~74.

(13)Feng GAO, The research of residence indoor thermal environment in old industrial regions of Harbin and it's optimizational design, Master thesis of Xi'an University Of Architecture And Technology,2014.

(14)Feng GAO, Tiegang ZHOU, Research and Optimal Analysis on Indoor Thermal Environment of Existing Residence in Winter at Harbin, Construction Conserves Energy, 2016, 44(3):37~42.

(15)Zhaojun WANG, Study on indoor thermal environment and comfort in severe cold zone, Doctor thesis of Harbin Institute of Technology,2002.

(16)Zhaojun WANG, Analysis on the results of thermal comfort field study in residential buildings in Harbin, Building Energy & Environment, 2004, 23(3):5~8.

(17)Fei TIAN, Research on energy saving of living environment for new urban residence in Qingdao region, Master thesis of Xi'an University Of Architecture And Technology,2012.

(18)Bo YaMing, Yu Hang, Peng Hao, Investigation and Analysis of Heating Situations of Residential Buildings in Small Town of North China, Energy Conservation Technology, 2005, 23(4):343~347.

(19)Chen LIN, Xiaotong PENG, Energy consumption simulation and analysis of example composite structure residential in cold region, Architecture Technology, 2010, 44(3):205~208.

(20)Cuiyu GE, Hongguang WANG, Probe into Urban Residential Building Energy Saving in Cold Zone, Housing Science, 2004,(8):46~48.

(21)Xiaojie ZHOU, Prediction of residential building heating energy consumption based on thermal measurement of exterior wall, Master Thesis of Tianjin University, 2007.

(22)Zhiyong LIU, Simulation & research on heating energy consumtion for Xi’an residential building, Master thesis of Xi'an University Of Architecture And Technology,2008.

(23)Zhiqiang LU, Research on the influencing factors of energy consumption for Tianjin residential buildings, Master Thesis of Tianjin University, 2012.

(24)Huaizhu WANG, Research on economic and mechanism of energy consumption for low energy consumption residential housing in cold region of Inner Mongolia, Master Thesis of Inner Mongolia University of Science and Technology,2015.

(25)Ke HUANG, The feasibility of net zero energy buildings in China for residential buildings, Master Thesis of Tianjin University, 2014.

(26)Xin WU, Existing residential buildings in cold areas energy saving heating strategy—The case study of existing buildings in Zhangjiakou, Master Thesis of Hebei University of Technology,2011.

(27)Ping SUN, Simulation study on energy consumption of energy saving residential buildings, Master Thesis of Beijing University of Technology, 2005.

(28)En LI, Yasunori AKASHI, Daisuke SUMIYOSHI, Passive design strategy on residential buildings for sustainable development of Lhasa, Journal of Environmental Engineering. AIJ, July 2013 pp.471-480.

(29)Hairong DONG, Jiaping LIU, Thermal properties and energy analysis of residential building envelope in Zhangjiakou, HV&AC, 2003, 33(4):128~130.

(30)Hiroshi Yoshino, S. Guan, Y.F. Lun, Indoor thermal environment of urban residential buildings in China: winter investigation in five major cities, Energy and Buildings 36(2004), pp.1227-1233.

(31)Hiroshi Yoshino, Yasuko Yoshino, Qingyuan Zhang, Indoor thermal environment and energy saving for urban residential buildings in China, Energy and Buildings 38(2006), pp.1308-1319.

(32)Chengguang ZHAO, Research of external insulation energy saving reconstruction technology of Shandong existing building exterior wall, Master Thesis of Shandong Jianzhu University, 2010.

(33)Xiusong WU, The energy saving design and implementation on top frame shear wall structure building, Master Thesis of Changan University, 2011.

(34)Bin CHEN, Jinling ZHAO, Feifei PENG, Research on relationship between building envelope and indoor climate by means of surveying dwelling houses in winter in Dalian, Journal Heating Ventilating and Airconditioning, 2005, 35(7):117~121.

(35)Chen Mingdong, Shi Yuliang, Improvement of indoor thermal environment of rural residences with coupled heating of attached sunspace and energy saving hot-wall, Transactions of the Chinese Society of Agricultural Engineering, 2011, 27(11):232~235.

(36)Bo CHEN, Measurement and research on indoor thermal environment of residential buildings in winter in typical small towns in northern China, Master Thesis of Tianjin University, 2006.

(37)Xudong WAN, Investigation and numerical simulation of indoor thermal environment and energy consumption in residential buildings, Master Thesis of Beijing University of Technology, 2009.

(38)Feifei PENG, Study on indoor thermal and humid environment and adaptability of occupants in winter in residential buildings in cold zone, Master Thesis of Dalian University of Technology, 2003.

(39)Bin CHEN, Feifei PENG, Investigation and Research on indoor heat and humidity environment of urban residences in winter, Building Energy & Environment, 2002, 21(6):22~25.

(40)MAO Yan ,LIU Jiaping ,YANG Liu, Investigation and analysis on indoor thermal environment in summer for residential building in cold zone, Journal of Harbin Institute of Technology, 2009 (8):238~240.

(41)Gaochao DU, Improvement research on the indoor thermal environment in winter for residential buildings in the Zhenzhou, Master thesis of Xi'an University Of Architecture And Technology,2005.

(42)Yongqiang XIAO,Study on the thermal environment of air conditioning room in winter, Master thesis of Xi'an University Of Architecture And Technology,2004.

(43)Dengjia WANG, Yanfeng LIU, Yi WANG, Measurement and Evaluation of Indoor Thermal Environment of Residential Buildings in Lhasa in Winter, Building Science, 2011, 27(12):20~24.

(44)Lin DUAN, Jinping ZHANG, Changfeng LI, Measurement and Analysis of Winter Thermal Environment in Residential Buildings in Lanzhou, Building Energy ＆ Environment, 2010,(6):56~59.

(45)DI Yuhui, LIU Jiaping , HUANG Xiang, Thermal environment research of a tall residential building in Xi’an, Journal of Xi an University of Engineering Science and Technology, 2006, 20(1):108~111.

(46)Li Zhaojian, Xie Deqiang, Jiang Hongbin, Wei Xing. Testing Study on Operating Behavior and Energy Consumption of Air Conditioners in Residential Buildings in Beijing, Journal of HV&AC, pp15~20,Vol.44, No.2,2014.

(47)Weihao WANG, Dongyang WANG, Xilian LUO, Energy Consumption Simulation and Energy Saving Analysis on Envelope of Existing Building, Building science. 2007, 23(2):22~26.

(48)Yizai Xia,Rongyi Zhao,Yi Jiang. Study on thermal comfort of residential environment in Beijing, Journal of HV&AC, pp1~5, Vol.29, No.2, 2000.

(49)Zhu Peisheng, Guo Fei, Zhu Tong, Liu Shuguo. Field Investigation of Dalian Apartment Thermal Environments and Thermal Adaptation in winter, Journal of Low Temperature Architecture Technology, 2013, 183(9):127~129.

(50)Zhou Xiang, Zhang Qiqi, Zhang Jingsi, Survey and heat demand analysis of winter residential indoor environment in Shanghai, HV&AC, 2013, (6):64~67.

(51)SHI Xiaofei, PEI Ying, Investigation and Analysis on Influence Factors Affecting Residential Energy Consumption in Shanghai, Construction Conserves Energy, 2012, (1):68~70.

(52)WANG Xiaolin, YU Hang, Investigation and Analysis of Energy Consumption of Residential Buildingsin Shanghai Songjiang District, Construction Conserves Energy, 2007, 35(7):53~55.

(53)Zheng Shun, Zhou Xiang, Zhang Jingsi, Survey and analysis on energy consumption of air conditioning for residential buildings in Shanghai in summer,HV&AC, 2016, 46(3):38~41.

(54)Guangjun ZHU, Xiaoliang ZHANG, Simulation study on heating and air conditioning energy consumption of residential buildings in Shanghai, Building Science, 2004, (Z1):265~268.

(55)Jianguo Geng, Research on the indoor daylighting environment and energy consumption of Shanghai shaded residential building, Master thesis of Tongji University of Technology,2008.

(56)Fengmei SUN, Nianping LI, Liang YAO, Residential building energy consumption actual measurement hourly and energy characteristics study, Refrigeration& Air conditioning, 2006, 36(6):1~5.

(57)Han Bin, The research on residential energy saving design based on the energy consumption in Changsha area, Master thesis of Hunan University, 2013.

(58)Yang ZHANG, Zhijia HUANG, Comparison of air conditioning energy consumption in typical maintenance structures of multi-storey residential buildings in Ma'anshan, Energy Conservation, 2009, (7):40~41.

(59)Zhijia HUANG,Ting ZHANG, Comparison of energy consumption in typical residential buildings of different years in Ma'anshan, Heating refrigeration, 2011, (6):30~31.

(60)Xuchun WEI, Zhigang ZHANG, Influence and analysis of different exterior wall heat preservation methods on wall thermal performance, Energy Conservation, 2012, 31(10):49~54.

(61)LIU Qian , ZHANG Xu, Energy Consumption Simulation and Energy-saving Analysis on Residential Building Envelope in Shanghai, Building Science, 2007, 23(12):24~26.

(62)Longjun CAI, Lingfeng YAO, The effect of residential building envelope performance on the annual energy consumption of air conditioning in Shanghai, China Housing Facilities, 2008, (7):40~43.

(63)Longjun CAI, Lingfeng YAO, Envelope Performance of Residential Building on the Annual Air-conditioning Heating Energy Consumption in Shanghai, Construction Conserves Energy, 2010, (2):19~23.

(64)SUN Yulin, LIN Zhongping, WANG Xiaomei, An Investigation of Envelope Situation and Simulation of Heating/Cooling Energy Consumption for Rural Residential Buildings in Shanghai, Building Science, 2011, 27(2):38~42.

(65)Heng FU, Influence of external window on low energy resident building consumption, Master thesis of Nanjing University of Technology,2011.

(66)Jian Yiwen, Jiang Yi, Influence of window-wall ratio on annual energy consumption for heating and air conditioning in residential buildings, HV&AC, 2006, 36(6):1~5.

(67)Yougui PAN, Measurement and investigation of indoor environment and energy consumption of residential buildings in Changsha, Master Thesis of Hunan University, 2004.

(68)Xudong WAN, Jingchao XIE,Yaohua ZHAO, Survey and measurement result analysis on the thermal environment and energy consumption of urban residential buildings, Energy Conservation Technology, 2008, 26(147):68~74.

(69)Liu Jianlong, Xia Xiaoqian, Zhang Haiping, Investigation and Analysis on Indoor Thermal Environment of Urban Residential in Eastern Hunan, Journal of Hnnnan University of Technology, 2013, 27(4):34~40.

(70)FENG Xiaoping, QIAN Baoguo, ZHANG Pengfei, Measurement and Analysis on Indoor Thermal Environment of Town House in Southern Region of Jiangsu, Building Science, 2010, (4):44~47.

(71)Tiequn XU, The study on winter urban residential building indoor thermal environment in the edge of hot summer and cold winter zone—a case study of Bengbu, Master thesis of Xi'an University Of Architecture And Technology,2013.

(72)FENG Ya, NAN Yanli, ZHONG Huizhi, Energy Efficiency and Indoor Thermal Environment Design of Urban Buildings in Hot Summer and Cold Winter Zone, Building Science, 2012, 28(12):21~24.

(73)Yaya LI, The indoor thermal environment in winter of the residential for the hot summer and cold winter context—take Hangzhou, Hefei for example, Master thesis of Xi'an University Of Architecture And Technology,2013.

(74)Weiqing Meng, Research on indoor thermal environment of residential buildings in urban areas in hot summer and cold winter zone in winter season— take Hanzhong city as an example, Master thesis of Xi'an University Of Architecture And Technology,2013.

(75)Changhai PENG, Study on thermal environment of residential buildings in hot summer and cold winter zone in China, Doctor Thesis of Dongnan University, 2003.

(76)Shanshan YAO, Monitoring and analysis on indoor thermal environment of existing residential buildings in Nanjing, Master Thesis of Dongnan University, 2012.

(77)Chen Hongqing, Long Enshen, Huang Luhong, Discussion of the Indoor Thermal Environment of Prefab House in Winter of Chengdu, Refrigeration ＆ Air-condition, 2011, (1):60~64.

(78)Mingfang TANG, Research of residential thermal environment in summer in Chongqing, Journal Heating Ventilating and Airconditioning, 2001, 31(4):16~17.

(79)Shi Jie, Li Zhengrong, Song Dexuan, Indoor thermal environment investigation on high-rise residences in summer in Shanghai, HV&AC, 2007, 37(5):118~121.

(80)Xiaoyun PENG, Research on thermal environment for the loft of residence in Nanchang, Building Science Research of Sichuan, 2007, 33(5):194~197.

(81)Xia Bo, Song Dexuan, Research on the summer indoor thermal environment of Shanghai high-rise residential buildings, Industrial Construction, 2013, 43(4):45~48.

(82)Ruihua SHI, Zhenhai LI, An Investigation and Analysis on Indoor Thermal Environment of Urban Residential Buildings in Shanghai, Energy Technology, 2005, 26(1):27~30.

(83)Zhenhai LI, Ruihua SHI, Study on summer indoor thermal environment of residential building in Shanghai, Refrigeration Technology, 2005,(3):13~16.

(84)Pingfang Hu, Zhangning Jiang,Yuhan Leng, Investigation of thermal environment and energy consumption for Hubei residences, Journal of HV&AC, 2004, 34(6):21~22.

(85)W D Long, T Zhong,B H Zhang. Situation and trends of residential building environment services in Shanghai, Proceedings of the 2003-4th International Symposium on heating, Ventilating and Air conditioning. Beijing: Tsinghua University Press, pp493~498, 2003.

(86)Nianping Li. Investigation and analysis on summer energy structure of residential buildings in Changsha, Journal of HV&AC, pp14~17, Vol.34, No.5, 2004.

(87)Caixin Wei, Energy consumption simulation and analysis on the technical economy of air conditioning schemes of residential buildings in Hot Summer and Cold Winter Zone, Master Thesis, Dong Hua University, 2007.

(88)Longjun CAI, Lingfeng YAO, Envelope Performance of Residential Building on the Annual Air-conditioning Heating Energy Consumption in Shanghai, Construction Conserves Energy, 2010, (2):19~23.

(89)Nan LI. Impacts of human behavior on energy consumption of residential buildings in China’s Hot Summer and Cold Winter Zone, Doctor Thesis, Chongqing University, 2011.

(90)Xuan CHENG, Case study on influence of occupant behavior on residential air handing unit and energy consumption, Building Science,Vol.31,No.10,2015.

(91)Li Nianping, Pan Yougui, Hiroshi Yoshino. Field Measurement and Analysis of Indoor Thermal Environment of Changsha Urban Residential Buildings, Journal of Building Energy &Environment, 2004, 23(1):94~98.

(92)Yuan ZOU, Simulation & analysis of thermal performance and energy consumption of residential buildings in hot summer and warm winter zone, Master thesis of Xi'an University Of Architecture And Technology,2004.

(93)Lizhen YANG, Simulation and analysis of residential building energy consumption in Guangzhou, Master thesis of South China University of Technology,2002.

(94)YANG Lizhen, MENG Qinglin, Influence on energy consumption of air-conditioning by windows in Guangzhou's residential buildings, Journal of Xi'an University of Architecture & Technology, 2002, 34(1):30~33.

(95)Ran Maoyu, Liu Xiaoxun, Hu Shen, Wu Yang, The measurement and analysis of the natural ventilation and indoor thermal environment in summer for a beach residence at Xiamen, Fujian Architecture ＆ Construction, 2010, (9):98~101.

(96)LI Zhisheng, LIAO Jiawen, LIU Xuhong, Measurement and Analysis on Indoor Thermal Environment for Typical Residences in Urban Village in Guangzhou, Building Science, 2011, 27(8):24~28.

(97)Liao Jiawen, Measurement and Analysis of Thermal Environment in Dwellings of Low-income Families in Huangpu Village of Guangzhou, Contamination Control ＆ Air-Conditioning Technology, 2011, (3):6~9.

(98)Zengwen PU. Influence of Low-e glass on air conditioning load and building energy consumption, Journal of HV&AC, pp119~121, Vol.35, No.8, 2005.

(99)Ding Xiujuan, Zheng Qinghong, Hu Qinghua, Li Kuishan. Investigation of Thermal Environment of Residential Buildings in Dong Guan, Journal of Building Energy & Environment, 2007, 26(5):82~85.

(100)Zhu Wei, Zhou Wei, Qu Wen, Research on the Building Energy saving Situation of Highrise Residence in Kunming, Hua Zhong Architecture, 2012, 30(4):52~55.

(101)XU Bingfeng, FENG Yan, ZHOU Ming, Statistics and Analysis on Indoor Environmental Condition of Kunming’s Dwelling in Summer, Nonferrous Metals Design, 2006, 33(1):15~20.

(102)Peng RAN, Application of building exterior wall insulation and energy saving technology in building construction, Henan science and technology, 2010.

(103)Energy ramble：The South may also have central heating, China Petroleum Information Center, 2012.2.

# CHAPTER 3 FIELD INVESTIGATION OF INDOOR THERMAL ENVIRONMENT AND ENERGY CONSUMPTION IN MULTI-UNIT RESIDENCES IN WINTER

## 3.1 Introduction

So far, multi-unit residences are the main type of home for ordinary families in most urban cities in China [(1)]. However, because of different climate conditions, heating methods, thermal insulation structure, life styles, and energy consumption ideas, there are wide variations in indoor thermal environments and energy consumption of multi-unit residences in winter of different climate zones in China. However, there is little research that simultaneously compares the different climate zones in China and that comprehensively considers the indoor thermal environment and energy consumption. In order to grasp residential indoor thermal environment and heating energy demand in winter as well as its influencing factors comprehensively, the investigation on multi-unit residences of different climate zones in China was conducted through field measurement and questionnaire analysis. On such basis, rational improvement proposals and measures to improve the comfort of indoor thermal environments and energy conservation in winter are discussed.

## 3.2 Investigation Summary

### 3.2.1 Selection of investigation cities

The residences under winter investigation were located in the urban areas of Harbin from the Severe Cold Zone, Qingdao from the Cold Zone, Hangzhou from the Hot Summer and Cold Winter Zone, respectively. City selection was based on the international cooperation projects conducted by different local researchers. These are major cities in China, which are representative of each climate zone as shown in Figure 3-1.

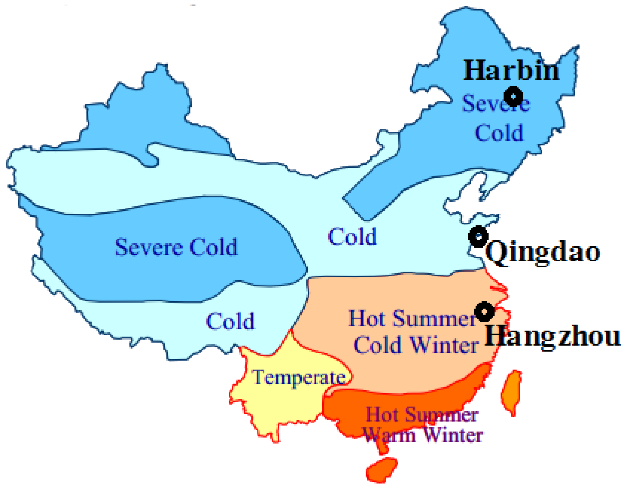



Figure 3-1 Selected cities in different climate zones

Building design requirements are different depending on climate conditions, because generally there is no need to consider the heat preservation in winter in the Hot Summer and Warm Winter Zone as well as the Temperate Zone [(2)], and less heating energy demand was proved in previous studies[(3)]. Therefore, the field measurement was not conducted in winter of the Hot Summer and Warm Winter Zone as well as the Temperate Zone.

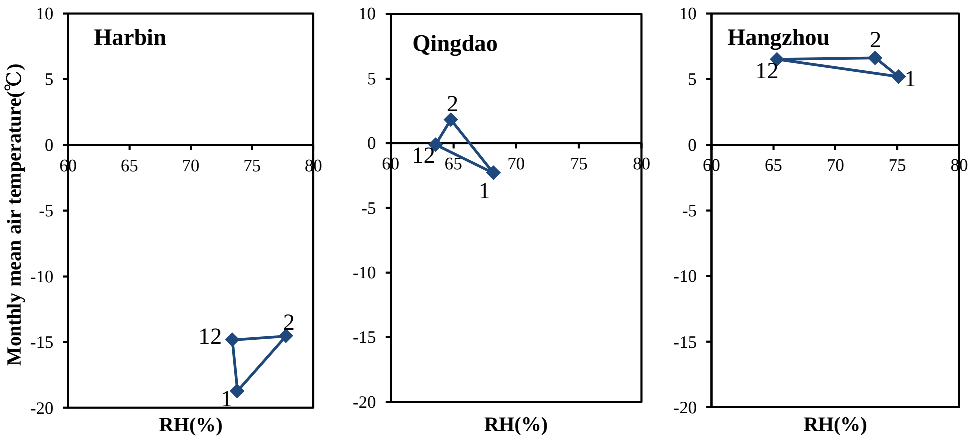



Figure 3-2 Climate characteristics of three representative cities

Figure 3-2 shows the winter climograph (Nov~Mar) of three cities for investigation in China. The climate data comes from the freely available Energy-Plus weather database-International Weather for Energy Calculations (IWEC)(4). Because of the lack of weather data for Qingdao in IWEC, here it was replaced with the nearby city of Longkou. It is worth noting that the climates of the different cities have great disparities.

Harbin is located in the Severe Cold Zone that is the coldest climate zone. It can be seen from the climograph of Harbin, the average temperature of the coldest month of Harbin is -18.7ºC with the relative humidity of 73.8%. The number of days that Daily Mean Temperature is lower than 5ºC accounts for 176. Therefore, there are district heating in most of the urban residences of Harbin, the heating period was about from October 20th to April 20th, as long as 182 days.

Qingdao is located in the Cold Zone that is warmer than Harbin and colder than Hangzhou in wnter. It can be seen from the climograph of Qingdao, the average temperature of the coldest month which is January of Qingdao is -2.3ºC with the relative humidity of 68%. The number of days that Daily Mean Temperature is lower than 5ºC accounts for 128. The most of the urban residences of Qingdao also has the district heating system, the heating period was about from November 16th to April 5th, as long as 141 days.

Hangzhou is located in the Hot Summer and Cold Winter Zone which is hotter than Qingdao in winter. It can be seen from the climograph of Hangzhou, the average temperature of the coldest month which is January of Hangzhou is 5.2ºC with the relative humidity of 75%. The number of days that Daily Mean Temperature is lower than 5ºC only accounts for 65. Considering the investment cost, the most of the urban residences in Hangzhou have no district heating system. Heating mainly rely on air conditioning and other heating equitments.

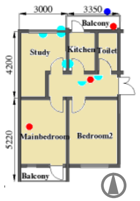
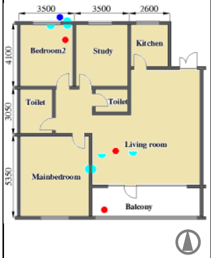
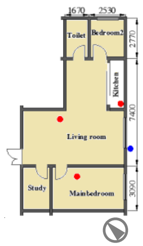
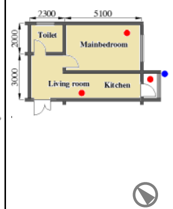
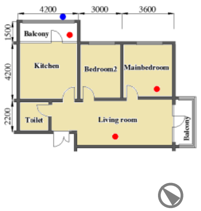
### 3.2.2 Field measurement summary

In each city, 9 participating families were random selected as the measured objects by local collaborative researchers based on whether the residents were willing or not. I undertook the field measurement in person in Harbin and Qingdao, and assisted the local collaborative researchers to conduct the measurement in Hangzhou throughout the survey. The field measurements lasted for about two weeks in each investigation city. Indoor and the outdoor air temperature and relative humidity as well as the surface temperatures were measured by small data loggers with sensors as shown in Table 3-1. Air temperature and relative humidity monitoring points were placed in the bedroom, living room, non heating room (at a height of about 1.1 m from the floor level) and outdoor (north side of the building shaded from the sun). Surface temperature monitoring points were placed in inside and outside surface of exterior wall, interior wall, exterior window as well as floor surface, ceiling surface. Because of the cumbersome setting of instruments and the strict requirements of monitoring points, the surface temperatures were measured only in Qingdao and Hangzhou as well as one residence in Harbin. Summary of measured residences and monitoring points are illustrated in Table 3-2.

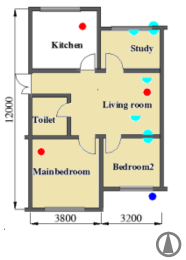
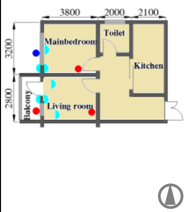
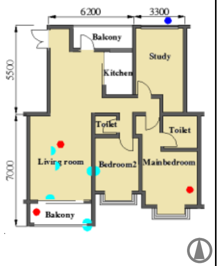
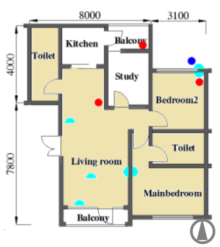
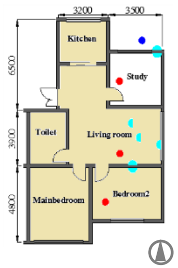
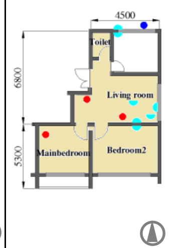
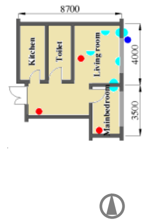
Table 3-1 Test instruments

| **Instrument** | TAG: temperature and humidity recorder | Thermo Recorder |
|---|---|---|
| **Model** | testo174H | TR-52i |
| **Range** | -20~+70°C, 0~100%RH | -60~+155°C |
| **Accuracy** | ±0.5°C,±3%RH | ±0.3℃ |
| **Test interval** | 10 minutes | 10 minutes |
| **Photograph** |  |  |

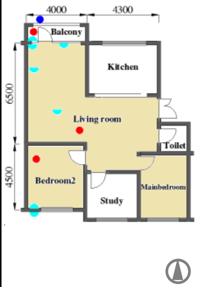
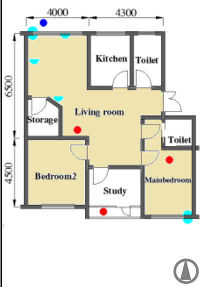
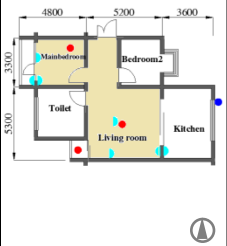
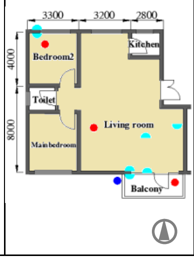
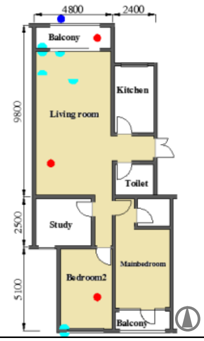
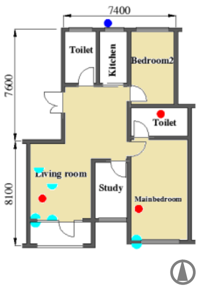
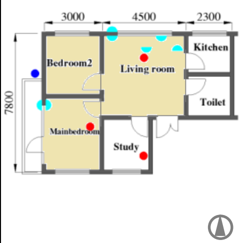
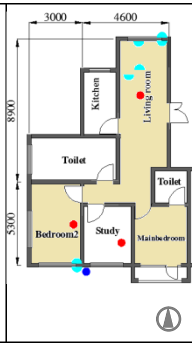
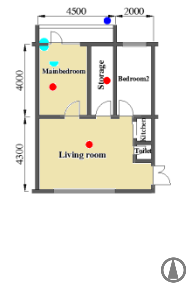
Table 3-2 Summary of measured residences and monitoring points

<table>
<tr><th colspan="2"></th><th colspan="16">The Severe Cold Zone(SC)—Harbin</th></tr>
<tr><th colspan="2">NO.</th><th>SC-1</th><th>SC-2</th><th colspan="3">SC-3</th><th colspan="2">SC-4</th><th colspan="2">SC-5</th><th colspan="3">SC-6</th><th colspan="2">SC-7</th><th>SC-8</th><th>SC-9</th></tr>
<tr><td colspan="2"></td><td></td><td></td><td colspan="3"></td><td colspan="4"></td><td colspan="3"></td><td colspan="3"></td><td></td></tr>
<tr><td colspan="2">Build/Repair year</td><td>1980s/2010</td><td>2001</td><td colspan="14">2012</td></tr>
<tr><td colspan="2">Structure</td><td>BC</td><td>BC</td><td colspan="14">RC</td></tr>
<tr><td colspan="2">Floor/Total</td><td>5/6</td><td>4/7</td><td colspan="3">5/24</td><td colspan="2">14/24</td><td colspan="2">2/24</td><td colspan="3">24/24</td><td colspan="2">3/24</td><td>19/24</td><td>4/24</td></tr>
<tr><td colspan="2">Construction area ($m^2$)</td><td>96</td><td>158</td><td colspan="3">120</td><td colspan="2">120</td><td colspan="2">120</td><td colspan="3">90</td><td colspan="2">120</td><td>48</td><td>115</td></tr>
<tr><td colspan="2">Position</td><td>West End</td><td>Middle</td><td colspan="3">Middle</td><td colspan="2">Middle</td><td colspan="2">Middle</td><td colspan="3">Middle</td><td colspan="2">Middle</td><td>East End</td><td>East End</td></tr>
<tr><td colspan="2">Envelope*</td><td>Unknown</td><td>Exterior window: k=3.0w/(m$^2$ • °C)<br>Exterior wall: k=0.63w/(m$^2$ • °C)<br>Roof: k=0.21w/( m$^2$ • °C)</td><td colspan="14">Exterior window: k=2.0w/(m$^2$ • °C)<br>Exterior wall: k=0.45w/(m$^2$ • °C)<br>Roof: k=0.21w/( m$^2$ • °C)</td></tr>
<tr><td colspan="2">Units of AC</td><td>0</td><td>0</td><td colspan="3">0</td><td colspan="2">0</td><td colspan="2">0</td><td colspan="3">0</td><td colspan="2">0</td><td>0</td><td>0</td></tr>
<tr><td rowspan="2">Family members</td><td>Age</td><td>30~40</td><td>60~</td><td>~10</td><td>30~40</td><td>60~</td><td>~10</td><td>30~40</td><td>~10</td><td>30~40</td><td>~10</td><td>10~20</td><td>30~40</td><td>~10</td><td>30~40</td><td>60~</td><td>40~50</td></tr>
<tr><td>Number</td><td>1</td><td>2</td><td>1</td><td>2</td><td>1</td><td>1</td><td>2</td><td>1</td><td>2</td><td>1</td><td>1</td><td>2</td><td>1</td><td>2</td><td>2</td><td>2</td></tr>
<tr><td colspan="2">Measured period</td><td colspan="5">2016.12.21~2017.1.5</td><td colspan="7">2017.1.6~1.19</td><td colspan="4">2017.1.19~2.3</td></tr>
<tr><td colspan="2" rowspan="2">Plan and monitoring points**</td><td></td><td></td><td colspan="3"></td><td colspan="4"></td><td colspan="3"></td><td colspan="2"></td><td></td><td></td></tr>
<tr><td colspan="16">● Outdoor air temperature ● Indoor air temperature ● Surface temperature</td></tr>
</table>

* Detailed materials of external envelope construction are shown in appendix.
** The fill color of the room represents the district heating area.

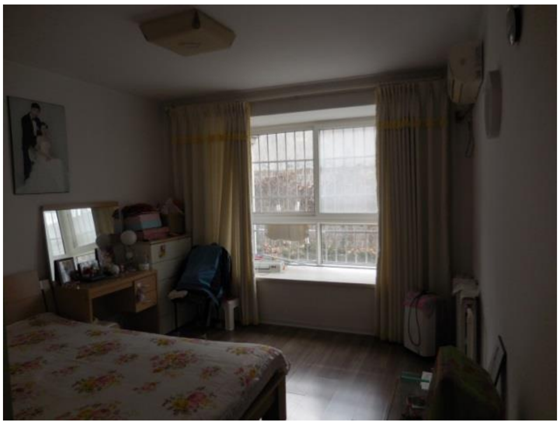
| | The Cold Zone(C)—Qingdao | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **NO.** | **C-1** | **C-2** | **C-3** | **C-4** | **C-5** | **C-6** | **C-7** | **C-8** | **C-9** |
| |  |  |  |  |  |  |  |  |  |
| **Build/Repair year** | 1998 | 1990 | 2007 | 2009 | 2004 | 2007 | 1996 | 2000 | 1987 |
| **Structure** | BC | BC | RC | RC | BC | RC | RC | RC | BC |
| **Floor/Total** | 1/7 | 1/6 | 3/8 | 6/21 | 3/6 | 6/8 | 7/7 | 3/7 | 3/8 |
| **Construction area ($m^2$)** | 92 | 49 | 128 | 135 | 113 | 128 | 80 | 70 | 56 |
| **Position** | Middle | North End | Middle | Middle | East End | Middle | East End | East End | Middle |
| **Envelope*** | Exterior window: k=3.4w/($m^2$ • °C) Exterior wall: k=1.20w/($m^2$ • °C) Roof: k=0.76w/( $m^2$ • °C) | Unknown | Exterior window: k=3.4w/($m^2$ • °C) Exterior wall: k=0.86w/($m^2$ • °C) Roof: k=0.41w/( $m^2$ • °C) | Exterior window: k=2.2w/($m^2$ • °C) Exterior wall: k=0.6w/($m^2$ • °C) Roof: k=0.36w/( $m^2$ • °C) | Exterior window: k=3.4w/($m^2$ • °C) Exterior wall: k=1.09w/($m^2$ • °C) Roof: k=0.46w/( $m^2$ • °C) | Exterior window: k=3.4w/($m^2$ • °C) Exterior wall: k=0.86w/($m^2$ • °C) Roof: k=0.41w/( $m^2$ • °C) | Unknown | Exterior window: k=3.4w/($m^2$ • °C) Exterior wall: k=1.09w/($m^2$ • °C) Roof: k=0.51w/( $m^2$ • °C) | Unknown |
| **Units of AC** | 1 | 0 | 2 | 2 | 2 | 2 | 2 | 2 | 1 |
| **Family members — Age** | 10~20 / 30~40 | ~10 / 30~40 | ~10 / 30~40 | ~10 / 30~40 / 60~ | 10~20 / 30~40 | 10~20 / 40~50 | 10~20 / 40~50 | ~10 / 30~40 | 20~30 |
| **Family members — Number** | 1 / 2 | 1 / 2 | 1 / 2 | 1 / 2 / 1 | 1 / 1 | 1 / 2 | 1 / 2 | 1 / 2 | 2 |
| **Measured period** | 2014.12.19~2015.1.3 | | | 2015.1.5~1.19 | | | 2015.1.19~2.2 | | |
| **Plan and monitoring points**** |  |  |  |  |  |  |  |  |  |
| | ● Outdoor air temperature ● Indoor air temperature ● Surface temperature | | | | | | | | |

* Detailed materials of external envelope construction are shown in appendix.
** The fill color of the room represents the district heating area.

<table>
<tr><th colspan="2"></th><th colspan="20">The Hot Summer and Cold Winter Zone(HSCW)—Hangzhou</th></tr>
<tr><th colspan="2">NO.</th><th colspan="2">HSCW-1</th><th>HSCW-2</th><th colspan="2">HSCW-3</th><th colspan="3">HSCW-4</th><th colspan="2">HSCW-5</th><th colspan="2">HSCW-6</th><th colspan="3">HSCW-7</th><th colspan="2">HSCW-8</th><th colspan="3">HSCW-9</th></tr>
<tr><td colspan="2"></td><td colspan="2"></td><td></td><td colspan="2"></td><td colspan="3"></td><td colspan="2"></td><td colspan="2"></td><td colspan="3"></td><td colspan="2"></td><td colspan="3"></td></tr>
<tr><td colspan="2">Build year</td><td colspan="3">2007</td><td colspan="2">2008</td><td colspan="3">1999</td><td colspan="2">2004</td><td colspan="2">2007</td><td colspan="3">1996</td><td colspan="2">2004</td><td colspan="3">1987</td></tr>
<tr><td colspan="2">Structure</td><td colspan="3">RC</td><td colspan="2">F</td><td colspan="3">RC</td><td colspan="2">F</td><td colspan="2">RC</td><td colspan="3">BC</td><td colspan="2">F</td><td colspan="3">BC</td></tr>
<tr><td colspan="2">Floor/Total</td><td colspan="2">5/6</td><td>5/6</td><td colspan="2">14/23</td><td colspan="3">6/6</td><td colspan="2">10/23</td><td colspan="2">2/15</td><td colspan="3">5/6</td><td colspan="2">10/23</td><td colspan="3">5/6</td></tr>
<tr><td colspan="2">Construction area ($m^2$)</td><td colspan="2">130</td><td>130</td><td colspan="2">120</td><td colspan="3">109</td><td colspan="2">180</td><td colspan="2">155</td><td colspan="3">80</td><td colspan="2">130</td><td colspan="3">56</td></tr>
<tr><td colspan="2">Position</td><td colspan="2">Middle</td><td>Middle</td><td colspan="2">Middle</td><td colspan="3">West End</td><td colspan="2">Middle</td><td colspan="2">Middle</td><td colspan="3">West End</td><td colspan="2">West End</td><td colspan="3">Middle</td></tr>
<tr><td colspan="2">Envelope*</td><td colspan="3">Exterior window: k=4.1w/(m$^2$ • °C)<br>Exterior wall: k=1.53w/( m$^2$ • °C)<br>Roof: k=0.76 w/( m$^2$ • °C)</td><td colspan="2">Exterior window:<br>k=3.2w/( m$^2$ • °C)<br>Exterior wall:<br>k=1.09w/( m$^2$ • °C)<br>Roof: k=0.76w/( m$^2$ • °C)</td><td colspan="3">Exterior window:<br>k=4.7w/( m$^2$ • °C)<br>Exterior wall:<br>k=1.53w/( m$^2$ • °C)<br>Roof:<br>k=1.19w/( m$^2$ • °C)</td><td colspan="2">Exterior window:<br>k=3.4w/( m$^2$ • °C)<br>Exterior wall:<br>k=1.16w/( m$^2$ • °C)<br>Roof: k=0.76w/( m$^2$ • °C)</td><td colspan="2">Exterior window:<br>k=4.1w/( m$^2$ • °C)<br>Exterior wall:<br>k=1.16w/( m$^2$ • °C)<br>Roof: k=0.76w/( m$^2$ • °C)</td><td colspan="3">Unknown</td><td colspan="2">Exterior window:<br>k=3.4w/( m$^2$ • °C)<br>Exterior wall:<br>k=1.16w/( m$^2$ • °C)<br>Roof:<br>k=0.76w/( m$^2$ • °C)</td><td colspan="3">Exterior window:<br>k=4.7w/( m$^2$ • °C)<br>Exterior wall:<br>k=2.03w/( m$^2$ • °C)<br>Roof: k=1.47w/( m$^2$ • °C)</td></tr>
<tr><td colspan="2">Units of AC</td><td colspan="2">3</td><td>3</td><td colspan="2">2</td><td colspan="3">3</td><td colspan="2">3</td><td colspan="2">3</td><td colspan="3">3</td><td colspan="2">3</td><td colspan="3">2</td></tr>
<tr><td rowspan="2">Family members</td><td>Age</td><td>30~40</td><td>10~20</td><td>20~30</td><td>10~20</td><td>30~40</td><td>~10</td><td>20~30</td><td>60~</td><td>10~20</td><td>30~40</td><td>~10</td><td>20~30</td><td>~10</td><td>30~40</td><td>60~</td><td>~10</td><td>30~40</td><td>~10</td><td>30~40</td><td>60~</td></tr>
<tr><td>Number</td><td>2</td><td>1</td><td>2</td><td>1</td><td>2</td><td>1</td><td>2</td><td>1</td><td>1</td><td>2</td><td>1</td><td>2</td><td>1</td><td>2</td><td>1</td><td>1</td><td>2</td><td>1</td><td>2</td><td>1</td></tr>
<tr><td colspan="2">Measured period</td><td colspan="5">2014.12.14~2015.1.2</td><td colspan="7">2015.1.3~1.18</td><td colspan="5">2015.1.18~2.1</td><td colspan="3">—</td></tr>
<tr><td colspan="2" rowspan="2">Plan and monitoring points**</td><td colspan="2"></td><td></td><td colspan="2"></td><td colspan="3"></td><td colspan="2"></td><td colspan="2"></td><td colspan="3"></td><td colspan="2"></td><td colspan="3"></td></tr>
<tr><td colspan="20">● Outdoor air temperature ● Indoor air temperature ● Surface temperature</td></tr>
</table>

* Detailed materials of external envelope construction are shown in appendix.
** The fill color of the room represents the rooms equipped with air conditioning.

(a) Living room panorama

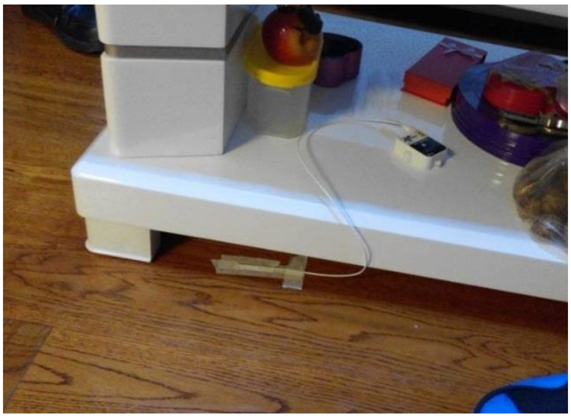


(b)Bedroom panorama

(c) Instrument set of indoor temperature and humidity

(d) Instrument set of ceiling surface

(e)Instrument set of wall surface



(f) Instrument set of floor surface

Figure 3-3 Photograph of field measurement

### 3.2.3 Questionnaire summary

In order to have a better understanding of the comfort requirements of residents and awareness of energy conservation, a detailed questionnaire survey was conducted at the same time. Occupants of field measurement residences were asked to answer a questionnaire, and the questionnaire data were collected at the end of the investigation. Questionnaire included basic information regarding their buildings, heating period, operation time during a day, clothing insulation, use of heating equipments and thermal sensation for indoor environments and energy consumption, and so on. Table 3-3 shows the contents of questionnaire.

Table 3-3 Contents of questionnaire

| | |
|---|---|
| **Building characteristic** | Construction/repair year, structure, floor areas, orientation, window and wall condition, layout and size |
| **Heating and cooling system** | Heating and cooling methods, ventilation system, operation time of heating, cooling and ventilation system |
| **Thermal sensation** | Thermal sensation for indoor environments, satisfaction rating |
| **Residential characteristic** | Number of occupants, age composition, occupation, occupancy time, clothing insulation value |
| **Energy consumption** | Consumption of city gas and electricity, annual district heating cost |

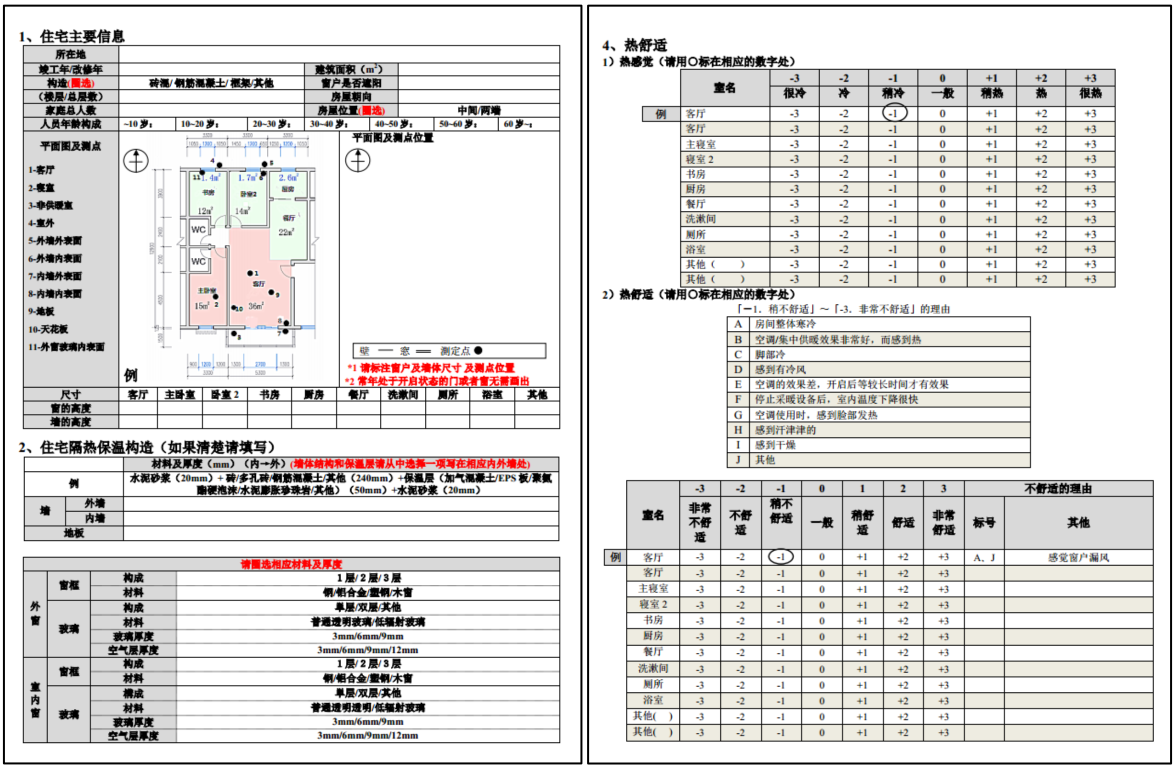


Figure 3-4 Photograph of questionnaire paper in Chinese

Table 3-4 shows the survey period, distribution number, answer number and response rate in each city.

Table 3-4 Questionnaire summary

| | Investigation city | Harbin | Qingdao | Hangzhou |
|---|---|---|---|---|
| Winter | Survey Period | 2016.12~2017.2 | 2014.12~2015.2 | 2014.12~2015.2 |
| | Distribution Number | 9 | 9 | 9 |
| | Answer Number | 9 | 9 | 9 |
| | Response Rate | 100% | 100% | 100% |

## 3.3 Investigation Results

3.3.1 Measured results in Harbin

3.3.1.1 Field measurement results

1. Indoor and outdoor temperature and relative humidity during the measured period

(1) Indoor and outdoor temperature

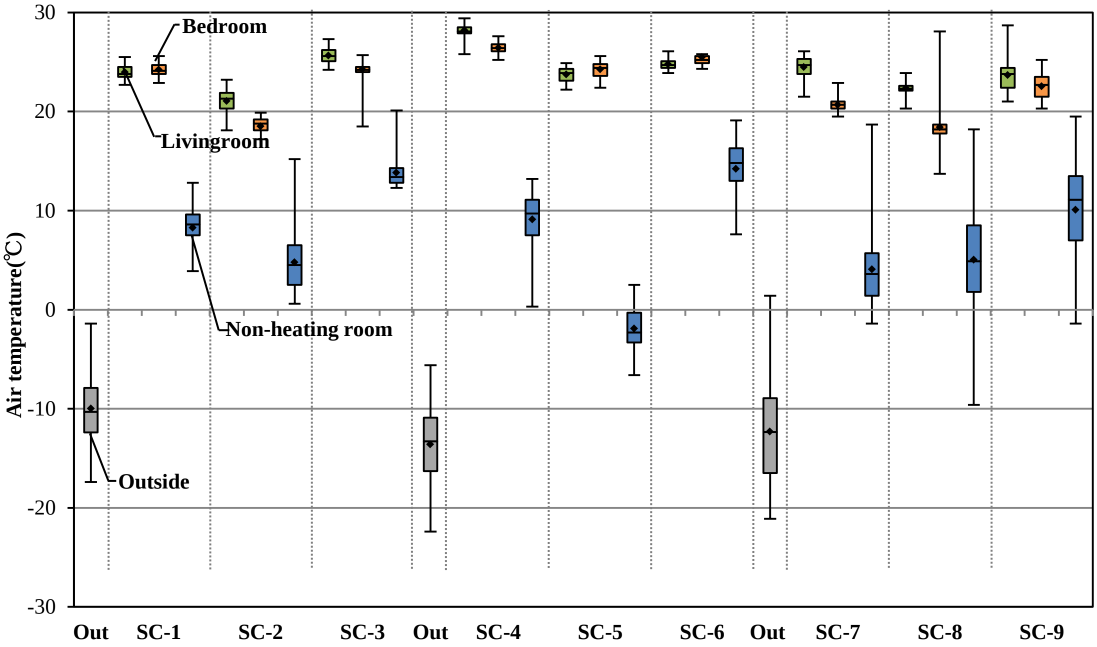



Figure 3-5 Temperature distribution in winter

Figure 3-5 shows the indoor and outdoor temperature distribution during the measured period in Harbin. The outdoor average temperature were all below -10 ºC during the three measured period, and even appeared the ultimate limit temperature of -22.4ºC in the second measured period. However, with the district heating system, the average temperatures of livingroom and bedroom were over 22ºC in most surveyed residences. And the distributions were concentrated that also benefited from district heating. SC-2 is a uninhabited house during field measurement, so the temperature distribution was relatively low. In addition, because the bedroom of SC-8 is located in the northeast, and the two sides are facing the outdoor, the indoor temperature was lower than the other residences which are located in the middle.

Although the temperatures of these two rooms were lower than that of the other residences, still slightly higher than the lower limit of the design temperature of district heating that is 18ºC. Because the charge method of district heating is based on floor area at present, with no household heat metering and moderating system. So even though the design temperature of district heating is 18ºC, in order to meet the heat demand of all households (including the residences which are located in the most disadvantageous circuit), so the actual indoor temperature in the reidences which located in the advantageous circuit is much higher than the design temperature. For example, the indoor temperature distribution of SC-4 even reached above 25ºC, the average temperatures of the living room and bedroom are 28.2ºC and 26.4ºC respectively. These temperature exceed the standard of district heating design temperature which are 18~22ºC, also far beyond the indoor comfort temperature range in winter which is specified by ASHRAE. Therefore, according to the surveys, because the temperature of district heating in winter is too high, many residents in this zone appeared the indoor overheating phenomenon. Except for the adjustment of clothing, the ventilation by openning window is often adopted.

In addition, it is worth noting that the temperature difference between indoor and outdoor of surveyed residences could reach up to 40ºC. Over large temperature difference between indoor and outdoor will lead to human disease, which not only can cause the unstable blood pressure but also can lead to the decrease of body resistance and be easy to catch a cold.

Moreover, the average temperatures of non-heating rooms of most residences were about 0~10ºC. The temperatures of non-heating rooms of residence SC-3 and SC-6 were relatively higher, the average temperatures were around 14ºC. This may be because the doors of heating and non-heating rooms are often open, resulting in the higher temperature of non-heating room. However, the temperature of non-heating room of residence SC-5 was relatively lower, the average temperature was only around -2ºC, it may be because the non-heating room is located in the balcony and the window is often open, resulting in the lower temperature. But the temperature of non-heating room may also be affected by the envelope structure performance and pattern of residential buildings. For example, compared with the other two residences during the same measured period, the residence SC-3 is a relatively new one with a better envelope external structure performance, so the temperature of non-heating room was higher. Residence SC-6 is located in the uppermost floor with better lighting, while the residence SC-5 is located in the bottom floor with poor lighting. So the temperature of residence SC-6 was higher than that of residence SC-5.

(2) Indoor and outdoor relative humidity

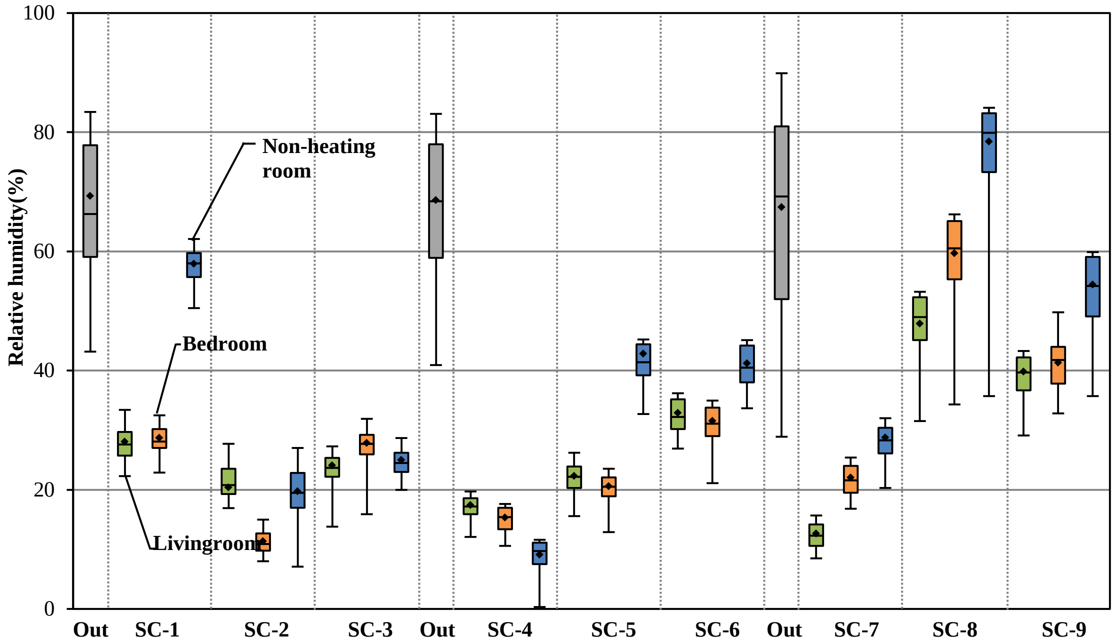
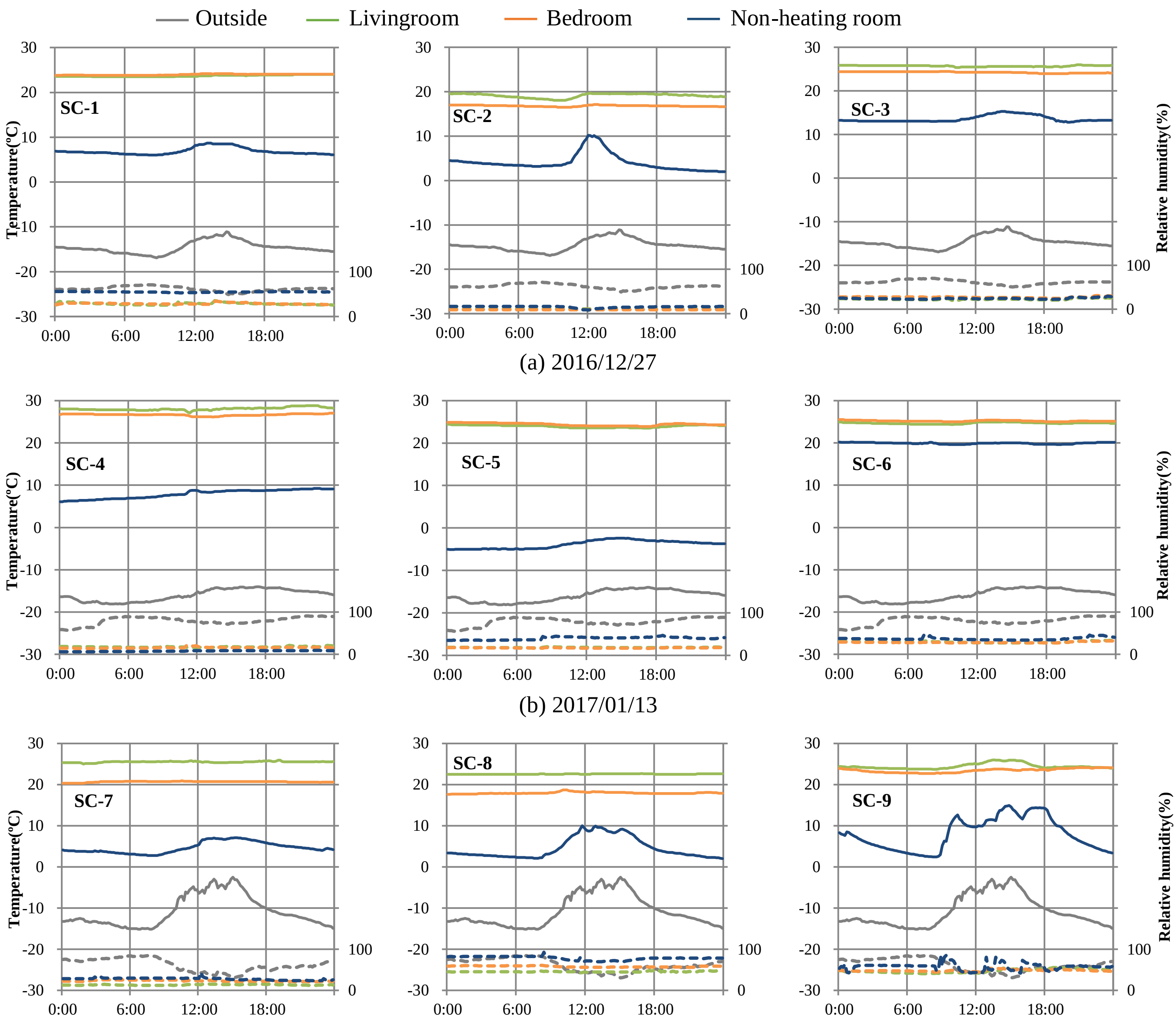



Figure 3-6 Relative humidity distribution in winter

Figure 3-6 shows the indoor and outdoor relative humidity distribution during the measured period in Harbin. The outdoor relative humidity was suitable in winter as shown in Figure 3-6. The distribution of outdoor relative humidity of three measured period were all about 50~80%. However, in addition to residence SC-8, the indoor humidity of the other residences were all lower than 40%, and even lower than 20% for partial residences, which is far beyond the acceptable comfort humidity range of human body. This is also because the heating temperature is over high, leading to the indoor air drying. The indoor environment with high temperature and drying air can make people feel mouth parched and tongue scorched, and even respiratory tract also becomes dry and specially suffered. Therefore, corresponding measures should be adopted for indoor humidification.

2. Variation curve of indoor and outdoor temperature and humidity in a typical day




(a) 2016/12/27

(b) 2017/01/13

(c) 2017/01/29

Figure 3-7 Variation curve of indoor and outdoor temperature and humidity in a typical day

Figure 3-7 shows the variation curve of indoor and outdoor temperature and humidity in a typical day in different measured period. It can be seen that the indoor temperature of heating rooms in all surveyed residences almost did not change along with outdoor temperature as a result of district heating.

It can be seen from Fig.(a) that the outdoor temperature difference between day and night was small in the first measured period. The temperature fluctuation range within 1 day was between -15~-11℃. Although there were district heating, the indoor temperature distribution among the three residences in the first measured period were slightly different. The indoor temperature of residence SC-3 was slightly higher than the other two residences due to better insulation performance of building envelope structure, maintained at around 25~26ºC. Although the construction age of residence SC-1 is relatively earlier, the envelope structure performance has been improved after renovation in recent years, so the indoor temperature was higher than residence SC-2. The indoor temperature of residence SC-2 was far lower than that of the other two residences, only maintained at around 20ºC in livingroom and 17 ºC in bedroom. On the one hand, residence SC-2 was built in the early 2000s, the residential building insulation standards and regulations were not yet perfect, so the insulation performance of the envelope structure was relatively poor. On the other hand, it was uninhabited in residence SC-2 during the measured period. Compared to the other two residences, there were no internal heat by occupants and heat dissipation from electrical equipment. Moreover, there was a significant difference in indoor temperature distribution between the non-heating rooms of multi-unit residences in different ages. The temperature of non-heating room of residence SC-3 was the highest, about 12~15ºC. In addition, it can be seen that because the testing point of non-heating rooms in residence SC-2 was located on the south facade balcony, the influence of solar radiation was relatively serious, the indoor temperature of non-heating room changed significantly along with the outdoor temperature, the indoor temperature reached the peak around 13:00 in the afternoon.

Compared to the first measured period, the outdoor temperature in the second measured period was lower, and almost unchanged along with the time. Therefore, it can be seen that no matter the heating rooms or the non-heating rooms, the indoor temperatures of the different residences all almost did not change along with time. In addition, the three residences during the second measured period are located in the same residential quarters and the envelope structure performance is same, but located in the different floor. From the temperature distribution of heating room, the indoor temperature of residence SC-4 which located in the middle floor was the highest, reached up to about 28ºC. While the indoor temperature of residence SC-5 which located in the bottom floor and residence SC-6 which located in the top floor were relatively lower, about 24ºC. This is because compared to the middle floor, the floor and roof heat dissipation results in the reduction of indoor temperature.

Compared to the first and second measured period, the outdoor temperature in the third measured period was higher and changed significantly along with the time. The indoor temperature of livingroom in residence SC-7 reached about 25.3ºC, while only maintained at about 20ºC in bedroom. The temperature difference between livingroom and beroom was up to 5ºC, so was residence SC-8. This may be because the bedroom located in the north with window, whil living room closed to the kitchen. Heat loss through windows in bedroom and heat gain from cooking led this temperature difference.

3. Indoor temperature distribution at different heights

Because of the effect of air natural convection and thermal updraughts, the situation that the temperature of upper part is high and the temperature of lower part is low exists in many space. Some researchers have studied the effect of vertical temperature variation on human thermal sensation(5). Although the occupants are in a neutral state, the more the temperature around the head is higher than that around the ankle, the people who felt uncomfortable are more. Figure 3-8 shows the experimental result of the relationship between the dissatisfaction and the temperature difference between head and ankle.

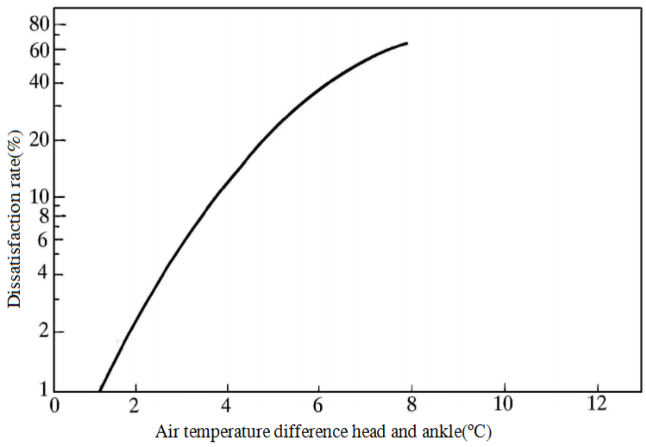



Figure 3-8 The relationship between the temperature difference of head and ankle as well as the dissatisfaction rate

Figure 3-9 shows the temperature distribution at different height in the living room in one day (12/22). It can be seen that compared with residence SC-2 and SC-3, the indoor temperature difference of different heights in residence SC-1 after renovation is little, the average temperature difference between top and bottom was only about 0.2ºC, the indoor temperature was evenly distributed. However, the indoor temperatures of residence SC-2 and SC-3 were not evenly distributed, the temperature differences between the ceiling (2.7m) and floor (0m) of residence SC-2 was about 4ºC. And the temperature differences between the ceiling (2.7m) and human activity area (1.1m) of residence SC-3 was about 3ºC. According to Figure 3-8, the 4ºC temperature difference between top and bottom could make the occupants feel hot head and cold feet, thereby the dissatisfaction rate would reach above 10%.

Moreover, compared with residence SC-2, the indoor temperature of different heights in residence SC-1 and SC-3 changed little along with time, only about 0.6ºC along with time within a single day. While the temperature difference of residence SC-2 between 0’clock and 21’clock was about 1.4ºC. In addition, it can be seen that at 0’clock, the ceiling temperature of residence SC-1 reached the lowest, but that of residence SC-2 and SC-3 reached the lowest at around 21’clock. This is because the envelope performance is different, leading to different encroachment time of cold air.

Furthermore, for the residences with a common wall-type radiator, due to the thermal updraughts, the floor temperature should be the lowest, the ceiling temperature should be the highest. But from the indoor temperature distribution of residence SC-1, the temperature difference between the floor (0m) and human activity area (1.1m) was not so big, only about 0.5ºC. This may be due to the poor insulation performance of ceiling in this residence, the heat in the celling of downstairs transfer upward, leading to the increase of temperature on the floor. In addition, it is worth noting that compared with the other two residences, the floor temperature of residence SC-3 was far higher than that in the human activity area. This is because this residence adopted the radiant floor heating, the radiator was located under the floor about 70~80mm, and this kind of heating method can avoid the phenomenon of ‘hot head cold feet’, which can improve the comfort of residence.

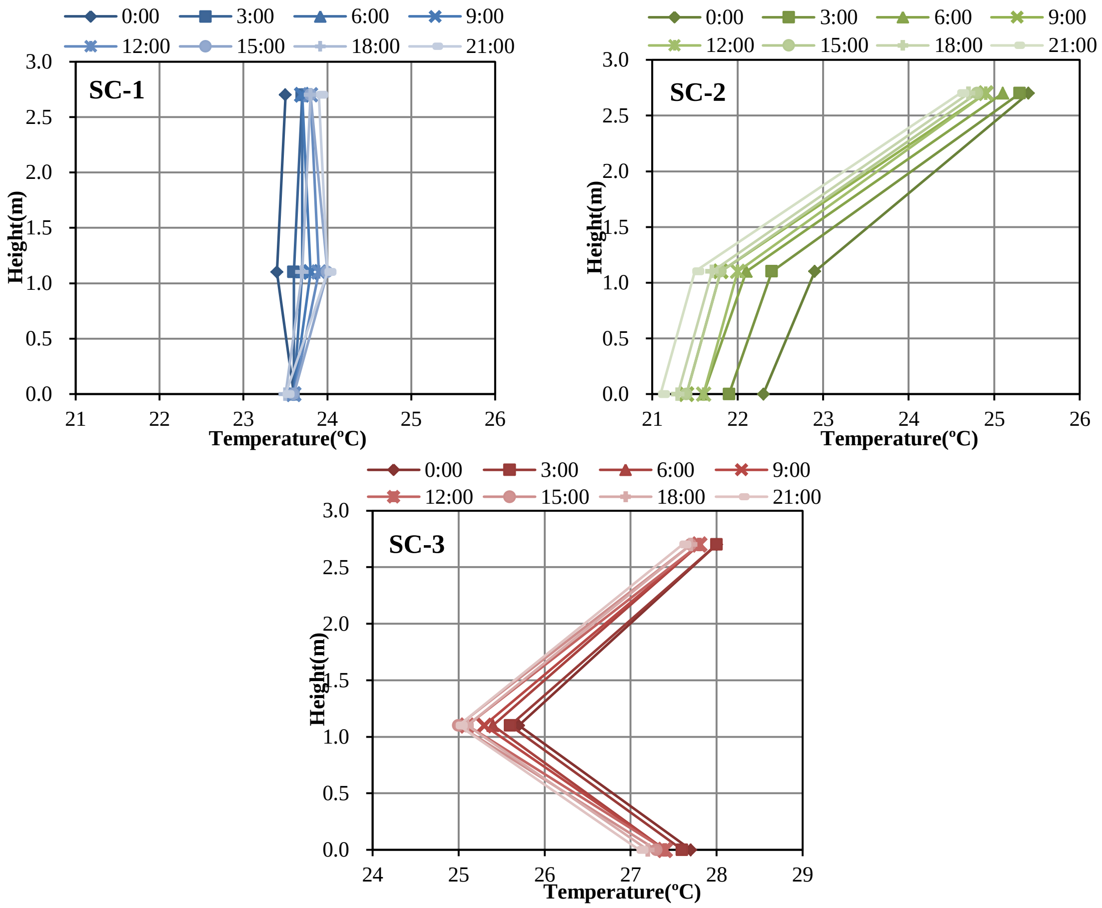



Figure 3-9 Temperature distribution at different height in the living room

4. ASHRAE comfort zone

ASHRAE comfort zone is used to evaluate the indoor thermal comfort conditions of living room for all the surveyed residences, as shown in Figure 3-10. Although there is a new version, the comfort zone of ASHRAE standard-2005[(5)] was used in this paper. Previous studies are periodically reviewed to update ASHRAE Standard 55, Thermal Environmental Conditions for Human Occupancy, which specified conditions or comfort zones where 80% of sedentary or slightly active persons find the environment thermally acceptable. In the middle of zone, a typical person wearing the prescribed clothing would have a thermal sensation at or very near neutral. Near the warmer boundary of zone, a person would feel about +0.5 warmer on the ASHRAE thermal sensation scale; near the cooler boundary of zone, that person may have a thermal sensation of -0.5. Because people typically change clothing styles to suit indoor temperature, ASHRAE Standard 55 specifies different comfort zones appropriate for clothing insulation levels of 0.9 and 0.5 clo, respectively.

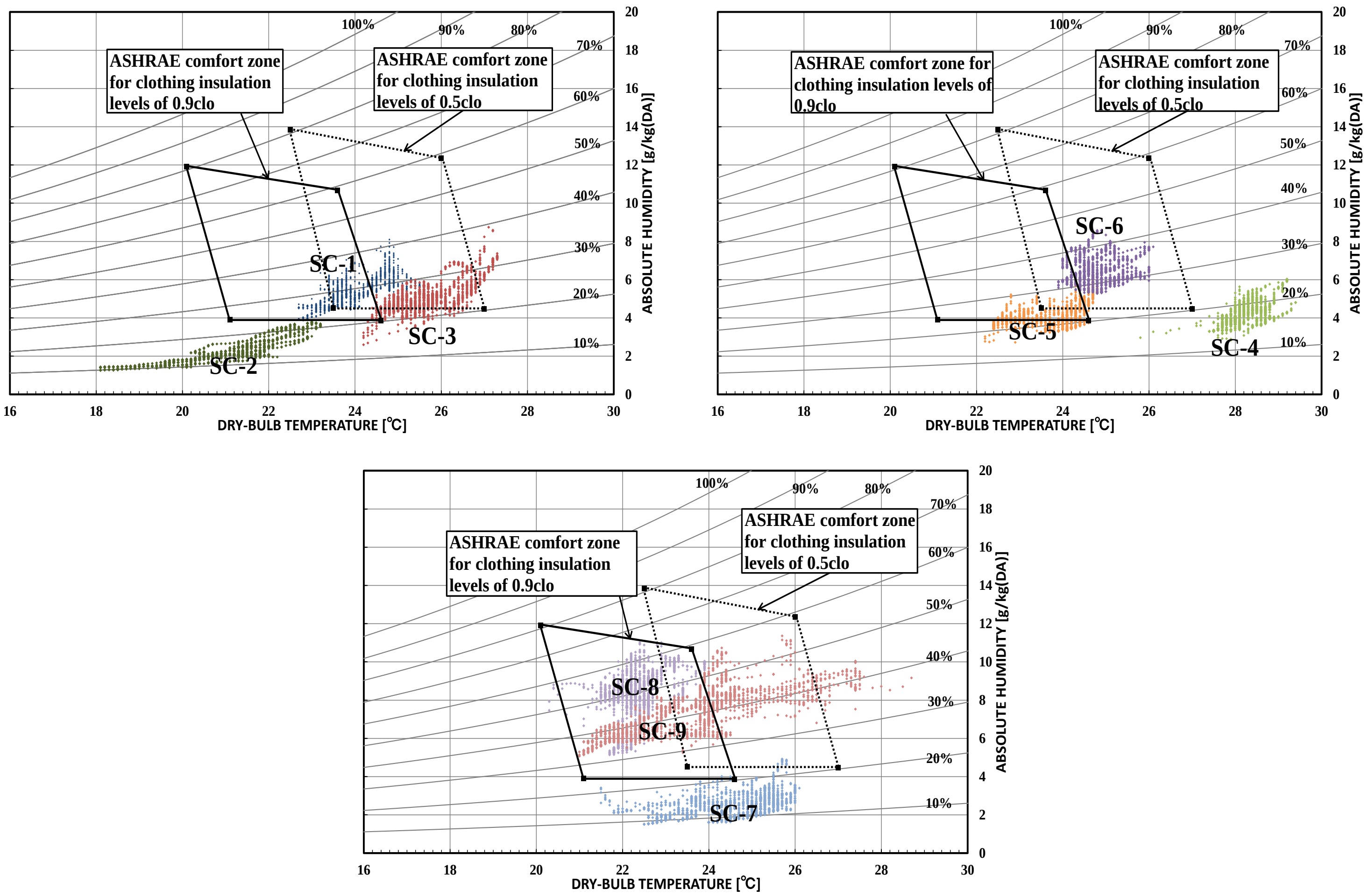



Figure 3-10 Indoor thermal comfort conditions

It can be seen that only the whole temperature and humidity data of residence SC-8 and a portion of the data of residence SC-1 and SC-9 fell into the ASHRAE comfort zone for clothing insulation levels of 0.9clo. The indoor temperatures of residence SC-5, SC-2 and SC-7 were not so high, which is preferred, but the indoor relative humidity of these two residences were relatively low. The indoor thermal comfort did not agree well with ASHRAE comfort zone in the case of 0.9clo clothing insulation. In addition, the indoor temperature and humidity data of residence SC-3 and SC-6 also could not fall into the comfort zone in the case of high clothing insulation because the indoor temperatures were found too high in these residences. The farthest from the comfort zone was residence SC-4 not only because of the highest indoor temperature but also due to the lower relative humidity.

Although the comfort zones for other clothing levels can be approximated by increasing the temperature borders of the zone by 0.6 K for each 0.1clo increase in clothing insulation, the comfort zone moves right with lower clothing insulation. After moving, the indoor temperature and humidity data of residence SC-3 and SC-6 also fell into the comfort zone. But the indoor thermal comfort of residence SC-2, SC-4, SC-5 and SC-7 still could not agree well with ASHRAE comfort zone in the case of lower clothing insulation mainly because the indoor relative humidity of these residences were lower. Low humidity will dry the skin and mucous surfaces and lead to comfort complaints about dry nose, throat, eyes, and skin, too dry sensation tends to increase discomfort.

6. Predicted Mean Vote (PMV)

The PMV index predicts the mean response of a large group of people according to Fanger's thermal comfort equation. PMV is widely used and accepted for the design and field assessment of comfort conditions. It is used in this paper to evaluate the indoor thermal environment. PMV uses the 7 level scale which are +3, +2, +1, 0, -1, -2, -3 corresponds to the thermal sensation of hot, slightly hot, warm, neutral, cool, slightly cold, cold. Compared with simply defining the comfort zone by the indoor temperature and humidity, the indoor comfort state of occupants can be initially predicted through the PMV value. PMV adds more variables which can affect human thermal comfort, such as metabolic rate (M), radiation temperature (TR), thermal insulation of clothing (Icl) and indoor average wind speed (Va). PMV was calculated by the software which comes from Tanabe Lab(7). PMV calculation conditions are as follows: T, MRT, RH and Icl were derived from field investigations results. Metabolic rate was assumed to set as 1.2met; Velocity of air was assumed to be 0.1m/s in winter and 0.25m/s in summer according ASHRAE specification.

Figure 3-11 shows the proportion of PMV value of the living room in Harbin. It can be seen that the PMV values of only residence SC-5 and SC-8 both remained at between -0.5~0.5 during the measured period, which indicated that indoor thermal environments of the living rooms of these two residences were both in a comfortable state. The proportion of PMV value in the -1~-0.5 range that means cool accounted for about 20%. In addition, except the residence SC-2, other residences at a part of the time were all in a thermal sensation state with warm or slightly hot, especially after 12 o'clock in noon, the PMV value increased significantly. Moreover, in line with the ASHRAE comfort zone, the indoor thermal comfort of residences SC-4 was relatively poor, the PMV value at most of the time was between 1~2 that means slightly hot, followed by the residence SC-3 and SC-9 which were also in slightly hot state at a part of time.

Therefore, for this climate zone, the design heating temperature of district heating system should be reduced properly according to the thermal adaptation of local people. At the same time, the household heat-regulating system should be put into practice as soon as possible.

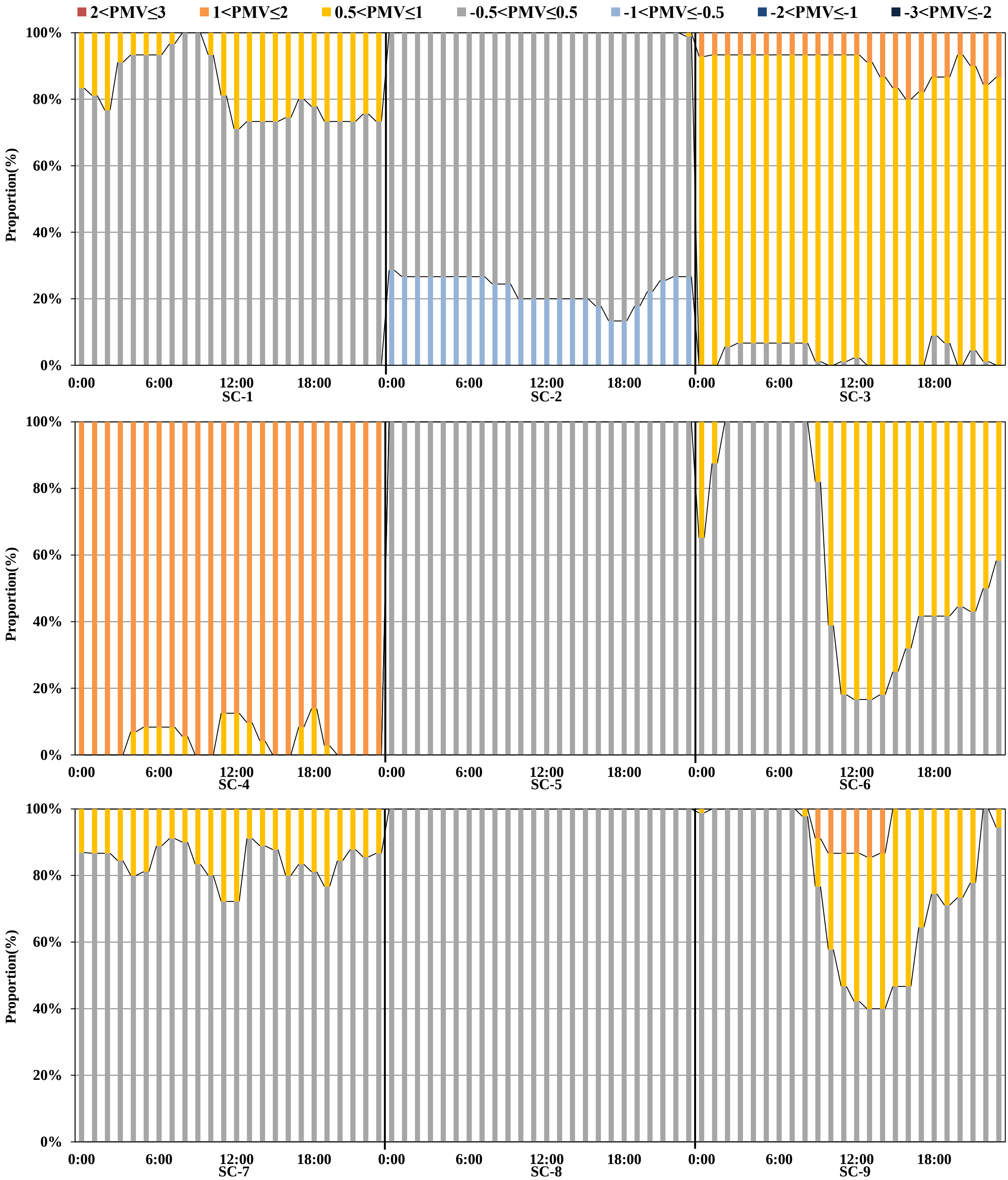



Figure 3-11 Proportion of PMV in Harbin

（Annotation: PMV’s calculation condition: M=1.2met, v=0.1m/s）

### 3.3.1.2 Questionnaire survey results

#### 1. Clothing insulation

(1) Clothing insulation value

In general, the indoor temperature and residents' condition are factors for the selection of clothing. The residents were asked to record the common clothing that they wore during the measured period. The clothing insulation value was calculated according to the clothing insulation questionnaire created by Yuji Kawakami, as shown in Figure 3-12.

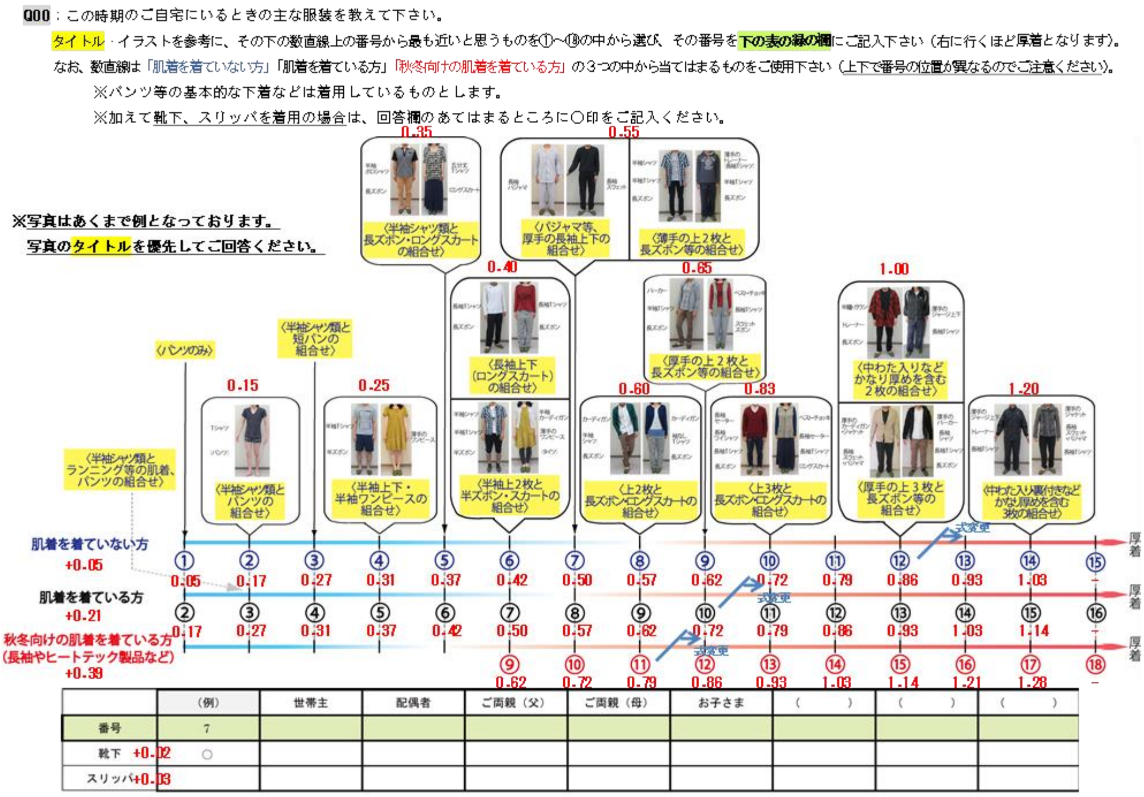



Figure 3-12 Clothing insulation questionnaire

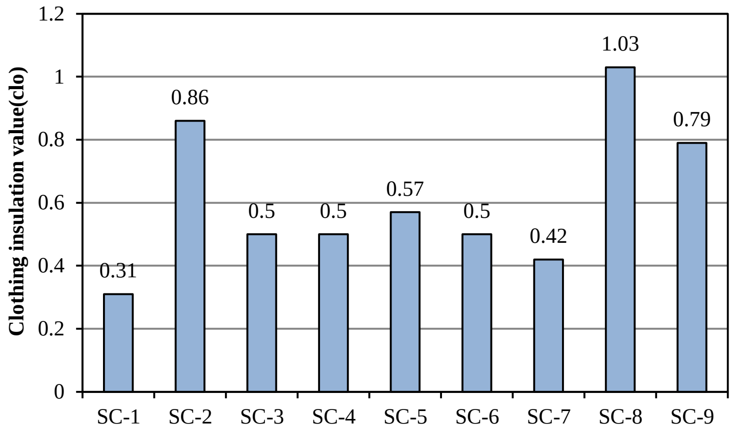



Figure 3-13 Clothing insulation value in winter in Harbin

Figure 3-13 gives clothing insulation values for typical indoor clothing of the surveyed residences. It can be seen that clothing insulation levels was low due to better effect of district heating. The clothing insulation value of most of surveyed residences concentrated in about 0.5clo. It means that residents usually only wear long sleeved shirts and trousers. Even to the extent that occupants of residence SC-1 often only wear short sleeves and shorts at home, the clothing insulation value was only 0.31clo, almost same as that of summer. This may be because the effect of district heating was well, led to the indoor overheating, and the thermal resistance of occupants is relatively low. Therefore, the occupants not only opened window for ventilation to adjust the indoor temperature, but also decreased the clothing thermal resistance to improve the thermal comfort. In addition, the clothing thermal resistance values of residence SC-2, SC-8 and SC-9 were in accordance with the normal values in winter, 0.86clo, 1.03clo, 079clo, respectively.

(2) Relationship between clothing insulation value and living room temperature

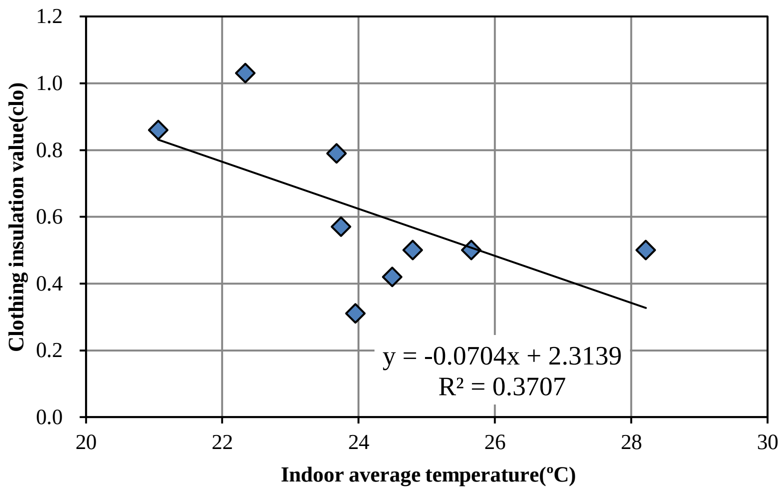



Figure 3-14 Relationship between clothing insulation value and indoor average temperature

Figure 3-14 shows the relationship between the clothing insulation and indoor average temperature. The clothing insulation shows a weaker correlation with indoor temperature. Because the district heating effect was better, maybe there were other factors than indoor temperature which influenced on the clothing selection. In addition, although this correlation was relatively weak but it still can be seen that with the increase of the average indoor temperature, the clothing insulation value was reduced. It means that there were still residents adjust the amount of clothing according to the indoor temperature.

2. Thermal comfort condition

There are two expression in the survey of residential indoor thermal environment comfort conditions—Thermal sensation vote(TSV) and thermal comfort vote(TCV).

(1) Thermal sensation vote (TSV)

TSV can accurately indicate the thermal sensation of occupants in the indoor thermal environment. Quantitative thermal sensation evaluation can be obtained based on the questionnaire survey of the occupants. And then, it is possible to describe the relationship between the various parameters of the thermal environment and the thermal sensation of the occupants in residential buildings. According to ASHRAE seven scale thermal sensation index, TSV value of +3, +2, +1, 0, -1, -2, -3 corresponds to the thermal sensation of hot, slightly hot, warm, neutral, cool, slightly cold and cold.

1) TSV value

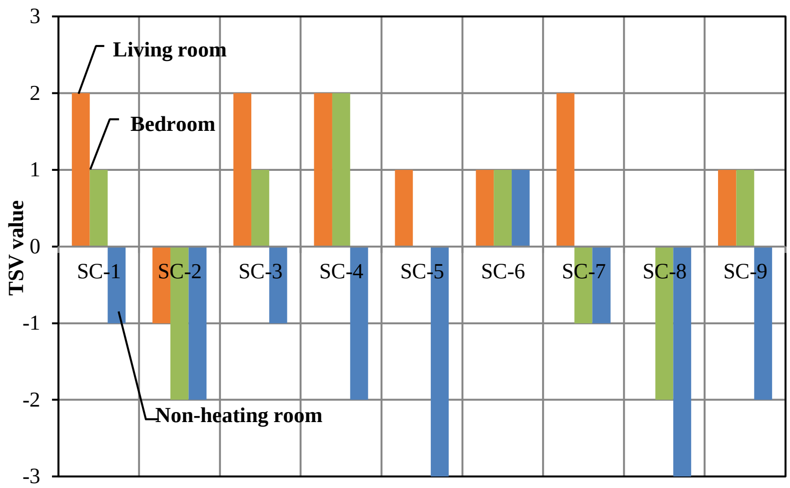



Figure 3-15 TSV value

Figure 3-15 gives the TSV value in different residences. It can be seen that the TSV value concentrated in 1~2 in the living room of most surveyed residences except for residence SC-2 and SC-8. The TSV value in the living room of SC-2 was -1 which means that indoor thermal environment in cool condition. Only the living room of residence SC-8 was in a comfortable condition which the TSV value is 0. Compared with the living room, the comfort of bedroom in most surveyed residences seemed to move in the colder direction by one level. This shows that the requirement of occupants on the bedroom temperature is higher than the living room. Due to the low level of human body metabolism when they are sleeping, so even at the same temperature, the thermal sensation when sleeping is cooler. For example, although the bedroom temperature was higher than the living room temperature in residence SC-5, the occupants of residence SC-5 assessed thermal sensation in bedroom as neutral, while warm in living room. In addition, unlike other residences, the TSV of non-heating room in residence SC-6 presented warm. This is because the monitoring points of non-heating room of other residences were all located in the balcony, while located in kitchen in residence SC-6. Under the heat influence of cooking in the kitchen, so the thermal sensation appeared to be warm.

2) TSV and indoor average temperature

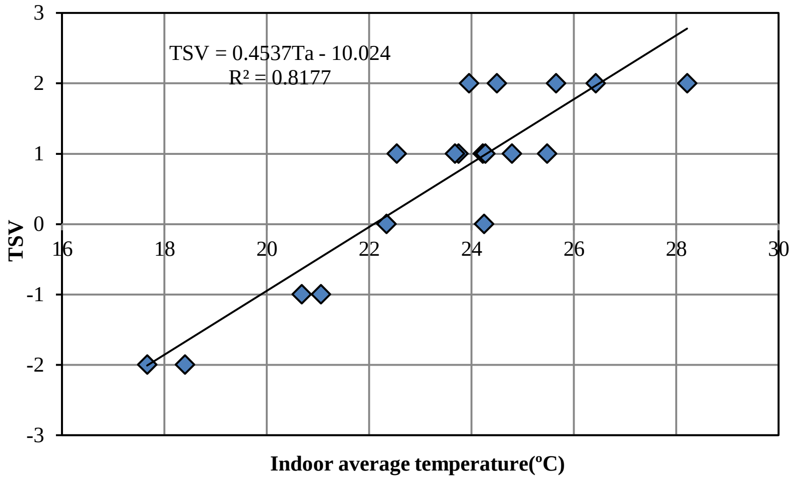



Figure 3-16 The relationship between TSV and indoor average temperature

Figure 3-16 shows the relationship between TSV and indoor average temperature. Air temperature is one of the most important physical parameters which affect the actual thermal sensation of people. It can be seen from Figure 3-16 that there is a strong linear relationship between the subjective average thermal sensation of occupants and average indoor temperature, and the fitting linear equation of the subjective thermal sensation vote (TSV) and average indoor temperature (Ta) can be obtained as follows:

$$TSV = 0.4537Ta - 10.024 \ (R^2 = 0.8177)$$

Moreover, the neutral temperature is the most moderate temperature of thermal sensation of human body. According to the linear regression equation of the average thermal sensation and average indoor temperature, it can be obtained 22.1ºC when TSV is 0 as the thermal neutral temperature as well as 19.9 ºC and 24.3 ºC when TSV is -1 and +1 as acceptable temperature of human body in winter of this climate zone.

Thus we can find that due to the better effect of district heating and no household heat metering and moderating system, the indoor temperature of most surveyed residences was higher than the thermal neutral temperature. This can not only lead to occupants discomfort, but also can result in waste of energy.

3) The relationship between TSV and clothing insulation

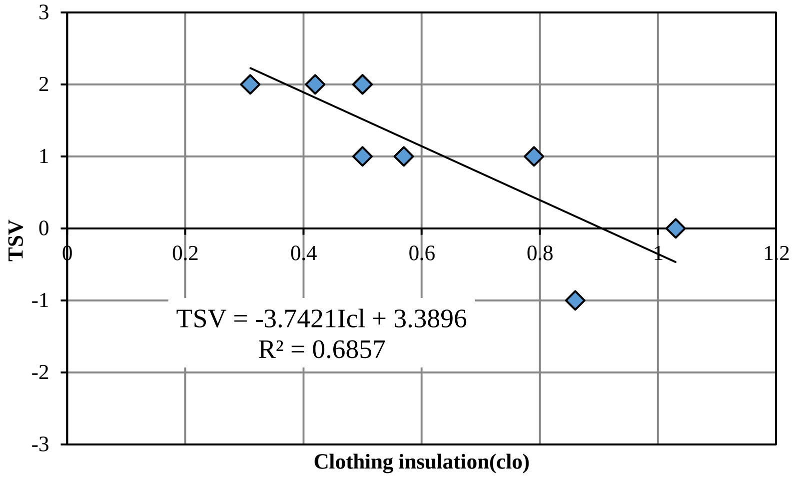



Figure 3-17 The relationship between TSV and clothing insulation

Figure 3-17 shows the relationship between TSV and indoor clothing insulation. Occupants can increase or decrease the amount of clothing to adjust their thermal sensation. Therefore, clothing insulation is also one of parameters which can indirectly affect the actual thermal sensation of occupants. It can be seen from Figure 3-17 that there is a linear relationship between the subjective average thermal sensation of occupants and indoor clothing insulation, and the fitting linear equation of the subjective thermal sensation vote (TSV) and indoor clothing insulation (Icl) can be obtained as follows:

$$TSV = -3.7421Icl + 3.3896 \quad (R^2 = 0.6857)$$

Moreover, according to the linear regression equation of the average thermal sensation and indoor clothing insulation, it can be obtained 0.9clo when TSV is 0 as the most suitable indoor clothing insulation in winter of this climate zone. This is exactly the same as the clothing insulation value of ASHRAE standard.

4) The relationship between TSV and PMV

PMV is the predicted mean vote for a thermal environment based on Fanger's thermal comfort equation. However, TSV reflects the actual thermal sensation of residents. Figure 3-18 gives the comparison of TSV and PMV. The result shows that the calculated PMV value was significantly lower than the surveyed TSV value. This means thermal sensation in the actual thermal environment moved to the warmer side than the predicted mean vote in the same temperature range. The indoor temperature is 22.7ºC when PMV=0, slightly higher than the surveyed thermal neutral temperature that is 22.1ºC. It is proved that human comfortable temperature range in the actual thermal environment is wider than the theoretical prediction. It also means that the actual thermal environments created by thermal design specifications are not completely consistent with the thermal adaptation of occupants, which will lead to energy waste.

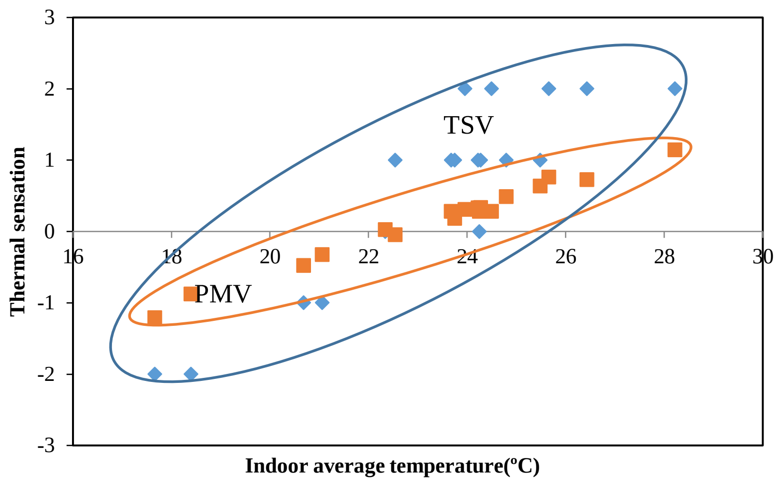



Figure 3-18 Comparison between TSV and PMV

(2) Thermal comfort vote (TCV)

The human body obtains the comfortable feeling synthetically through the self-thermal balance and the environmental condition that feels. The thermal comfort indicates a state of consciousness in which the human body is satisfied with the thermal environment, some researchers believe that the thermal sensation that the human body is in the hypothermal neutral state is thermal comfort, the other researchers think that the thermal comfort is different from thermal sensation, thermal sensation is assumed be associated with the skin thermosensor activities, while the thermal comfort is assumed to depend on the thermal regulation reaction from regulating center. For example, when the body temperature is low, the hot water in the bathtub will make the subjects feel comfortable and pleasant, but the thermal evaluation on it should be "warm" rather than "neutral". Due to the separation phenomenon between the thermal comfort and thermal sensation, in the experimental research on the comfort conditions of residential indoor thermal environment, not only thermal sensation vote (TSV) but also thermal comfort vote (TCV) which evaluates the thermal comfort levels are both set up. According to ASHRAE seven scales, TCV still uses the 7 level which are +3, +2, +1, 0, -1, -2, -3 corresponds to the comfort evaluation of very comfortable, comfortable, slightly comfortable, universality, slightly uncomfortable, uncomfortable and very uncomfortable.

1) TCV value

Figure 3-19 shows the results of thermal comfort vote. Although the thermal environment of bedroom in residence SC-3 and SC-9 were evaluated as 1 which means slightly comfortable and 2 which means comfortable in the bedroom of residence SC-5, it can be seen that the TCV value concentrated in -1~-2 in the living room and bedroom of most surveyed residences. It means that the evaluations of indoor thermal environment of residential buildings by residents were slightly uncomfortable and uncomfortable. The comfort of the bedroom was a little better than the living room.

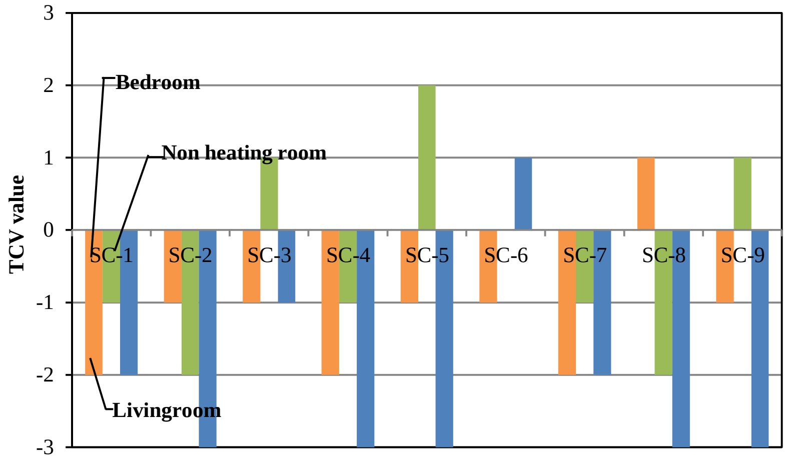



Figure 3-19 TCV value

In addition, the evaluation of thermal comfort for non-heating room was worse, mainly concentrated in the -2~-3. Therefore, it can be seen that the residents were not satisfied with the indoor thermal environment whether heating or non-heating room. But the reasons for this dissatisfaction may differ from one another.

2) Uncomfortable reason

Figure 3-20 shows the uncomfortable reason in district heating room and non-heating room, respectively. It can be seen that the uncomfortable reason in heating rooms were mainly the residents feel hot and dry because of the very good effect of district heating. Only the residents of residence SC-2 and SC-8 felt cold and cold-blast air especially around the feet. This is not only because the indoor temperatures of residence SC-2 and SC-8 indeed were lower than that of the other residences, may also be because the occupants of these two residences were old people with low-activity and slow metabolism, the requirements for the indoor temperature was higher. In addition, some residents said that the sunlight was relatively strong at noon in the balcony, lead to the higher temperature of living room, so they felt uncomfortable. However, for the non-heating rooms, the reason why most of the residents feel uncomfortable was that the rooms were cold overall and they felt cold-blast air, there were also residents said that although these were non-heating rooms, the indoor relative humidity was low and they felt dry relatively.

The reasons of 「-1．Slightly uncomfortable」~「-3．Very uncomfortable」(Multiple choice)

| | |
|---|---|
| A | Room is cold overall |
| B | Feel hot, because of the very good effect of Air conditioning / district heating |
| C | Feet feel cold |
| D | Feel cold-blast air |
| E | The effect of air-conditioning is poor, it works after a long time with open |
| F | Indoor temperature drops rapidly after stopping the heating equipment |
| G | Feel flushed face with hot when using the air-conditioning |
| H | Feel sweaty |
| I | Feel dry |
| J | Others |

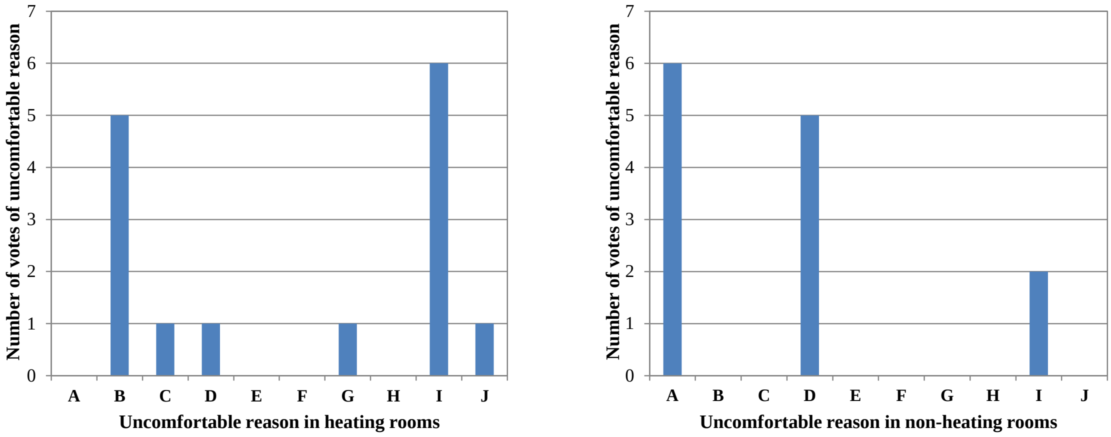



Figure 3-20 Uncomfortable reason

3. The statistics of occupation condition

(1) Family members

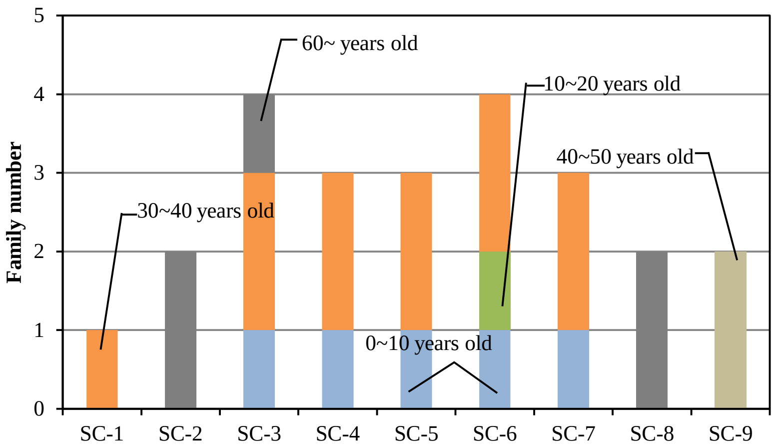



Figure 3-21 Family population and age distribution

Figure 3-21 shows the family population and age distribution in different residences. Because the university staff houses were taken as the objects of this survey, the occupants are all university teachers or relatives. It can be seen that the overall number of family people in most of residences is 2~3, the family structure is a couple aged 30~40 years old and a child under 10 years old. In addition, some residents chose to live with older parents together such as the residence SC-3. In addition to the young teaching staff, the retired old staffs who are older than 60 also were taken as the object of this survey.

(2) Occupation time

Table 3-5 Occupation time schedule

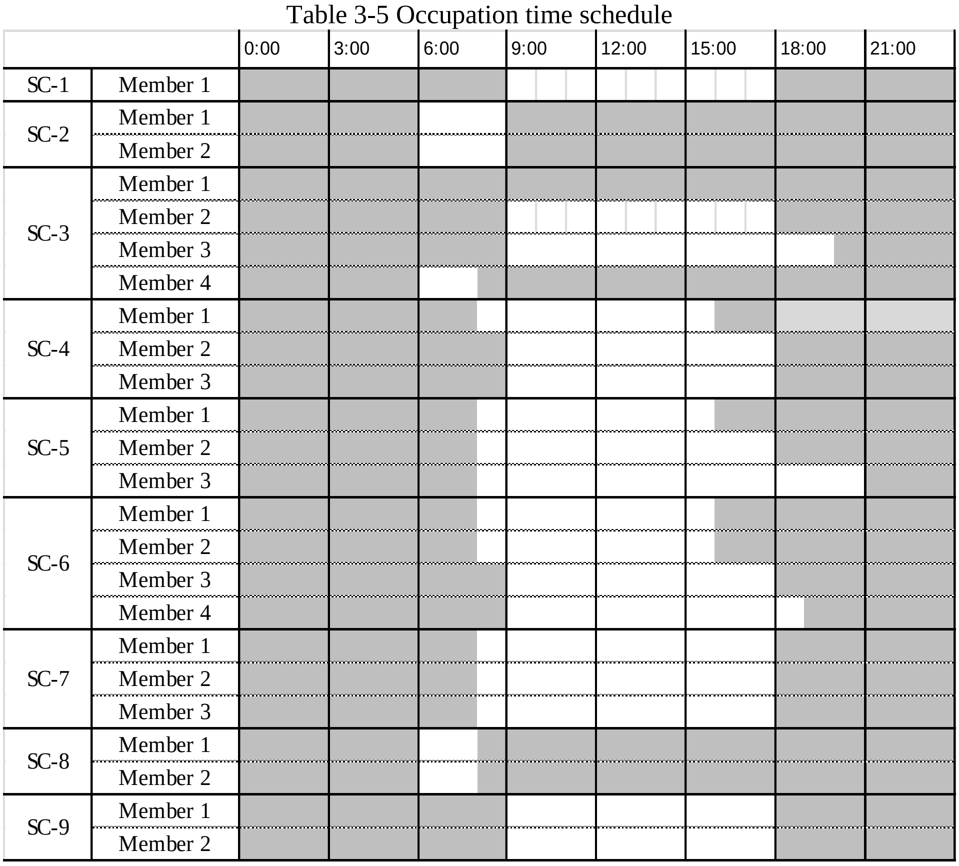



Table 3-5 shows the occupation time schedule of residents. It can be seen that because of the nature of university teachers' job, the time at home in the daytime is less, basically leave home for the work in the morning (around 9:00) and return home in the evening (about 18:00), and they are not in the room for about 9 hours. However, in addition to the exercise out in the morning, the older residents are basically in the room at the other time. The existing district heating system runs 24 hours uninterruptedly all day long, there is no switch to adjust depend on the residents in the room or not. For the residents who are not in the room in the daytime relatively, this kind of heating system is undoubtedly a waste of energy.

4. Energy consumption

(1) Charging system

Table 3-6 Charging system in Harbin(yuan)

| Electricity/kWh | ~170kWh | 171~260kWh | 260~kWh |
|---|---|---|---|
| | 0.51 | 0.56 | 0.81 |
| District heating/m$^2$ | 34.32 | | |
| Gas/m$^3$ | 2.8 | | |

Table 3-6 shows the charging system of different energy in Harbin. Aiming at the explosion of electricity consumption of Harbin in winter and the rapid increase of electricity bill, the tiered pricing has been implemented by Harbin power supply department in order to reasonably control the monthly electricity consumption. As can be seen from Table 3-5, the electricity bill is divided into three-tiered pricing depend on the monthly electricity consumption, the more the electricity consumption, the electricity price is more expensive.

About heating charging system, because the charge of district heating is based on floor area at present, heating price per square meter is fixed annually. The heating price is 34.32 yuan/m$^2$ in the 2016. Heating period is from the beginning of October 20th to the end of the following year in April 20th, total of 181 days.

Due to the different residential plan, the proportion of the heating area is also different. The district heating area consists of the residential actual usable floor area (excluding the wall), the balcony area of heating and the public area of heating. Usually, it do not install heating radiator in closed balcony, kitchen, storage room and other room which need to keep cool. The balcony without the installation of heating facilities is not included in the heating building area. The charge area of living room, kitchen, bathroom, etc. without the installation of heating facilities is calculated according to the 50% of constructed area. Figure 3-22 shows the heating area and heating proportion in surveyed residences.

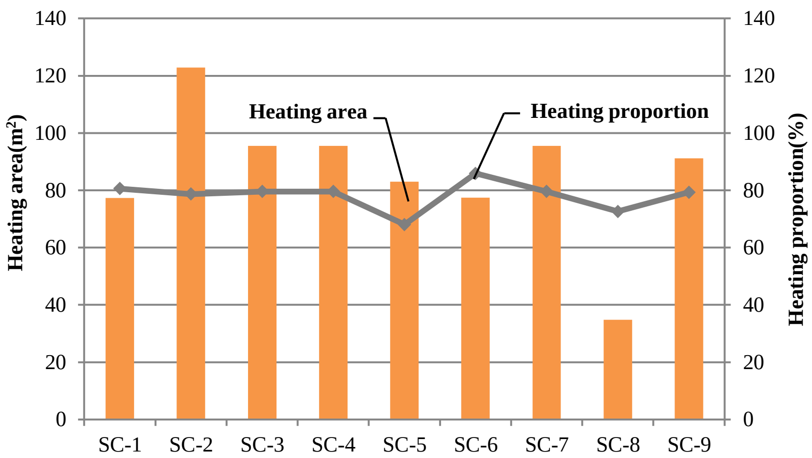



Figure 3-22 Heating area and heating proportion

It can be seen that because the total construction area was different, heating area was also different. However, the heating proportion of most surveyed residences was around 80%. The heating proportion of residence SC-5 was the least, about 68%. And the heating proportion of residence SC-6 was the largest, about 85.9%.

At present, the natural gas has covered the whole urban residential building. There have been few residents using bottled gas. The gas price is 2.8 yuan/m$^3$ in the 2016.

(2) Energy consumption statistics

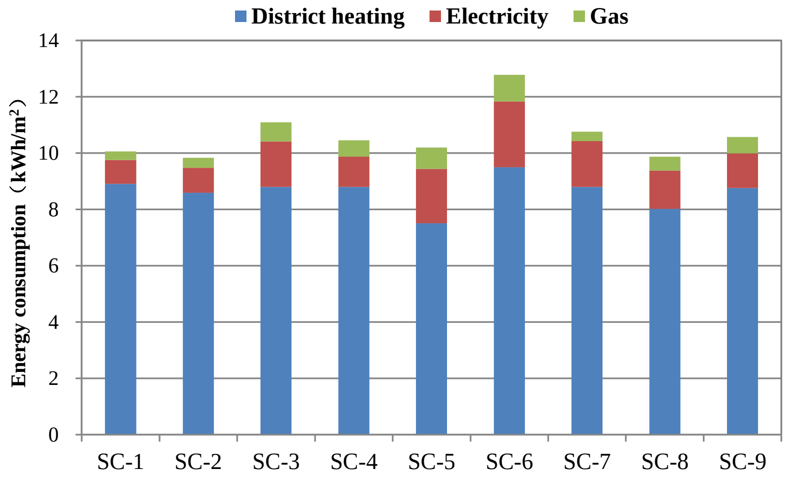



Figure 3-23 Monthly energy consumption statistics in Harbin

Figure 3-23 shows the statistics results of monthly energy consumption. It can be seen that, compared to the electricity and gas consumption, the district heating accounted for the main part of total energy consumption. After converting the district heating energy consumption into the corresponding electricity consumption per square meter monthly, the distribution curve was consistent with heating proportion. The heating energy consumption monthly of residence SC-5 was the least, while that of residence SC-6 was the largest, the other surveyed residences mainly concentrated in 8.5 kWh/m$^2$/month. In addition, compared to the district heating and electricity, the energy consumption of gas was the least; the gas consumption of majority of residences was about around 0.5 kWh/m$^2$/month. The gas consumption of residence SC-6 was largest, up to 0.94 kWh/m$^2$/month. Not only that, the electricity consumption of residence SC-6 was also the largest, which may because of large number of appliances and smaller floor area. As a result, the total energy consumption monthly of residence SC-6 became the largest, and about 12.77 kWh/m$^2$. However, the total consumption monthly of the other surveyed residences had little difference, and about 10 kWh/m$^2$.

### 3.3.2 Measured results in Qingdao

#### 3.3.2.1 Field measurement results

1. Indoor and outdoor temperature and relative humidity during the measured period

(1) Indoor and outdoor temperature

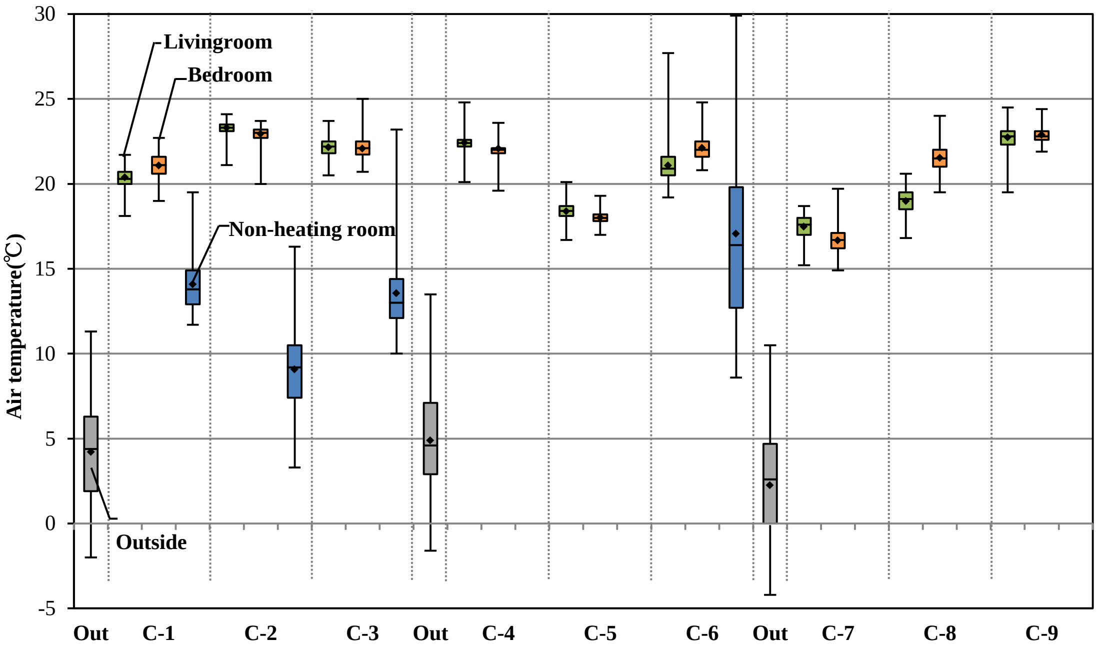



Figure 3-24 Temperature distribution during the measured period

Figure 3-24 shows the indoor and outdoor temperature distribution during the winter measured period in Qingdao. The outdoor temperature had little difference during the three measured period, all distributed in 0~10ºC in most of the time. And the average temperature were 4.21ºC, 4.8ºC and 2.25ºC, respectively. However, due to the district heating system, the average temperatures of heating rooms were over 20ºC except for C-5, C-7 and living room of C-8. At the same time, it can be seen that the temperature distributions of heating rooms were very concentrated that benefited from district heating. It can be found that under the same condition of district heating, the indoor temperatures of residences in Qingdao were relatively lower than that in Harbin. The indoor temperature of heating rooms were almost not higher than 25ºC. Although the design temperature of district heating is the same, which is 18~22º C, but there was a big difference in the actual indoor temperature. This may be due to the residential insulation performance of Qingdao which located in Cold Zone is worse than Harbin which located in Severe Cold Zone.

Compared with other residences, the temperature distribution of heating rooms in residence C-2 were the highest. The average temperature of living room and bedroom were 23.3ºC and 22.9ºC respectively. The main reason is that the vertical-pipe type hot water circulation heating was adopted for central heating in Qingdao. The circulation direction of hot water is the bottom-up, causing that the indoor heating effect of low-rise residence is better that that of high-rise residence. Because the residence C-2 is located in the bottom, the heating effect is the best, the indoor temperature of heating room was the highest.

In addition, the temperature distributions of heating rooms in residence C-5 and C-7 were relatively low, and even the indoor temperatures of livingroom and bedroom in residence C-7 were both lower than the lower limit (18ºC) of district heating temperature specified and designed in the《The Code for Design of Heating Ventilation and Air conditioning》, which will lead to the reduction of indoor comfort. Except for the effects of thermal insulation performance aspects of residence, on the one hand, the occurrence of this phenomenon was because the temperature of hot water in the upper part is relatively lower due to the vertical-pipe type hot water circulation heating, the indoor temperatures of residence C-7 which is located in the top is lower than other floors. On the other hand, the roof heat dissipation of the residence which is located in the top is also much than that of residence which are located in the middle-rise and lower-rise, so the indoor temperature reduced accordingly.

Moreover, because a part of residences installed heating radiator in all rooms, there was no indoor temperature and humidity data of the non-heating rooms in these part of residences. Compared to the heating rooms, affected by the outdoor temperature and solar radiation conditions, the indoor temperature range of non-heating rooms were relatively scattered, the indoor temperature distribution of non-heating rooms in residence C-1 and C-3 were in the range of 10~15ºC. While the indoor temperature of non-heating room in residence C-2 was relatively low, the average temperature was only 8ºC, which may be due to the poor insulation performance of external envelope structure in residence C-2. On the other hand, the indoor temperature of non-heating room in residence C-6 was higher, the average temperature was about 17 ºC and even exceeded 29 ºC in part time. It is likely to be because the temperature and humidity measuring points of non-heating room in residence C-6 were located in the balcony without the baffle to shade the sunlight like the residence C-3, the location of the measuring points can be directly exposed to the sun, leading to the extremely high temperature.

(2) Indoor and outdoor relative humidity

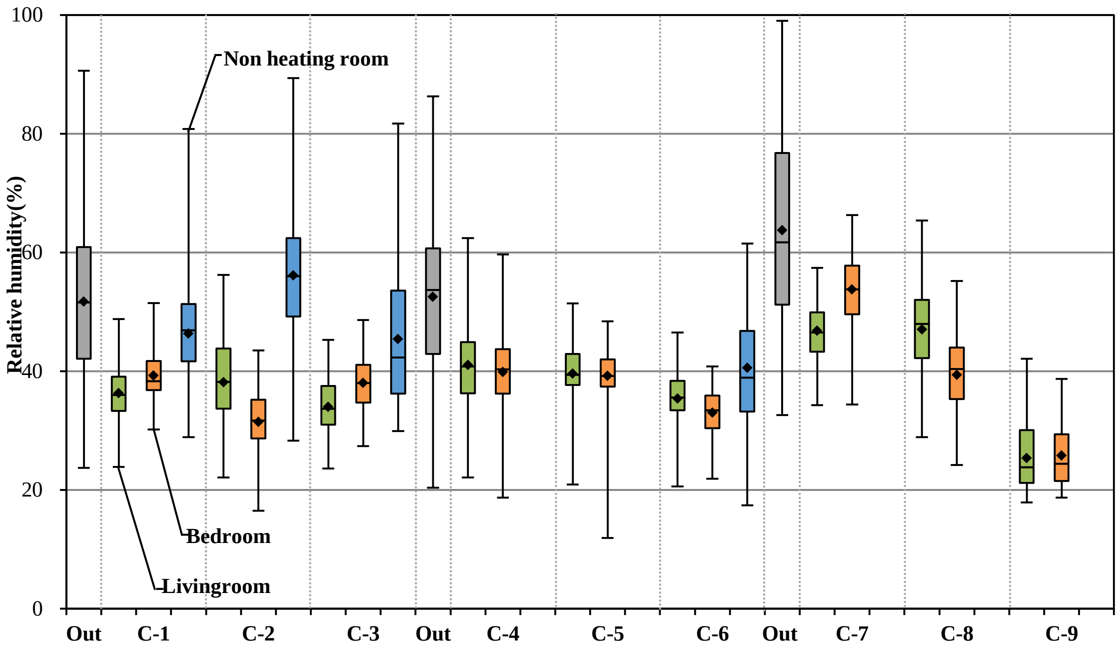



Figure 3-25 Relative humidity distribution during the measured period

Figure 3-25 shows the indoor and outdoor relative humidity distribution during the summer measured period in Qingdao. The outdoor relative humidity was suitable in the first two measured period as shown in the figure. The outdoor relative humidity distribution of the first two measured period were all about 40~60%, the average value were 51.7% and 52.1%, respectively. However, the outdoor relative humidity was relatively high in the third measured period, between 50% and 80%, and even some time run up to more than 90%.

In addition, it can be seen the indoor humidity distribution of heating room in most surveyed residences were about 30%~60% except for the residence C-9. This relative humidity distribution were relatively higher than that of Harbin. There was no indoor air too dry phenomenon that due to the district heating. Only the indoor relative humidity of residence C-9 was relatively low, the average value of living room and bedroom were all about 25%, measures should be taken to the indoor wetting.

The average indoor humidity distribution of non-heating room in surveyed residences were all above 40%.The indoor humidity was relatively moderate in non-heating than that of heating rooms.

2. Variation curve of indoor and outdoor temperature and humidity in a typical day

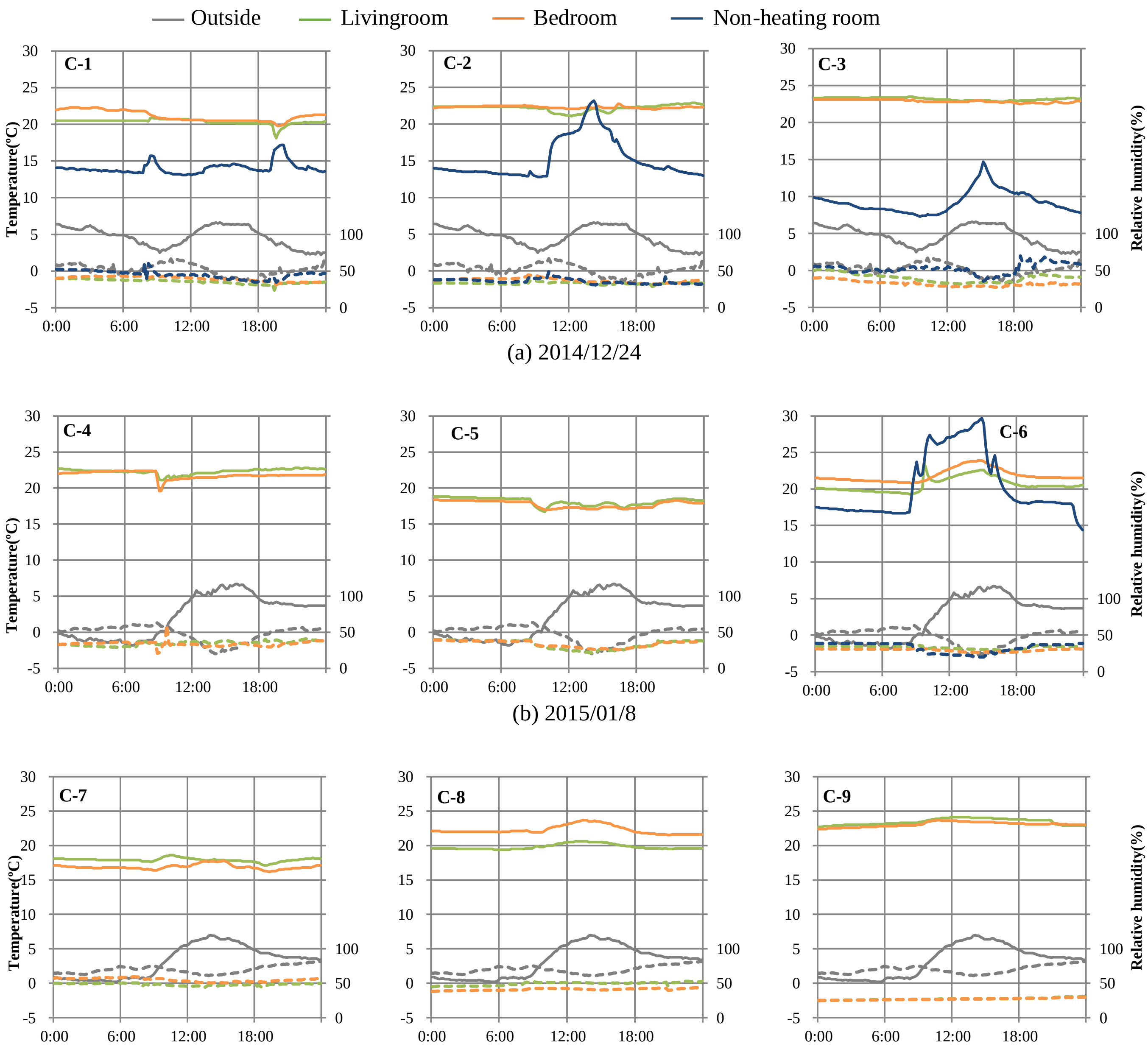



Figure 3-26 Variation curve of indoor and outdoor temperature and humidity in a typical day

Figure 3-26 shows the variation curve of indoor and outdoor temperature and humidity in a typical day. It can be seen that temperatures of livingroom and bedroom in most surveyed residences in a different day changed gently, basically unchanged along with the outdoor temperature as a result of district heating. And the temperature difference between the living room and bedroom was smaller. However, the temperature of non-heating rooms varied greatly along with the time.

In addition, it can be seen from the Fig. (a), the outdoor temperature reached the minimum at 9:00 am and reached the maximum around 2:30 in the afternoon, the temperature fluctuation range within 1 day was 2.5~6.6ºC. From the indoor temperature distribution curves of three residences in this measured period, it can be seen that the indoor temperature of heating rooms in residence C-3 was the highest, about 22.5ºC. While the indoor temperature of heating rooms in residence C-1 was the lowest and around 20ºC under the condition of non-human body heat dissipation interference. Compared with the residence C-1, there was little difference in the indoor temperatures between living rooms and bedrooms in residence C-2 and C-3, and almost unchanged along with time. However, the temperature of bedroom was about 1.5ºC higher than that of living room in residence C-1 at night (22:00~8:00). This may be because the residents slept in the bedroom at night, the human body heat dissipation resulted in the rise of bedroom temperature. In contrast, there was almost no difference in the temperatures of living rooms and bedroom in the daytime. Moreover, it is worth noting that the temperatures of living room and bedroom decreased significantly at about 19:30, which may be due to the short ventilation by openning window after dinner, resulting in a short-time decline in the indoor temperature.

In addition, from the temperature distribution curves of non-heating rooms during the first measured period, it can be seen that the indoor temperatures of the non-heating rooms in residence C-2 and C-3 increased significantly along with the outdoor temperature in the afternoon. This is because that the temperature and humidity measuring points of non-heating rooms in these two residence were located in the balcony, thus significantly affected by the solar radiation. In contrast, the temperature and humidity measuring points of non-heating room in residence C-1 were located in the kitchen in the north, the fluctuation along with the outdoor temperature was not obvious, but the heat gain from cooking in the kitchen led to an obvious increase of the indoor temperature at 8:30 in the morning and 19:00 in the evening. Meanwhile, the latent heat gain from cooking also had a significant effect on the indoor relative humidity of the kitchen.

It can be seen from the Fig. (b), the outdoor temperature fluctuation range of the second measured period was larger than that of the first measured period, reached the minimum at 6:30 am which was about -1.8ºC and reached up to 6.7ºC around 4:00 in the afternoon. From the heating indoor temperature distribution curves of three residence, it can be seen that the indoor temperature of heating rooms in residence C-4 was the highest, about 22.5ºC. While the indoor temperature of heating rooms in residence C-5 was the lowest and basically hovered around 18ºC. Compared with the residence C-6, there almost was little difference in the indoor temperatures of living rooms and bedrooms in residence C-4 and C-5, and both there were a short-time decline in the temperatures between 9:00~10:00 in the morning. This may be because these two residents were accustomed to open window for short-time ventilation after getting up to improve the air quality. From the indoor temperature distribution curves of heating rooms in residence C-6, it can be seen that the temperature of bedroom was slightly 1.5ºC higher than that of living room. It can be seen from the fluctuation tendency, the indoor temperature of heating rooms had an obvious rise with the outdoor temperature in the afternoon. This may be because the locations of the measuring points were relatively in the south, the sunlight in the daytime increased the temperature around the measuring points. In addition, it can be found that the temperature of living room had a temporary rise about 9:30, which may be result from having breakfast in the living room. Moreover, because the temperature and humidity measuring points of non-heating room in residence C-6 was located in the balcony, without the baffle to shade the sunlight like the residence C-3, the location of the measuring points can be directly exposed to the sun, the temperature began to abnormality increase at 8:40, the highest value was close to 30ºC and began to decrease from 15:00.

It can be seen from the Fig. (c), the outdoor temperature during the third measured period was higher than that of the second measured period, the temperature fluctuation range within 1 day was between 0.2~7ºC. It can be seen that the temperatures of bedroom in residence C-9 and C-8 were both distributed in around 22.5ºC, while the temperature of living room in residence C-8 was only maintained at around 20ºC. The indoor temperature of heating rooms in residence C-7 was relatively low and the temperature of bedroom was even lower than the lower limit value (18ºC) of district heating setting temperature in most of the time. In addition, from the heating indoor temperature distribution of heating rooms in residence C-8, it can be seen that the temperature of bedroom was significantly higher than that of living room. On the one hand, this is because the bedroom was located in the south and affected by the solar radiation. On the other hand, the exterior walls and exterior windows of living room had the larger heat dissipation, while there was a fully enclosed balcony outside the windows of bedroom, and the west wall of bedroom was separating-residence interior walls, the heat dissipation was smaller. Therefore, the temperature of bedroom was higher than that of living room.

3. Indoor temperature distribution at different heights

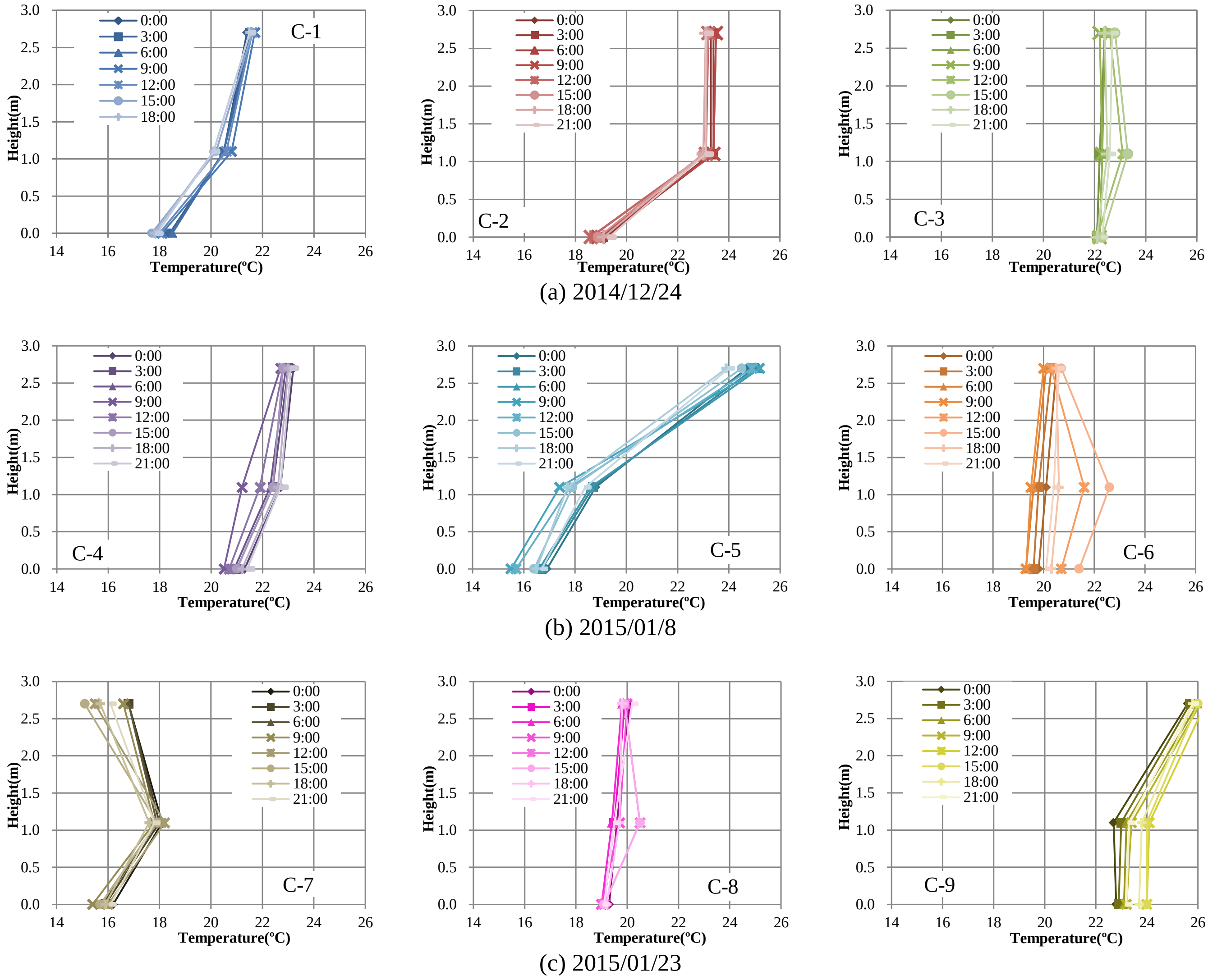



Figure 3-27 Temperature distribution at different height in the living room

Figure 3-27 shows the temperature distributions at different heights in the living rooms of different residences. Compared with the three residences during the first measured period, it can be seen that the indoor temperature distributions at different heights in residence C-3 were the most uniform, the temperature difference between top and bottom was less than 1ºC. It is followed by residence C-1, the temperature difference between the ceiling (2.7m) and floor (0m) was about 4ºC. It is worth noting that the temperature difference in residence C-2 was larger, and even close to 6ºC. According to the research [(5)], even if the occupants are in a thermal neutral state, but the larger temperature difference between the head and the feet, the occupants will feel more uncomfortable. The temperature difference of 6ºC between top and bottom could make the occupants feel hot head and cold feet, thereby the dissatisfaction rate would reach above 30%. In addition, compared with the residence C-1 and C-2, the indoor temperatures at different heights in residence C-3 changed significantly along with time, especially at 12:00 in the noon and 15:00pm. This is because the living room of residence C-3 was located in the south, there was an enclosed balcony with about 1.5 meters wide in the south, but the indoor temperature of living room was still increased when the solar radiation intensity was relatively strong, especially in the personnel activity areas. Because of the delayed temperature variation of floor and ceiling, the temperature difference between the indoor personnel activity areas and the floor as well as the ceiling was increased when the solar radiation intensity was relatively strong.

Moreover, from the indoor temperature distributions at different heights in the three residences during the second measured period, it can be observed that eliminating the influence of solar radiation on the temperature of personnel activity areas, the indoor temperatures at different heights in residence C-4 and C-6 were distributed uniformly, the temperature differences between top and bottom were both less than 2ºC. However, it can be found that the temperature around the floor in residence C-5 was only 16ºC, while the temperature around the ceiling reached up to 25ºC, the vertical temperature difference between top and bottom was close to 9ºC, which will seriously result in the phenomenon of hot head cold feet. According to the relationship curve of the dissatisfaction rate and the temperature difference between head and foot, it can be observed that the dissatisfaction rate reached up to 80% caused by the uneven indoor temperature distributions. Therefore, the occupants should take timely some measures to avoid the occurrence of this temperature difference. On the one hand, start with the residential structure, the thermal insulation performance of the envelope structure is needed to be improved, especially the floor; on the other hand, the floor radiant heating with low temperature water can be used to improve the temperature around the floor, thereby the vertical temperature difference between the personnel activity areas and the floor as well as the ceiling can be reduced.

Compared with the indoor temperature distributions at different heights in the different residences during the third measured period, the indoor temperature distributions at different heights in residence C-8 was the most uniform, the temperature differences between top and bottom was less than $2^{o}$ C. However, the surface temperature of the floor in residence C-7 was about 2ºC lower than that in personnel activity areas. It is worth noting that, because the residence C-7 was located in the top, the thermal insulation performance of roof was poor, caused that the temperature around the celling was lower than that of personnel activity areas. As a result, the top residence should pay attention to improve the thermal insulation performance of roof. In addition, although the temperature around the floor in residence C-9 was almost the same with that in personnel activity areas, both about 23~24ºC. The temperature around the ceiling was relatively higher, which may be due to the unique installation position of the radiator. The heating radiators of the other residence all were installed on the surface of indoor wall below 1.0m as shown in Figure 3-28, while the heating radiators of residence C-9 presented upper and lower distribution, the highest installation location was only 0.3m away from the ceiling, as shown in Figure 3-29.


Figure 3-28 Normal installation position of radiator


Figure 3-29 Installation position of radiator in residence C-9

Furthermore, from the indoor temperature distributions at different heights in the nine residences, it can be observed that because the installation modes of indoor radiators were all the common wall-type radiator, none of residence used the floor radiant heating with low temperature water, the temperature around the floor was all lower than that in personnel activity areas. However, studies have shown that because the hands and feet of human body are located in nerve endings, the temperatures of hands and feet are lower than that of the other parts of human body, the head temperature is the highest in particular. The lower temperature around the floor will make feet feel cold, which will bring discomfort feelings. Therefore, taking advantage of the floor radiation heating with low temperature water can avoid the discomfort feelings of human body caused by the over low temperature around the floor.

4. ASHRAE comfort zone

Figure 3-30 shows the indoor temperature and relative humidity distribution as well as the location of ASHRAE comfort zone in winter. It can be seen that the indoor temperature and humidity distribution of residences during the first measured period were relatively concentrated than of the other two measured period, the temperature was mainly distributed in 19~24ºC, the relative humidity was mainly distributed between 20%~30%. Considering the temperature and relative humidity comprehensively, most of the indoor temperature and humidity data of residence C-2, C-3 and only a portion of the indoor temperature and humidity data of residence C-1 fell into the ASHRAE comfort zone for clothing insulation levels of 0.9clo. So from the point of view of temperature and relative humidity, the indoor thermal comfort condition of residence C-2 and C-3 were higher than that of residence C-1.

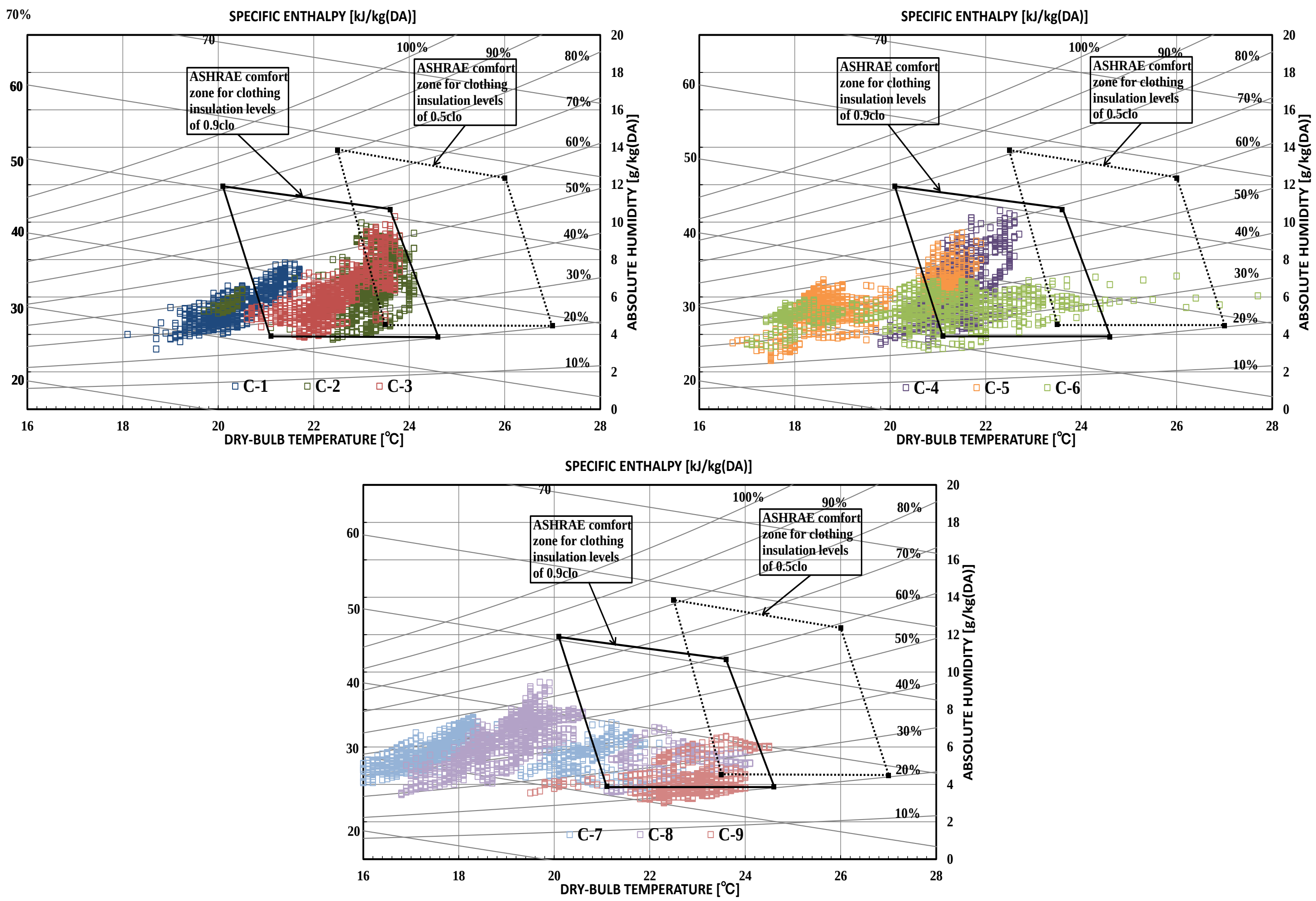



Figure 3-30 Indoor temperature and relative humidity distribution and ASHRAE comfort zone in winter

Compared with the first measured period, the indoor temperature and humidity distribution of residences during the second measured period was relatively dispersed, especially for the residential C-5 and C-6. The lowest indoor temperature was around 17ºC, the highest temperature reached up to 26ºC. Due to the lower temperature and relative humidity, there was only a part of data of these two residence fell into the ASHRAE comfort zone for clothing insulation levels of 0.9clo. However, the indoor thermal comfort condition of residence C-4 was better, most of the indoor temperature and humidity data of residence C-4 fell into the ASHRAE comfort zone for clothing insulation levels of 0.9clo.

Compared with the second measured period, the indoor temperature and humidity distribution of residence C-7 and C-8 during the third measured period was more dispersed. The temperature of residence C-7 and C-8 at most of the time was lower than 20ºC, so most of the time was outside the comfort zone. However, most portion of the indoor temperature and humidity data of residence C-9 fell into the ASHRAE comfort zone for clothing insulation levels of 0.9clo profiting from the higher indoor temperature distribution.

5. Predicted Mean Vote (PMV)

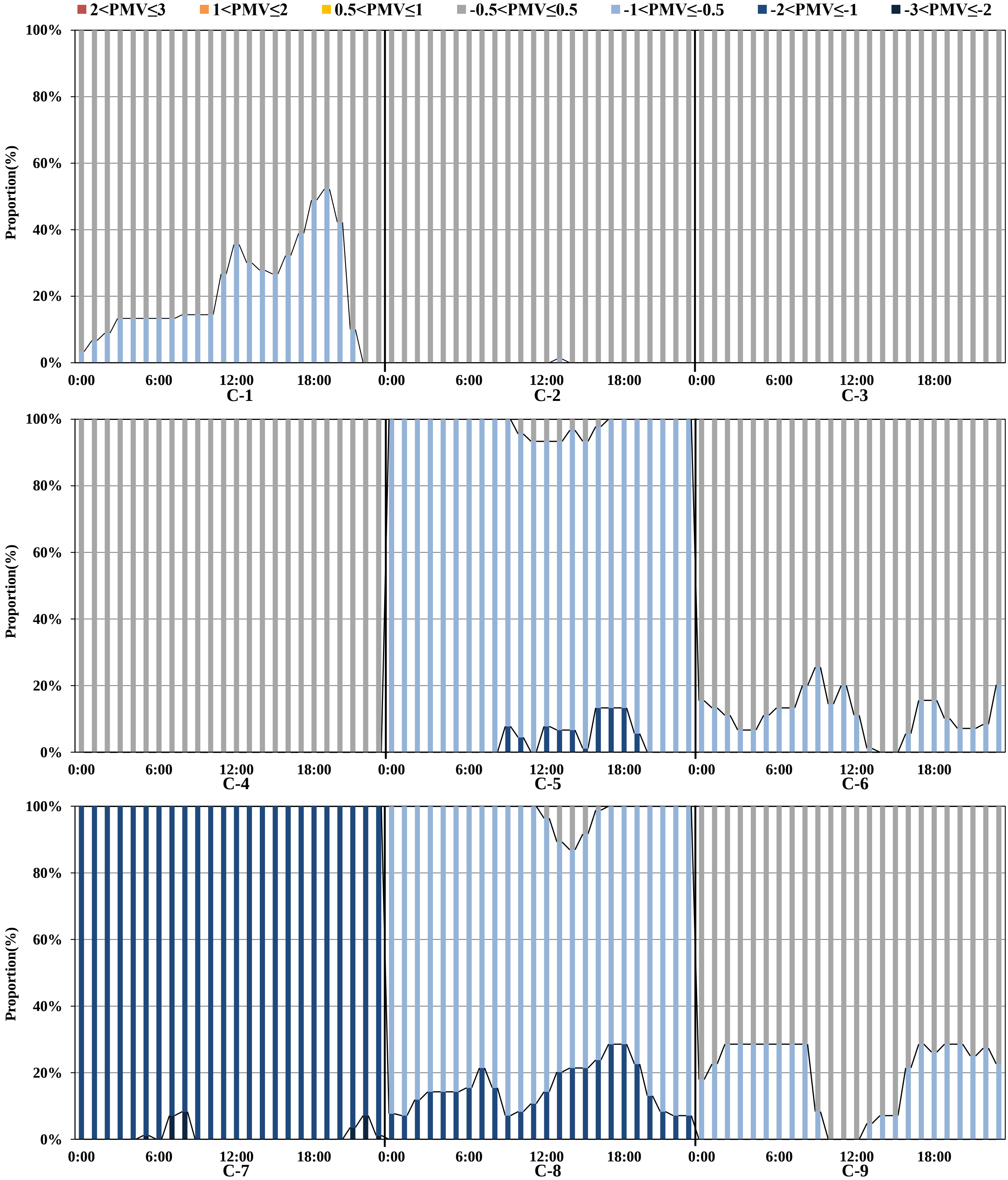



Figure 3-31 Proportion of PMV in winter of Qingdao

（Annotation: PMV’s calculation condition: M=1.2met, v=0.1m/s）

Figure 3-31 shows the proportion of PMV value of the living room in winter of Qingdao. Compared to the PMV values and its proportions of indoor thermal environment of the three residences during the first measured period, it can be seen that the PMV value evaluation results were consistent with those of ASHRAE comfort zone evaluation. The PMV values of indoor thermal environment for almost all time in residence C-2 and C-3 were between -0.5 and 0.5 which means the indoor thermal environment was comfortable.However, the PMV values of indoor thermal environment in residence C-1 was lower than that of residence C-2 and C-3. The PMV values of residence C-1 in the range of -1~-0.5 which meant the residents feel cool accounted for about 15% at night and this proportion even reached 50% at about 19:00. Therefore, the indoor thermal comfort condition of residence C-1 was not as well as residence C-2 and C-3.

Compared to the PMV values and its proportions of indoor thermal environment of three residences during the second measured period, it can be seen that the comfort proportions of the PMV value of indoor thermal environment in residence C-4 in the range of -0.5~0.5 which meant the residents feel the neutral accounted for 100% at different time. However, it is worth noting that the indoor thermal comfort condition in residence C-5 was relatively poor. The PMV value of indoor thermal environment for almost all time in residence C-5 was between -1 and -0.5, and even the PMV value as low as -2~-1 which means the residents feel the slightly cold at noon. The PMV values of residence C-6 in the range of -0.5~0.5 which meant the residents feel comfotbale accounted for about 80%, and this proportion increase around 12:00.

Compared to the PMV values and its proportions of indoor thermal environment of three residences during the third measured period, it can be seen that the indoor comfort condition was quite poor in residence C-7. The PMV values of indoor thermal environment for almost all time in residence C-7 was between -2 and -1, and even as low as -3~-2 which means the residents feel the cold in the morning and at night around 23:00. The indoor comfort condition of residence C-8 was improved, but the PMVvalues still located in the range of -1~-0.5 in the most of time. The indoor comfort condition of residence C-9 was better than that of residence C-7 and C-8. The comfort proportions of the PMV value of indoor thermal environment in residence C-9 in the range of -0.5~0.5 which means the residents feel the neutral accounted for 80%.

3.3.2.2 Questionnaire survey results

1. Clothing insulation

(1) Clothing insulation value

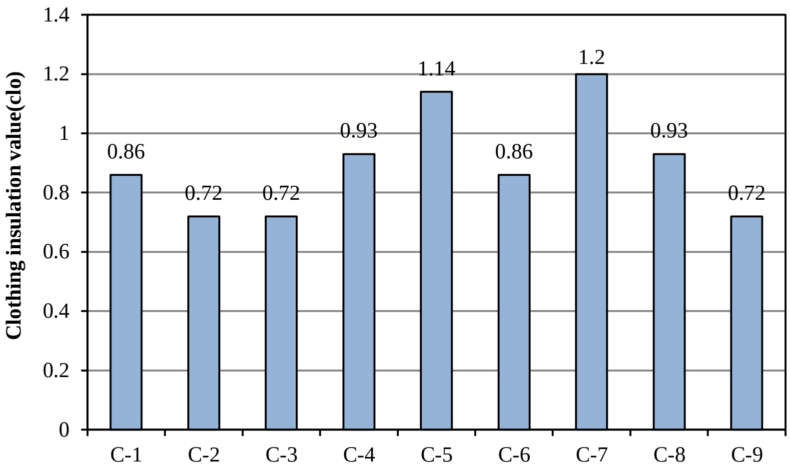



Figure 3-32 Clothing insulation value in winter in Qingdao

Figure 3-32 shows clothing insulation values for typical indoor clothing of the surveyed residences during winter measurement in Qingdao. Although there is district heating in Qingdao same as Harbin, the indoor temperature of Qingdao was far lower than that of Harbin. Therefore, it can be seen that clothing insulation levels was higher than that of Harbin. The clothing insulation value of most of surveyed residences in Harbin concentrated in about 0.5clo. However, the clothing insulation values of most of surveyed residences in Qingdao differ from one another. Due to lower indoor temperature, the clothing insulation level of residence C-7 was the highest among the surveyed residences, which was 1.20clo. It means the occupants of residence C-7 need to wear clothes with warm function at home. It is followed by residence C-5, which is 1.14clo. In addition, the clothing insulation value of residence C-4 and C-8 was 0.93clo. It also means that residents usually wear trousers with long sleeved shirts, long sleeved sweater as well as jacket. The clothing thermal resistance values of other residences were in accordance with the normal values in winter, 0.72clo and 0.86clo respectively.

(2) Relationship between clothing insulation value and living room temperature

In general, the indoor temperature and residents' condition are factors for the selection of clothing. Figure 3-33 shows the relationship between the clothing insulation and indoor average temperature. Unlike Harbin, the clothing insulation showed a strong linear relationship with indoor temperature in winter of Qingdao. It can be seen that with the decrease of the average indoor temperature, the clothing insulation value is increased. It means that there are residents adjust the amount of clothing according to the indoor temperature despite having district heating in Qingdao. In addition, the fitting linear equation of the clothing insulation value (Icl) and indoor average temperature (Ta) can be obtained as follows:

$$Icl = -0.0903Ta + 2.7711\ (R^2 = 0.8664)$$

According to the linear regression equation of the clothing insulation value and average indoor temperature, the appropriate temperature can be clarified in different level of clothing insulation condition. For example, the appropriate temperature is 20.72ºC when the clothing insulation is 0.9clo which is ASHRAE recommended value in winter.

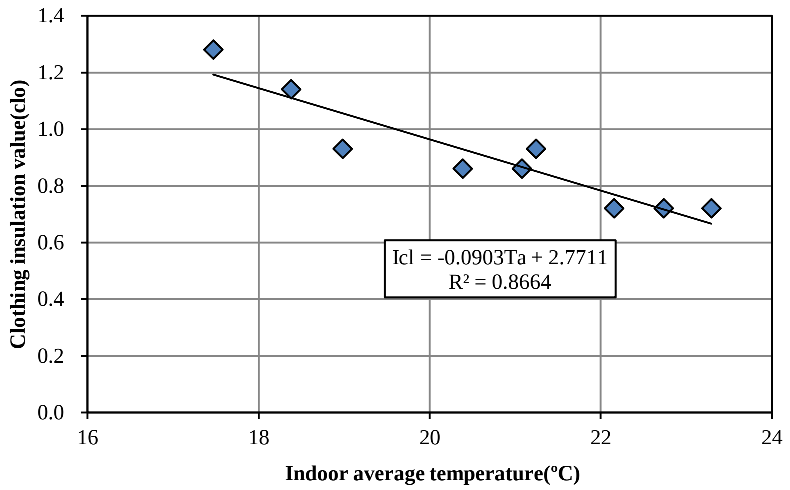



Figure 3-33 Relationship between clothing insulation value and indoor average temperature

2. Thermal comfort condition

(1) Thermal sensation vote (TSV)

1) TSV value

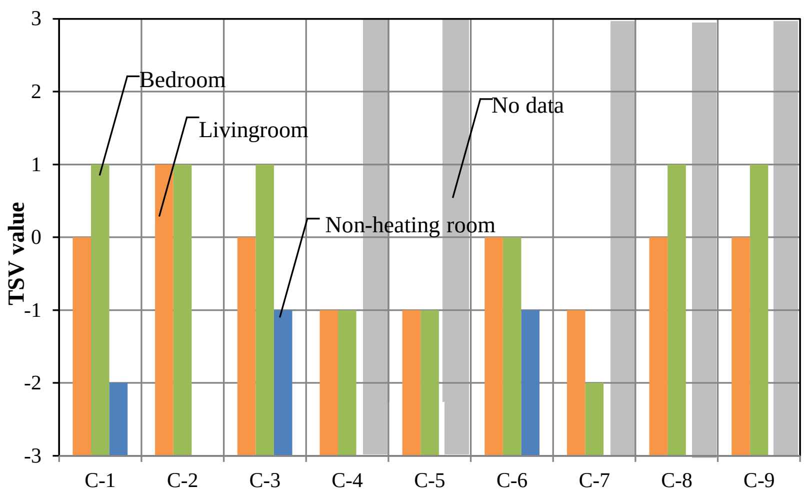



Figure 3-34 TSV value

Figure 3-34 gives the TSV value in different residences in Qingdao. It can be seen that the TSV value concentrated in 0 in the living room of most surveyed residences. This means that these residents feel the living room was a neutral thermal environment. The TSV value in the living room of C-4, C-5 and C-7 were -1. It means that indoor thermal environment in cool condition. Only the living room of residence C-2 was in a warm condition which the TSV value was 1. Compared with the living room, the comfort of bedroom in most surveyed residences seemed to move in the warmer direction by one level except for the bedroom of residence C-7. The indoor thermal environment of residence C-7 showed a cold state. In addition, the TSV of non-heating room in all measured residences presented cool, slightly cold and cold.

2) TSV and indoor average temperature

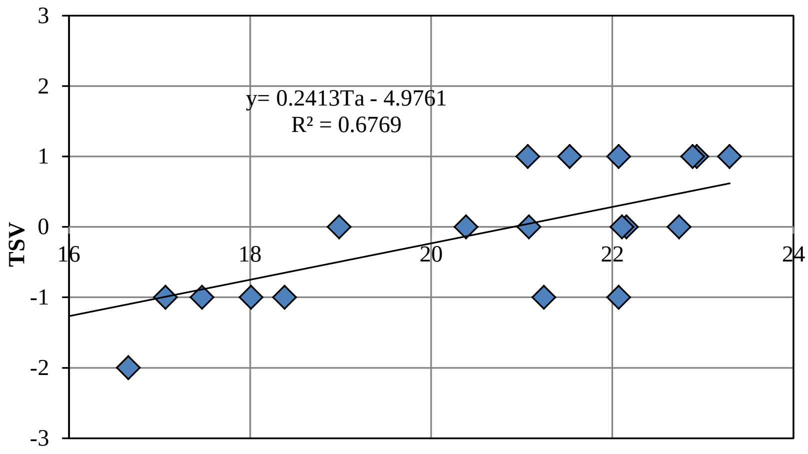



Figure 3-35 The relationship between TSV and indoor average temperature

Figure 3-35 shows the relationship between TSV and indoor average temperature in winter. Although the correlation is not as strong as Harbin which the correlation coefficient is 0.8177, it also can be seen that there is a relatively significant linear relationship between the subjective average thermal sensation of occupants and average indoor temperature, and the fitting linear equation of the subjective thermal sensation vote (TSV) and average indoor temperature (Ta) can be obtained as follows:

$$TSV = 0.2413Ta - 4.9761 \ (R^2 = 0.6769)$$

Moreover, the neutral temperature is the most moderate temperature of thermal sensation of human body. According to the linear regression equation of the average thermal sensation and average indoor temperature, it can be obtained 20.6ºC when TSV is 0 as the thermal neutral temperature as well as 16.48ºC and 24.76ºC when TSV is -1 and +1 as acceptable temperature of human body in winter of this region. Thus we can find that due to the district heating, the indoor temperatures of most surveyed residences were slightly higher than the thermal neutral temperature except for residence C-5 and C-7. But the indoor temperature of most surveyed residences were all within acceptable temperature range (16.48~24.76ºC) except for residence

C-7. Only the indoor temperature of part time in residence C-7 was below the lower limit of acceptable temperature.

Meanwhile, compared with the result of Harbin, it can be found that the thermal neutral temperature in winter of Qingdao is lower than that of Harbin which is 22.09ºC. And the acceptable temperature range in Qingdao is also wider that of Harbin which is from 19.89 ºC to 24.29ºC. This illustrates that the thermal sensations of people to same temperature are different depend on different climate zones, and the requirements or expectations to thermal comfort are also different.

3) The relationship between TSV and clothing insulation

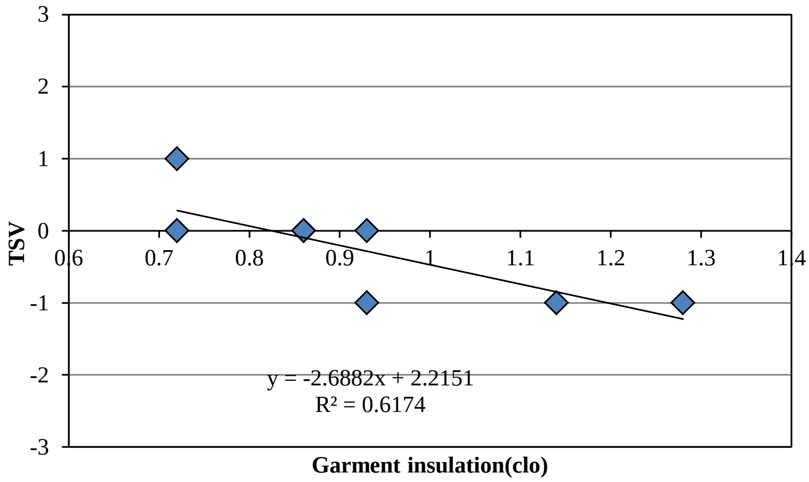



Figure 3-36 The relationship between TSV and clothing insulation

Figure 3-36 shows the relationship between TSV and indoor clothing insulation. Occupants can increase or decrease the amount of clothing to adjust their thermal sensation. Therefore, clothing insulation is also a one of parameters which can indirectly affect the actual thermal sensation of occupants. It can be seen from Figure 3-36 that there is a linear relationship between the subjective average thermal sensation of occupants and indoor clothing insulation, and the fitting linear equation of the subjective thermal sensation vote (TSV) and indoor clothing insulation (Icl) can be obtained as follows:

$$TSV = -2.6882 Icl + 2.2151 \quad (R^2 = 0.6174)$$

Moreover, according to the linear regression equation of the average thermal sensation and indoor clothing insulation, it can be obtained 0.82clo when TSV is 0 as the most suitable indoor clothing insulation in winter of Qingdao. It can be found that the suitable indoor clothing insulation level in Qingdao is lower than that of Harbin which is 0.9clo.

4) The relationship between TSV and PMV

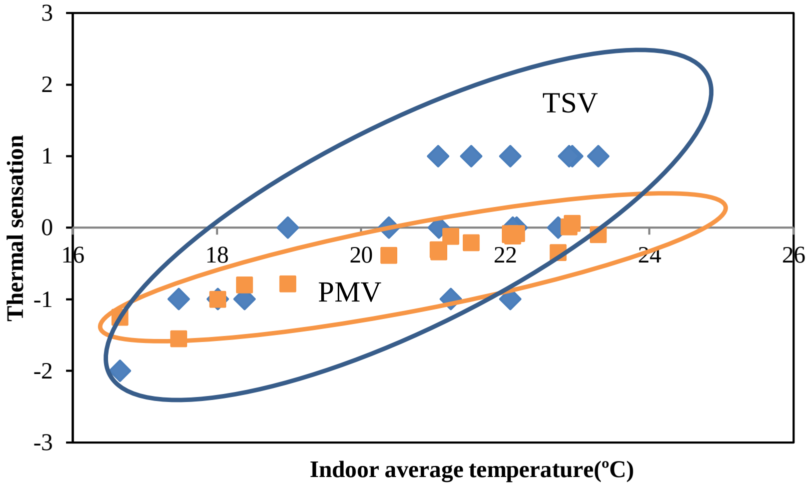



Figure 3-37 Comparison between TSV and PMV

Figure 3-37 shows the comparison of TSV and PMV in Qingdao. The result shows that the subjective TSV value is slightly wider than calculated PMV value. However, the difference between TSV and PMV value in Qingdao reduced compared with that in Harbin. The calculated PMV value was significantly lower than the subjective TSV value in most of surveyed residences. This means thermal sensation in the actual thermal environment moved to the warmer side than the predicted mean vote in the same temperature range. The indoor temperature is 22.8°C when PMV=0, higher than the surveyed thermal neutral temperature that is 20.6°C. It is proved that human comfortable temperature range in the actual thermal environment is wider than the theoretical prediction. It also means that the actual thermal environments created by thermal design specifications are not completely consistent with the thermal adaptation of people, which will lead to energy waste.

(2) Thermal comfort vote (TCV)

1) TCV value

Figure 3-38 shows the results of thermal comfort vote. It can be seen that only the TCV value of heating rooms in residence C-3 and C-9 presented +2, which means the occupants in these two residences feel the indoor thermal environment of heating rooms were comfortable. And the TCV values of heating rooms in residence C-7 were the lowest, which means the residents were not satisfied with the indoor thermal environment. This may be due to lower indoor temperatures. Although the indoor temperatures of other residences were not low, the TCV values still mainly locate in -1 which means slightly uncomfortable. Even if the indoor temperature is the main factor affecting comfort, but the reasons for this dissatisfaction may differ from one another. For example, the temperature of heating rooms in residence C-2 were relatively moderate, but the occupants of residence C-2 still felt slightly uncomfortable. In addition, the evaluation of thermal comfort in non-heating room was worse than that in heating rooms, mainly concentrated in the -1~-2.

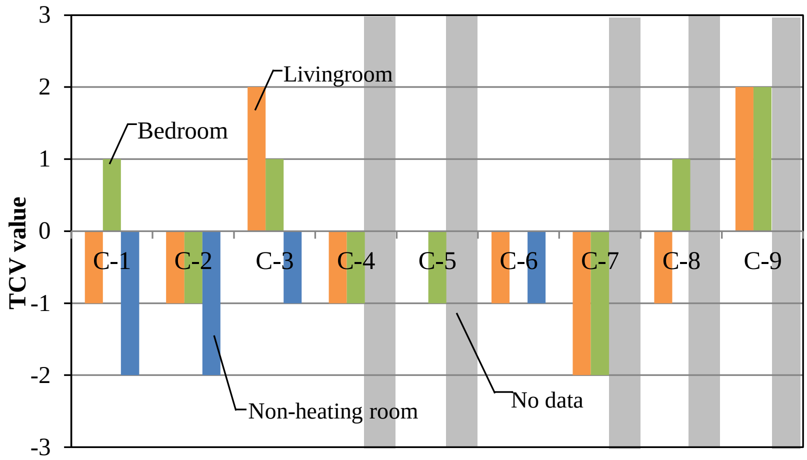



Figure 3-38 TCV value

2) Uncomfortable reason

The reasons of 「-1. Slightly uncomfortable」~「-3. Very uncomfortable」((Multiple choice)

| | |
|---|---|
| A | Room is cold overall |
| B | Feel hot, because of the very good effect of Air conditioning / district heating |
| C | Feet feel cold |
| D | Feel cold-blast air |
| E | The effect of air-conditioning is poor, it works after a long time with open |
| F | Indoor temperature drops rapidly after stopping the heating equipment |
| G | Feel flushed face with hot when using the air-conditioning |
| H | Feel sweaty |
| I | Feel dry |
| J | Others |

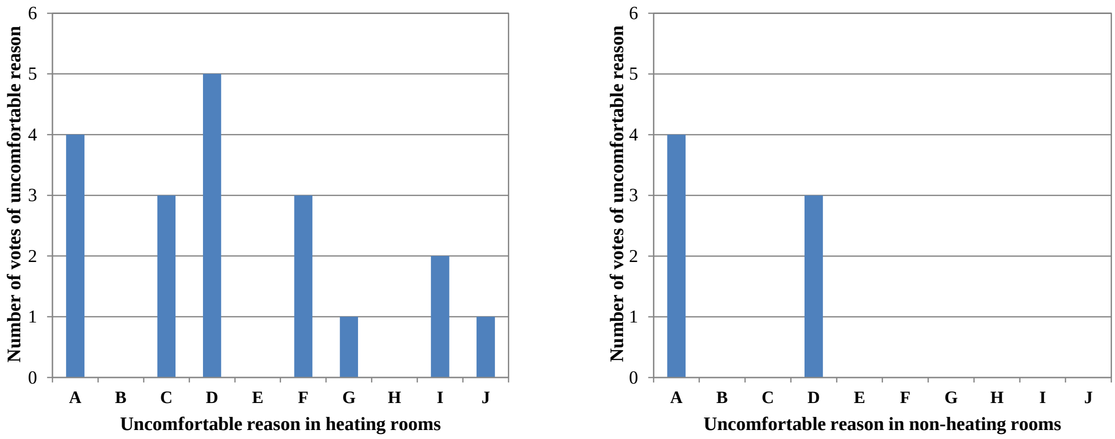



Figure 3-39 Uncomfortable reason

Figure 3-39 shows the uncomfortable reason in district heating room and non-heating room, respectively. It can be seen that the uncomfortable reason in heating room were mainly the residents felt cold and cold-blast air because of the not good effect of district heating. And in some residences, the temperature differences between human activity area (1.1m) and floor (0m) were large, and the temperatures of floor were low. Thus the occupants felt feet cold and uncomfortable. In addition, some residents selected the "Indoor temperature drops rapidly after stopping the heating equipment". May be residents felt cold and opened air conditioning or electric heater for auxiliary heating. After stopping the heating equipment, the indoor temperature drops rapidly, so they feel uncomfortable. There were also a few residents feel the windows were not tight, there was a cold wind blowing through the window seam. It is worth noting that there were only 10.53% of residents felt dry, while it was 40% in Harbin. The phenomenon of indoor air drying had been improved. And only 5.26% of residents felt flushed face with hot due to the well effect of district heating. For the non-heating rooms, the reason why most of the residents feel uncomfortable was that the room was cold overall and they felt cold-blast air.

3. The statistics of occupation condition

(1) Family members

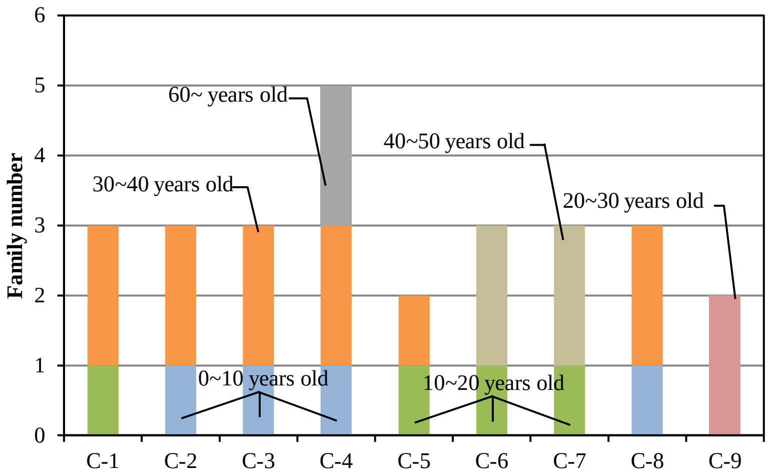


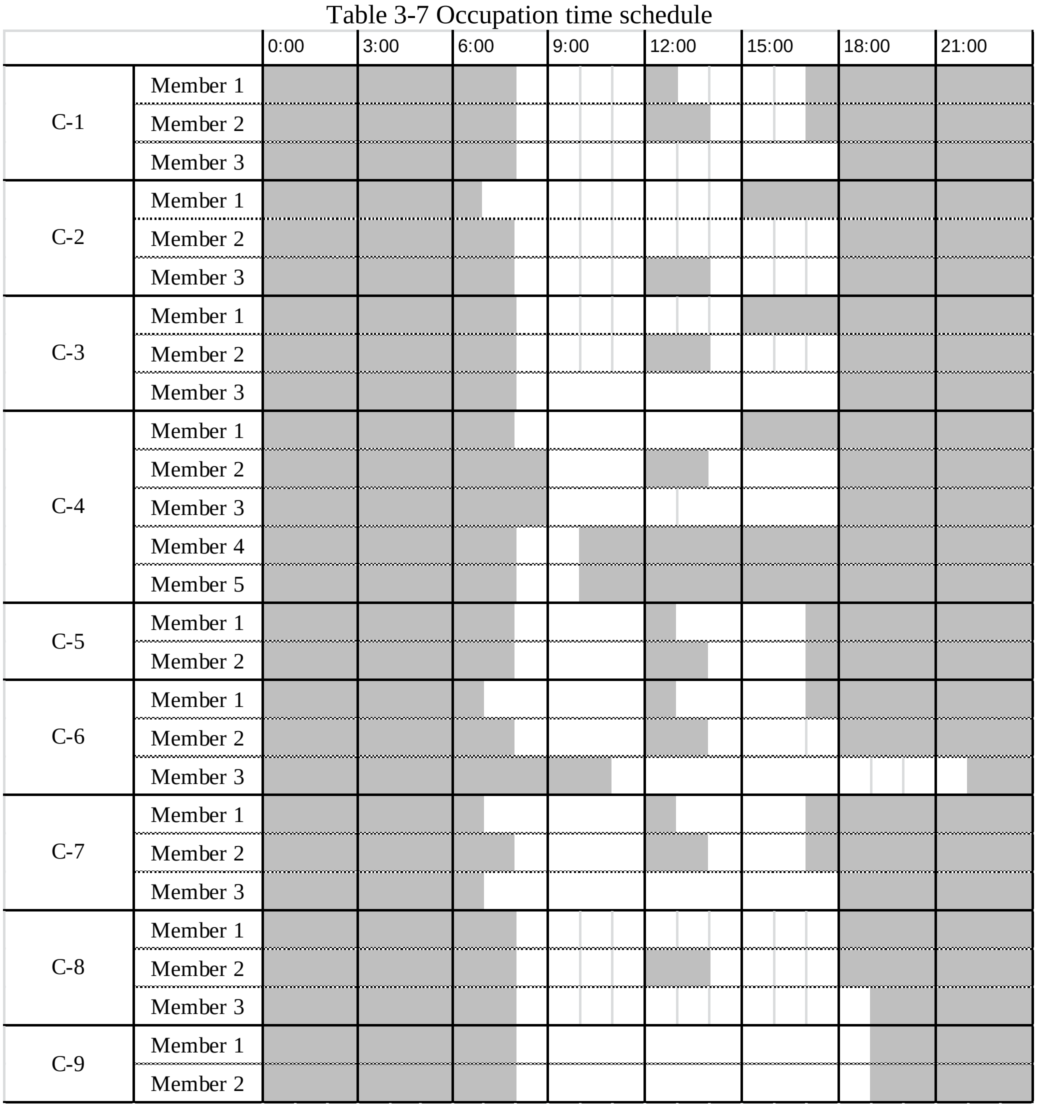

Figure 3-40 Family population and age distribution

Figure 3-40 shows the family population and age distribution in different residences. The same as the investigation condition in Harbin, the residents are all university teachers or relatives. It can be seen that the overall number of family people in most of residence is 3, the family structure is a couple aged 30~50 years old and a child aged 0~20 years old. In addition, only residence C-4 chose to live with older parents together.

(2) Occupation time

Table 3-7 shows the occupation time schedule of residents in different residences. It can be seen that because of the nature of university teachers' job, the time at home in the daytime is less, basically leave home to go to school in the morning (around 8:00) and return home in the evening (about 18:00). Unlike the previous survey in Harbin, since the university is relatively close to their residences. Some residents are used to return home for lunch and have a short rest at noon (about 12:00~14:00). Most of the children are at school during the daytime and return home in the evening. Only the older residents are basically in the room in addition to the exercise out in the morning. Therefore, the majority of residents are not in the room for about 8~9 hours during the daytime. However, same as the district heating system in Harbin, the existing district heating system runs 24 hours uninterruptedly all day long, there is no switch to adjust depend on the residents in the room or not. For the residents who are not in the room in the daytime relatively, this kind of heating system is undoubtedly a waste of energy.

Table 3-7 Occupation time schedule



4. Energy consumption

(1) Charging system

Table 3-8 Charging system in Qingdao(yuan)

| | | | ~210kWh | 171~260kWh | 260~kWh |
|---|---|---|---|---|---|
| Electricity/kWh | Current price | | 0.55 | 0.60 | 0.85 |
| | Plan implementation | 8:00~22:00 | 0.58 | 0.63 | 0.85 |
| | | 22:00~8:00 | 0.38 | 0.43 | 0.68 |
| District heating/m$^2$ | | | 30.4 | | |
| Gas/m$^3$ | | | 2.4 | | |

Table 3-8 shows the charging system of different energy in Qingdao. As can be seen, the electricity bill is divided into two valuation methods with three-tiered pricing. Aiming at the explosion of electricity consumption and the rapid increase of electricity bill, in order to reasonably control the monthly electricity consumption, not only the tiered pricing has been implemented by Qingdao power supply department but the peak and valley TOU (time-of-use) electricity price of pilot residential electricity consumption also will start to be carried out from 2017. According to the pilot program, based on the current tiered electricity pricing standards, plus 0.03 yuan per kilowatt hour during the peak period (8:00~22:00), cut 0.17 yuan per kilowatt hour during the valley period (22:00~8:00). Residents voluntarily choose whether to implement the pilot program or not, valuation by original method for those who don't choose to implement.

The charge method of district heating system in Qingdao is based on floor area same as that in Harbin, heating price per square meter is fixed annually. The heating price is 30.4 yuan/m$^2$ in the 2016, a little cheaper than that in Harbin. Heating period is from November 16th to April 5th, as long as 141 days, 41 days shorter than the heating period in Harbin.

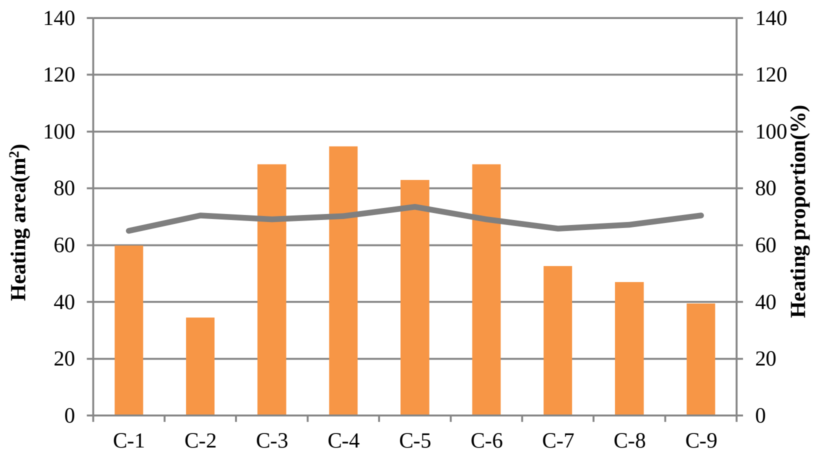



Figure 3-41 Heating area and heating proportion

Figure 3-41 shows the heating area and heating proportion in surveyed residences in Qingdao. It can be seen that because the total construction area is different, heating area is also different.

However, the heating proportion of most surveyed residences was around 70%. The heating proportions in Qingdao were relatively lower than that in Harbin which was about 80%. This may be due to the colder climate in Harbin than that in Qingdao.

(2) Energy consumption statistics

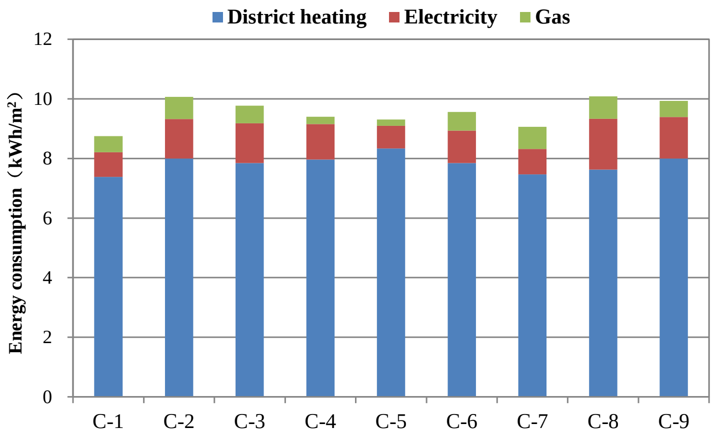



Figure 3-42 Monthly energy consumption statistics in Qingdao

Figure 3-42 shows the statistics results of monthly energy consumption in winter of Qingdao. It can be seen that, same as that in Harbin, compared to the electricity and gas consumption, the district heating consumption accounted for the main part of total energy consumption. After converting the district heating energy consumption into the corresponding electricity consumption per square meter monthly, the distribution curve was consistent with heating proportion. The heating energy consumption monthly of residence C-7 was the least, about 7.4kWh/m$^2$. This may also be a cause of lower indoor temperature in residence C-7. While that of residence C-5 was the largest, about 8.33kWh/m$^2$. This may be because there is no balcony in residence C-5.The heating area is all usable area in addition to the wall area and public area. Although there is also no balcony in residence C-1, the kitchen has no district heating. So, the district heating energy consumption in residence C-1 was lower. The district heating consumption of other surveyed residences was mainly concentrated in 8.0kWh/m$^2$/month. It was relatively lower than that in Harbin. Although the energy consumption of gas was the least compared to the district heating and electricity, the gas consumption of different residences was differ from each other. The gas consumption of residence C-5 was the least, only about 0.21kWh/m$^2$/month. However, that in residence C-8 reached 0.75kWh/m$^2$/month, almost 2.6 times more than residence C-5. Not only that, the electricity consumption of residence C-8 was also the largest, which may be because of large number of appliances and smaller floor area. As a result, the total energy consumption monthly of residence C-8 became the largest, and about 10.08 kWh/m$^2$. However, the total consumption monthly of the other surveyed residences had little difference, and about 9kWh/m$^2$, slightly lower than that in Harbin.

### 3.3.3 Measured results in Hangzhou

#### 3.3.3.1 Field measurement results

1. Indoor and outdoor temperature and relative humidity during the measured period

(1) Indoor and outdoor temperature

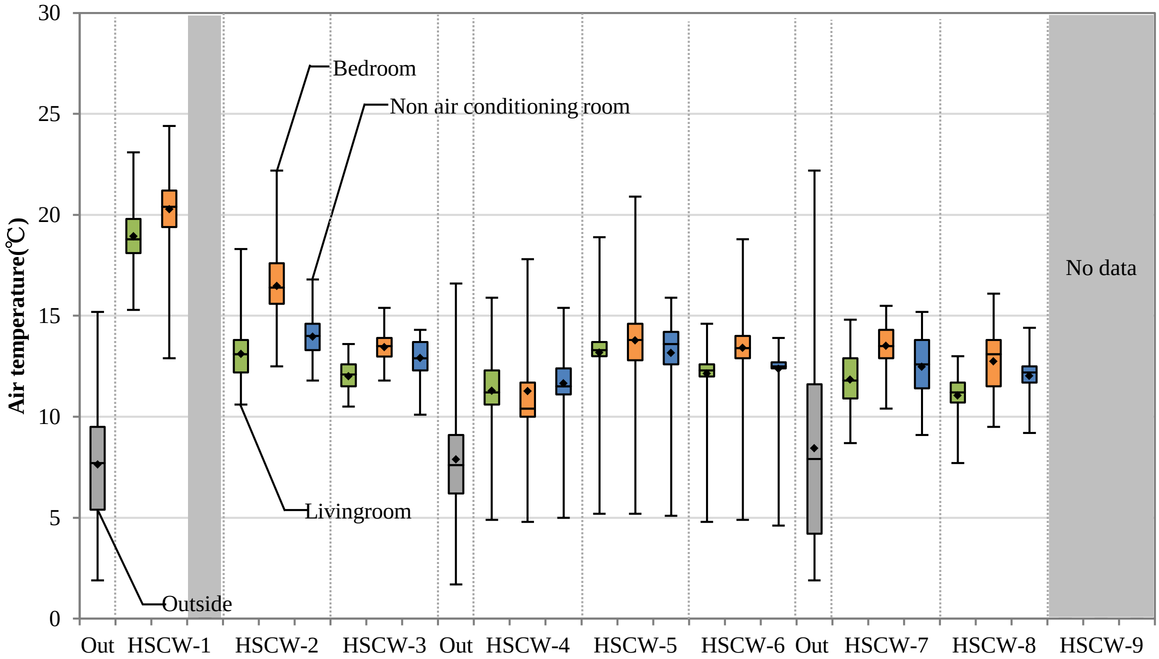



Figure 3-43 Temperature distribution during the measured period

Figure 3-43 shows the indoor and outdoor temperature distributions during the whole measured period in winter of Hangzhou. There was little difference in the outdoor temperature between the former two measured periods, and both distributed in 5~10ºC at most of the time, while the outdoor temperature distribution of the third measured period was more dispersed, the difference between the minimum and the maximum value was over 20ºC. However, the average temperatures of these three different periods were not significant, 7.6ºC, 7.9ºC, 8.4ºC respectively.

Due to the failure of the temperature and humidity recorder for the indoor measuring points in non-air conditioning room of residence HSCW-1 during the measured period, the temperature and humidity data of the non-air conditioning room was not obtained. In addition, because the residents in residence HSCW-9 was away on a business trip during the measured period in winter. It was inconvenient to set the instrument, so the measured data in winter of this residence was also not obtained. Through the observation on the indoor temperature distributions of all residences, it can be seen that because there was no district heating system in winter of Hangzhou, the indoor temperatures of all the residences were lower than those of residences with the district heating system in Harbin and Qingdao. Meanwhile, because the service condition of heating equipment in different residence was different, there were a large differences in the indoor temperature distributions of different residences. For example, compared with the indoor temperatures of different residences. The indoor temperature of residence HSCW-1 was much higher than that of the other residences, the average temperatures of living room and bedroom were 18.9$^{o}$C and 20.3$^{o}$C, respectively. It can be inferred that the residence usually use the heating equipment. Compared to the other residences, the average indoor temperatures of other residences were all lower than the lower limit (18$^{o}$C) of design heating temperature specified and designed by the《The Code for Design of Heating Ventilation and Air conditioning》, which will lead to the reduction of indoor comfort. In addition, according to the Chinese Hygiene Standard, 12$^{o}$C is taken as the lower limiting temperature in winter. As shown in Figure 3-43, the average indoor temperatures of part of the residences were even lower than this standard. When the indoor temperature was lower than this standard, the human body cannot sit still for a long time, meanwhile the risk of respiratory disease will increase. Therefore, as for Hangzhou without the district heating system, the indoor thermal environments of majority of the residences were relatively poor.

In addition, through the observation on the indoor temperature distributions of the different rooms, it can be seen that except for the residence HSCW-4, the average indoor temperatures of bedroom in the other residences were all higher than that of living room and non-heating room, which indicated that most of the residences usually use the heating equipment in the bedroom. However, the heating equipment was hardly used in the living room, the indoor temperature of living room was relatively low, even the average indoor temperatures of living room were lower than that of non-heating room in the most of the residences.

(2) Indoor and outdoor relative humidity

Figure 3-44 shows the indoor and outdoor relative humidity distribution during the measured period of Hangzhou in winter. Compared to that in the two former cities, the outdoor relative humidity of Hangzhou in winter was larger. Compared with the different measured periods, the outdoor relative humidity of the first measured period was relatively lower, and generally distributed between 40%~60% at most of the time. However, the outdoor relative humidities of the other two measured periods were both more than 60% at most of the time, and even reached up to more than 90% some time, which may be due to the overcast and rainfall weather during the measured period. The average values of these three measured periods were 54.3%, 67.4% and 71.4%, respectively.

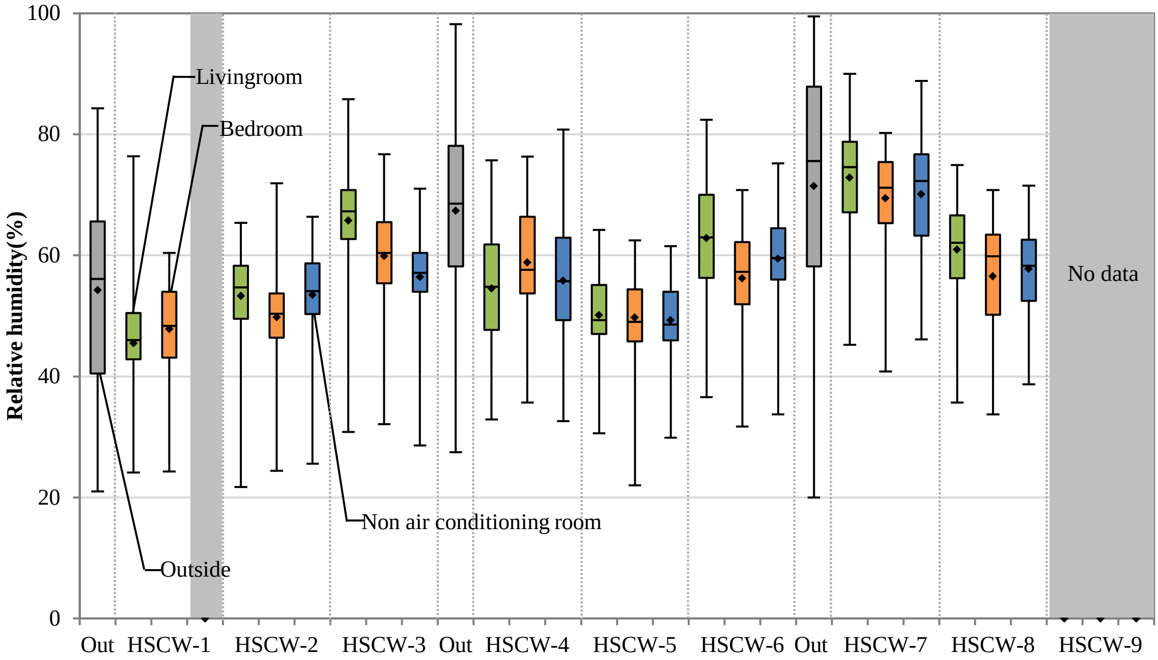
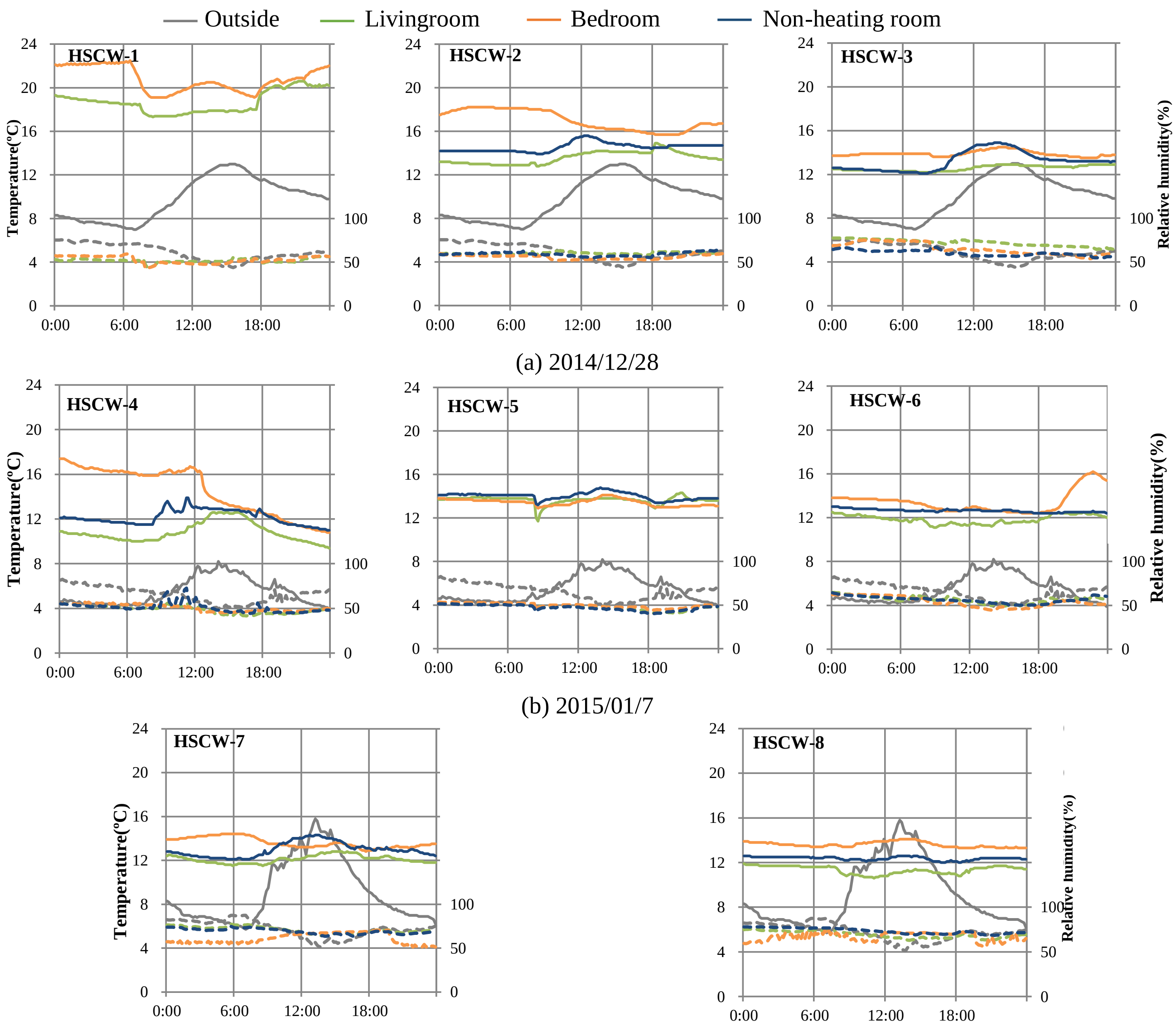


Figure 3-44 Relative humidity distribution during the measured period

For the non-district heating residences, the outdoor relative humidity condition can directly affect the indoor relative humidity. It can be seen that the relative humidity distribution was higher than those of Harbin and Qingdao which equipped with the district heating system. The indoor relative humidity distributions of heating room in most of the surveyed residences were about 40%~60%. The indoor relative humidity of living rooms of parts of residences and residence HSCW-8 was higher than 60%. This may be because the different living habits and indoor humidity sources (cooking and dining, plant factors, water etc.) of residents led to the certain difference in the indoor relative humidity. In addition, it can be seen from the comparison of the different rooms in a same residence, because the residents often used the heating equipment in the bedroom, leading to the reduction of relative humidity in the bedroom.

Compared to the summer, the relatively high indoor relative humidity in winter is more likely to lead to the breeding of mold, which not only can occur the phenomenon of frost and mildew, but also can cause the respiratory tract infection of human body. Therefore, corresponding measures should be taken the to reduce the indoor relative humidity in winter of this climate zone.

2. Variation curve of indoor and outdoor temperature and humidity in a typical day




(a) 2014/12/28

(b) 2015/01/7

(c) 2015/01/22

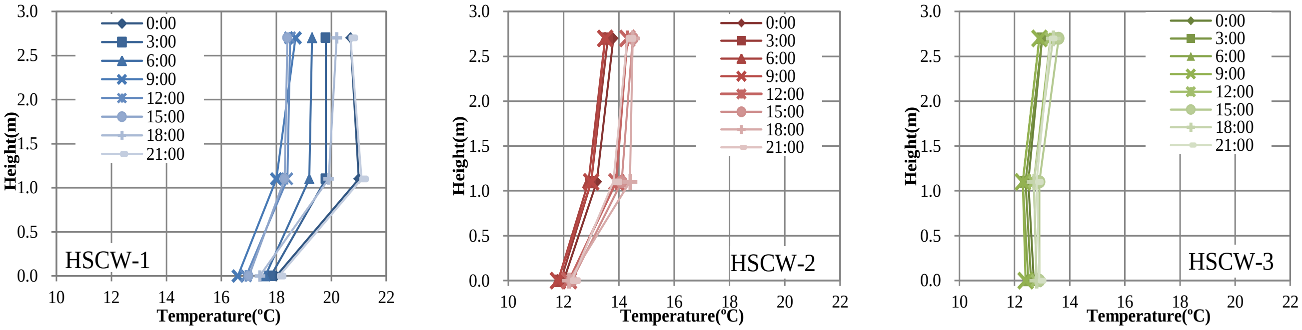
Figure 3-45 Variation curve of indoor and outdoor temperature and humidity in a typical day

Figure 3-45 shows the variation curves of indoor and outdoor temperature and humidity in a typical day in winter. Based on the indoor temperature distribution curve, the service condition of heating equipment can be obviously observed. In the room without the use of heating equipment, the indoor temperature changed along with the time slightly, and the temperature difference of different rooms was not large.

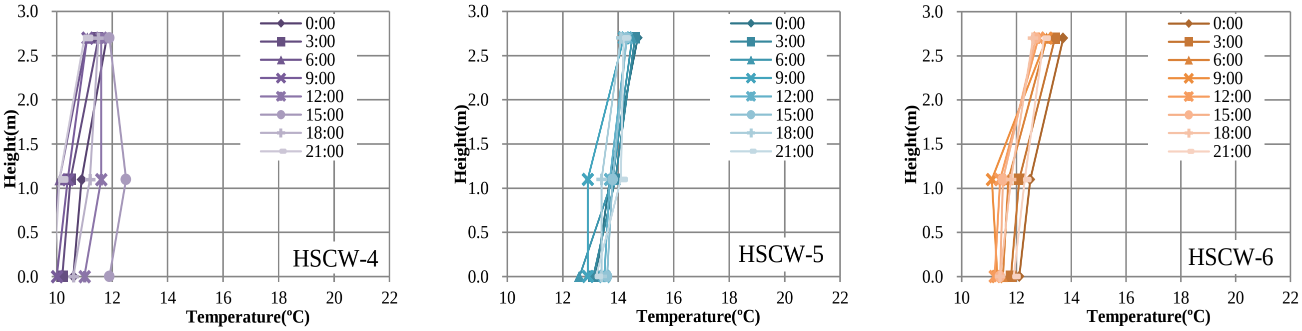
It can be seen from the Fig. (a), the outdoor temperature difference between day and night was small, the temperature at night remained at around 8$^{o}$ C. It reached the minimum at 7:00 am and reached the maximum at around 15:00 in the afternoon, the temperature fluctuation range within 1 day was between 7.0~13.0ºC. From the indoor temperature distribution curves of these three residences, it can be found that the bedroom temperatures at night of only residence HSCW-1 and HSCW-2 remained at above 18ºC. According to the survey, a guest lodged in the living room of residence HSCW-1 during the measured period, and the old and children stayed at home all day along, so the air conditionings in the living room and bedroom were both used for heating in all-weather conditions. However, the setting temperatures of air conditioning in the living room and bedroom were different at different time periods. The setting temperature of air conditioning in the bedroom at night was about 22$^{o}$C, while the setting temperatures of bedroom and living room during the day almost were both around 18$^{o}$C. In addition, it can be seen from the temperature distribution curves, the indoor temperature of air conditioning was relatively stable due to the absence of other heat sources at night. Because the bedroom was located in the day-side, the bedroom temperature was slightly higher than the setting temperature of air conditioning which was affected by solar radiation during the day, and reached 20.5$^{o}$C at around 2:00 in the afternoon. The marks that used the air conditioning for heating in the bedroom at night can be observed from the temperature distribution curve of residence HSCW-2. The indoor temperature of living room in residence HSCW-3 was the lowest, remained at around 12$^{o}$C, the temperature of bedroom was slightly about 2$^{o}$C higher than that of living room. Compared to the first measured period, the outdoor temperature of the second measured period was relatively low, only around 4$^{o}$C at night, and the maximum value of temperature in the afternoon was only 8$^{o}$C. It can be seen from the comparison of three residential indoor temperature distribution curves that only the bedrooms of residence HSCW-4 and HSCW-6 used the air conditioning at part of the time. The air conditioning were used during the sleep period and throughout the morning 0:00~12:00 as well as before sleeping 20:00~23:00, respectively. However, the indoor temperature was still less than 18$^{o}$C although these two residences used the air conditioning, which indicated the setting temperature of air conditioning was lower. The air conditioning was not used in the living room of residence HSCW-4, the temperature at night was only around 10$^{o}$C, the temperature rised to 12.5$^{o}$C due to the solar radiation during the daytime. The residence HSCW-5 and HSCW-6 did not use the air conditioning, so the indoor temperature hardly fluctuated along with the time, remained at 14 $^{o}$C and 12$^{o}$C, respectively. In addition, it can be seen from the indoor temperature fluctuation of the residence HSCW-5, there was a short natural ventilation by opening the window at about 8:30 in the morning.

It can be seen from the Fig. (c), these two residences in the third measured period both did not use the air conditioning in the room.The indoor temperature distribution was relatively lower. The temperature of living room in residence HSCW-7 and HSCW8 remained at around 12$^{o}$C and 10$^{o}$C, respectively. The temperature of bedroom was 2$^{o}$C higher than that of living room probably due to the personnel heat radiation.

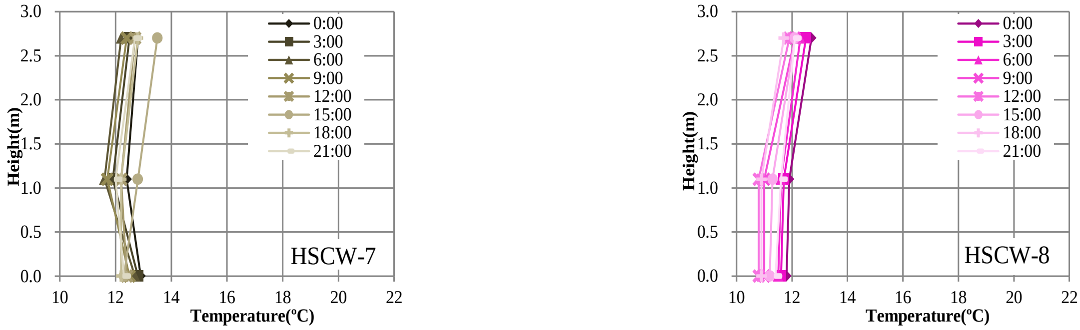
3. Indoor temperature distribution at different heights




(a) 2014/12/28




(b) 2015/01/7




(c) 2015/01/22

Figure 3-46 Temperature distribution at different height in the living room

Figure 3-46 shows the temperature distributions at different heights in the living rooms of different residences. Compared to the investigation cities which have district heating system, the indoor temperature distribution of Hangzhou in winter was relatively uniform. Compared with the three residences during the first measured period, it can be seen that the indoor temperature distributions at different heights in residence HSCW-3 were the most uniform, the temperature difference between top and bottom was less than 1ºC. It is followed by residence HSCW-2, the temperature difference between the ceiling (2.7m) and floor (0m) was about 2ºC. It is worth noting that the temperature difference between human activity area (1.1m) and floor (0m) in residence HSCW-1 was slightly larger, especially at 21:00 and 0:00. This is because that the split-floor type air conditioning was used in the living room, the height of air conditioning was about 1.8m, the general direction of air blower outlet was the downward, the temperature of the personnel activity zones was relatively higher. In addition, the temperature distributions of personnel activity zone in residence HSCW-1 and the ceiling were relatively dispersed at different time. There was about 3ºC temperature difference between 9:00 in the morning and 21:00 in the night, which is due to the higher setting temperature of air conditioning in the night. Compared with the indoor temperature distributions at different height of living room during the other two measured periods, it can be seen that as a result of the hardly use of air conditioning, there was no heat source in the room. Meanwhile, excluding that the living room of residence HSCW-4 was located in the south where can receive the direct solar radiation, the living rooms of the other residences all were located in the middle where was less affected by solar radiation. Therefore, the temperature distribution of living room was relatively uniform, the temperature difference at different height was small, basically was controlled below 2ºC. Due to the influence of solar radiation, the temperatures of floor and personnel activity zones in the living room in residence HSCW-4 were significantly increased at 12:00 and 15:00. Moreover, although the residence HSCW-4 was located in the topmost, but there was no significant reduction in the ceiling temperature, and the effect of solar radiation at noon on the ceiling temperature was also relatively small, which indicated that the thermal insulation measures of ceiling were better.

4. ASHRAE comfort zone

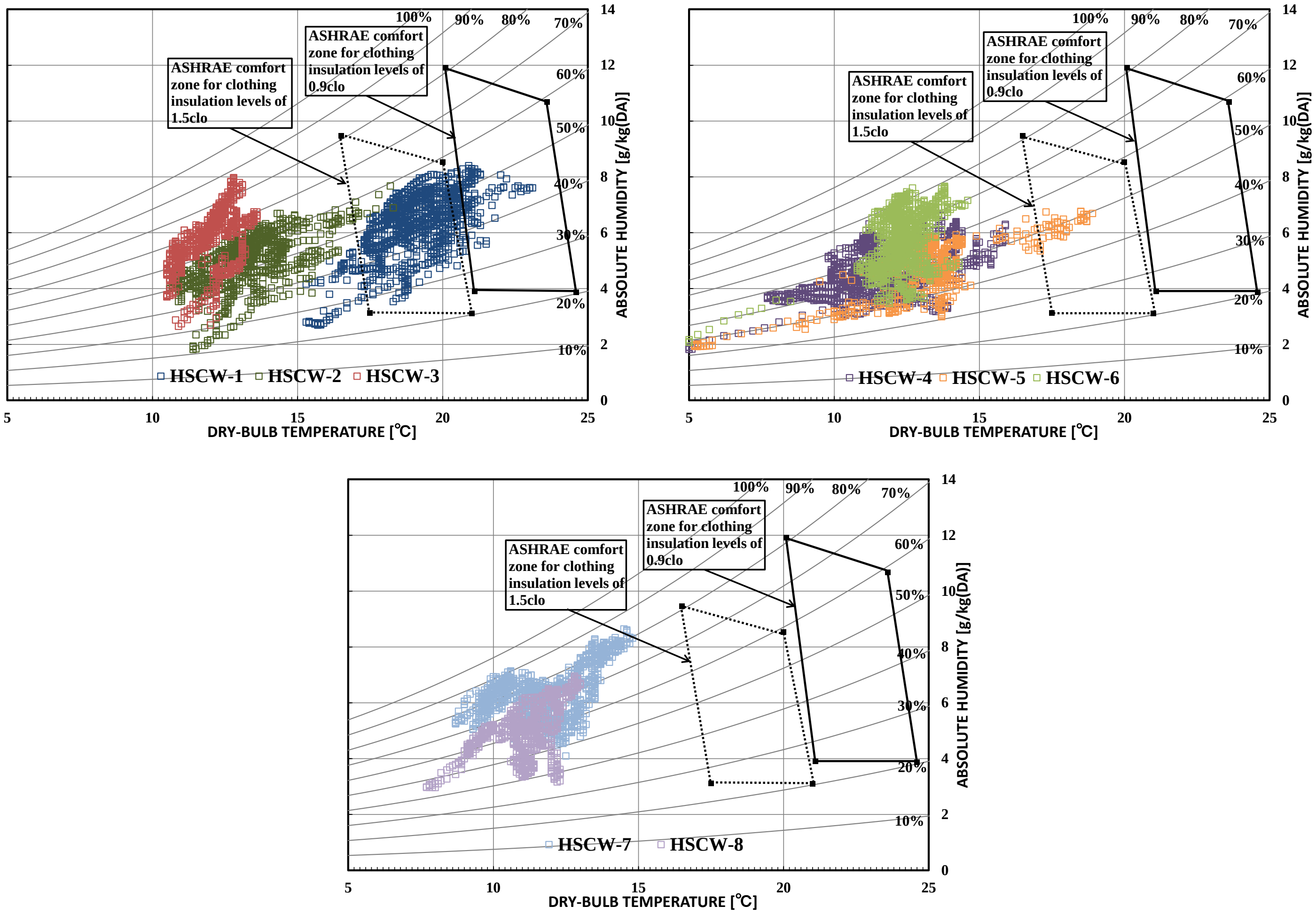



Figure 3-47 Indoor temperature and relative humidity distribution and ASHRAE comfort zone in winter

Figure 3-47 shows the indoor temperature and relative humidity distribution as well as the location of ASHRAE comfort zone in winter. Because of the low temperature, there was almost no data fell into the ASHRAE comfort zone for clothing insulation levels of 0.9clo except for part data of residence HSCW-1. Because the residents would adjust their own clothing thermal resistance depend on the thermal sensation. When the indoor temperature was low, the residents would feel cold so as to increase the clothing. Similarly, the ASHRAE comfort zones for more clothing levels can be approximated by increasing the temperature borders of this zone by 0.6K for each 0.1clo increase of clothing insulation, the comfort zone moved to the left along with the increase of clothing insulation. After moving, only most of the indoor temperature and humidity data of residence HSCW-1 and little part data of residence HSCW-5 fell into the ASHRAE comfort zone for clothing insulation levels of 1.5clo. Therefore, it can be judged from ASHRAE comfort standard that the residential indoor thermal environment of this climate zone in winter was relatively poor.

5. Predicted Mean Vote (PMV)

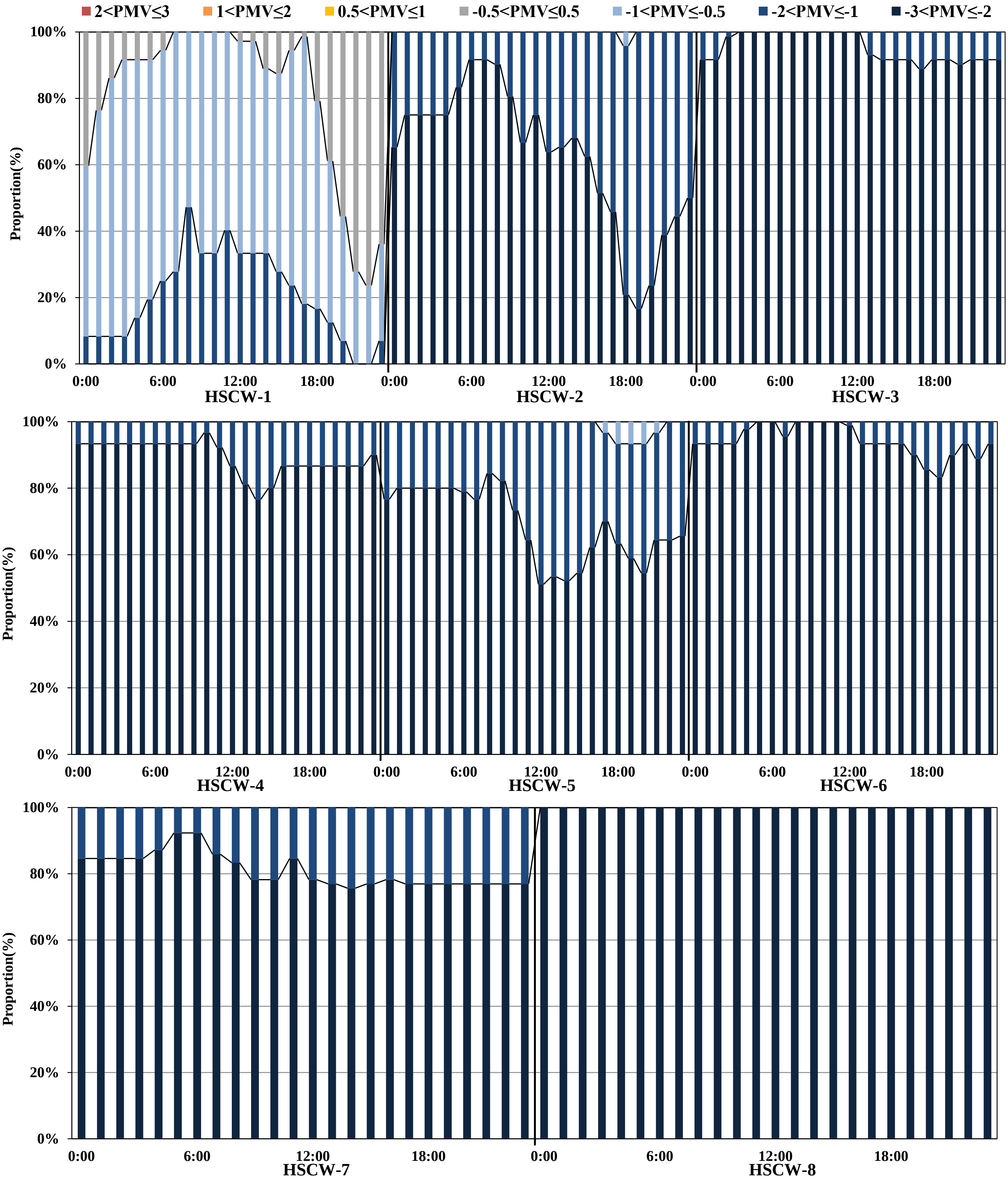



Figure 3-48 Proportion of PMV in winter of Hangzhou

（Annotation: PMV’s calculation condition: M=1.2met, v=0.1m/s）

Figure 3-48 shows the proportion of PMV value of the living room in winter of Hangzhou. Compared to the PMV values and its proportions of indoor thermal environment of the three residences during the first measured period, it can be seen that the PMV value evaluation results were consistent with those of ASHRAE comfort zone evaluation. The PMV values of indoor thermal environment for almost all time in most residences located in the range of -3~-2 which means the indoor thermal environment is very cold, and the proportion were all above 80% even reached 100% in residence HSCW-8. Only the residence HSCW-1 had data of PMV values located in the range of -0.5~0.5 which means the residents felt comfotbale, and this proportion increased at the entertainment time after dinner. It is because of the higher frequency of using of air conditioning in this time in the living room. It is also proved that if the heating equipment is not used in winter in this climate zone, the indoor thermal environment would be very poor.

3.3.3.2 Questionnaire survey results

1. Clothing insulation

(1) Clothing insulation value

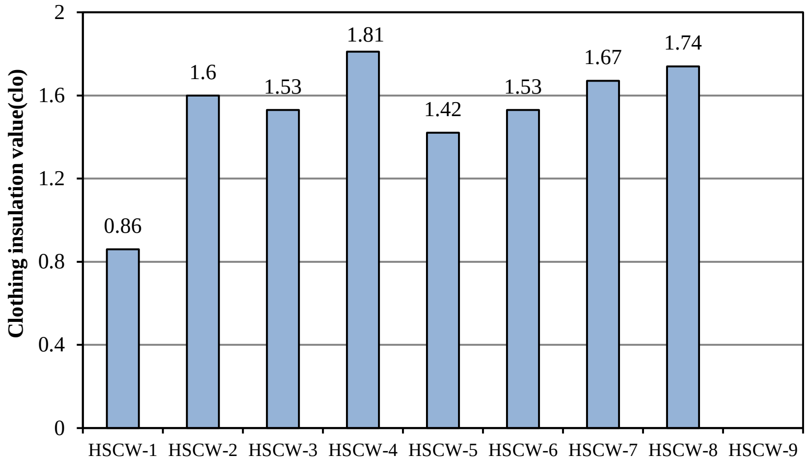



Figure 3-49 Clothing insulation value in winter in Hangzhou

Figure 3-49 shows clothing insulation values for typical indoor clothing of the surveyed residences during winter measurement in Hangzhou. Due to there is no district heating in Hangzhou, the indoor temperature of Hangzhou was far below that of Harbin and Qingdao in winter. Therefore, it can be seen that clothing insulation levels was far higher than that of Harbin and Qingdao. The clothing insulation value of most of surveyed residences in Harbin and Qingdao were concentrated in about 0.5clo and 0.9clo, respectively. However, the clothing insulation values of most of surveyed residences in Hangzhou were mainly concentrated in about 1.5clo. It means the occupants of Hangzhou need to wear clothes with warm function at home. The clothing insulation level of residence HSCW-7 was the highest among the surveyed residences, which was 1.81clo. It was followed by residence HSCW-8, which was 1.74clo. The clothing insulation level of residence HSCW-1 was the lowest, which was only 0.86clo. This is due to the indoor temperature in winter was much higher than other residence HSCW-1 which benefit from the using of air conditioning.

(2) Relationship between clothing insulation value and living room temperature

Figure 3-50 shows the relationship between the clothing insulation and indoor average temperature in winter in Hangzhou. The clothing insulation shows a very strong linear relationship with indoor temperature in winter of Hangzhou. The correlation coefficient is as high as 0.93. It can be seen that with the decrease of the average indoor temperature, the clothing insulation value increase. It means that there are residents adjust the amount of clothing according to the indoor temperature in Hangzhou.

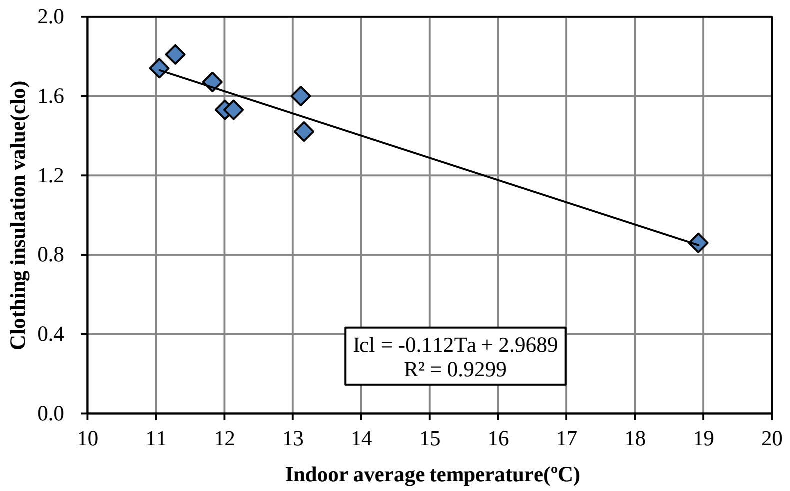



Figure 3-50 Relationship between clothing insulation value and indoor average temperature

In addition, the fitting linear equation of the clothing insulation value (Icl) and indoor average temperature (Ta) can be obtained as follows:

$$Icl = -0.112\ Ta + 2.9689\ (R^2 = 0.9299)$$

According to the linear regression equation of the clothing insulation value and average indoor temperature, the appropriate temperature can be clarified in different level of clothing insulation condition. For example, the clothing insulation is 1.17clo when the indoor temperature is 16°C which is the lower limit of the design temperature of air conditioning in winter in Hot Summer and Cold Winter Zone(6).

2. Thermal comfort condition

(1) Thermal sensation vote (TSV)

1) TSV value

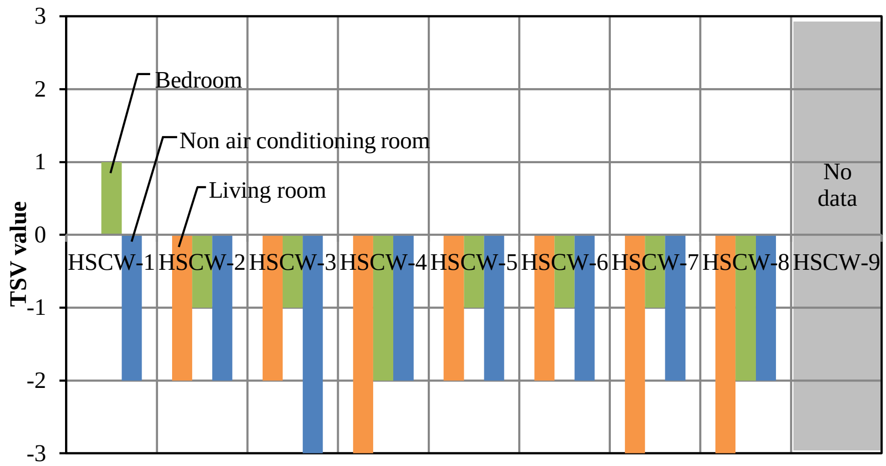



Figure 3-51 TSV value

Figure 3-51 shows the TSV value in different residences in winter in Hangzhou. It can be seen that the TSV value concentrated in -2 in living rooms and non-air conditioning rooms of most surveyed residences. This means that these residents felt the indoor environment was in a slightly cold condition. Even the thermal sensation values of some living room were evaluated as -3, which corresponded to the thermal sensation of cold. Compared with the living room, the comfort of bedroom in most surveyed residences seems to move in the warmer direction by one level. Only the indoor thermal environment of bedroom in residence HSCW-1 showed a warm state benefitting from the using of air conditioning.

2) TSV and indoor average temperature

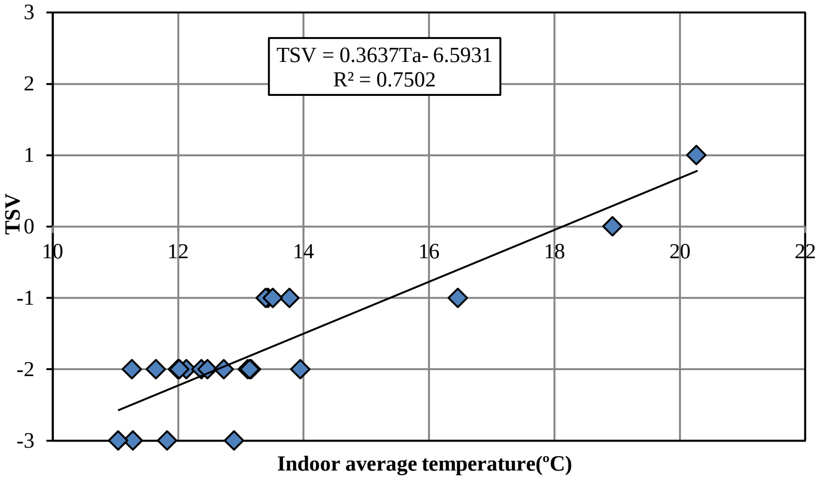



Figure 3-52 The relationship between TSV and indoor average temperature

Figure 3-52 shows the relationship between TSV and indoor average temperature in winter in Hangzhou. It can be seen that there is a relatively significant linear relationship between the subjective average thermal sensation of occupants and average indoor temperature in winter in Hangzhou. And the fitting linear equation of the subjective thermal sensation vote (TSV) and average indoor temperature (Ta) can be obtained as follows:

$$TSV = 0.3637Ta - 6.5931 \quad (R^2 = 0.7502)$$

Similarly, according to the linear regression equation of the average thermal sensation and average indoor temperature, it can be obtained 18.1ºC when TSV is 0 as the thermal neutral temperature as well as 15.4ºC and 20.9ºC when TSV is -1 and +1 as acceptable temperature of human body in winter of this climate zone. Thus we can find that due to residents do not often use air conditioning for heating, the indoor temperature of most surveyed residences were far lower than the thermal neutral temperature except for residence HSCW-1. And even the indoor temperatures of most surveyed residences were lower than the limit of acceptable temperature which is 15.4ºC. Only the indoor temperature of residence HSCW-1 was located within the acceptable temperature range (15.4~20.9ºC).

Meanwhile, compared with the result of Harbin and Qingdao, it can be found that the thermal neutral temperature in winter of Hangzhou is lower than that of Harbin and Qingdao which are 20.6ºC and 22.1ºC. This also illustrates that the thermal sensations of people to same temperature are different depend on different climate zones, and the requirements or expectations to thermal comfort are also different. The colder the zone is, the thermal neutral temperature of residents is the higher.

3) The relationship between TSV and clothing insulation

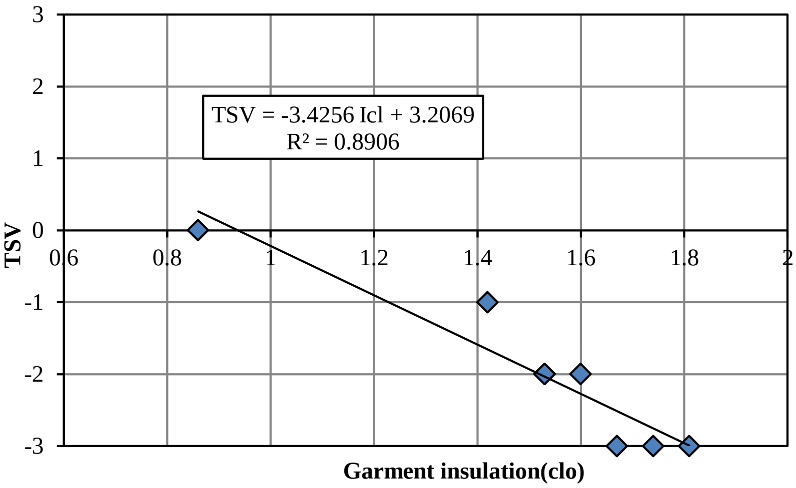



Figure 3-53 The relationship between TSV and clothing insulation

Figure 3-53 shows the relationship between TSV and indoor clothing insulation in winter in Hangzhou. Occupants can increase or decrease the amount of clothing to adjust their thermal sensation. Therefore, clothing insulation is also a one of parameters which can indirectly affect the actual thermal sensation of occupants. It can be seen from Figure 3-53 that there is a significant linear relationship between the subjective average thermal sensation of occupants and indoor clothing insulation, and the correlation is stronger than that in Harbin and Qingdao. The linear relationship indicates that clothing thermal insulation increased along with the decrease of TSV value which means the residents feel cold. The fitting linear equation of the subjective thermal sensation vote (TSV) and indoor clothing insulation (Icl) can be obtained as follows:

$$TSV = -3.4256 I_{cl} + 3.2069 \quad (R^2 = 0.8906)$$

Moreover, according to the linear regression equation of the average thermal sensation and indoor clothing insulation, it can be obtained 0.94clo when TSV is 0 as the most suitable indoor clothing insulation in winter of Hangzhou. It can be found that the suitable indoor clothing insulation level in Hangzhou is slightly higher than that of Harbin and Qingdao which are 0.9clo and 0.82clo, respectively.

4) The relationship between TSV and PMV

Figure 3-54 shows the comparison of TSV and PMV. The result shows that the subjective TSV value is slightly wider than calculated PMV value in winter in Hangzhou same as other surveyed cities. The indoor temperature is 22.31°C when PMV=0, far higher than the surveyed thermal neutral temperature that is 18.13°C. It is also proved that human comfortable temperature range in the actual thermal environment is wider than the theoretical prediction.

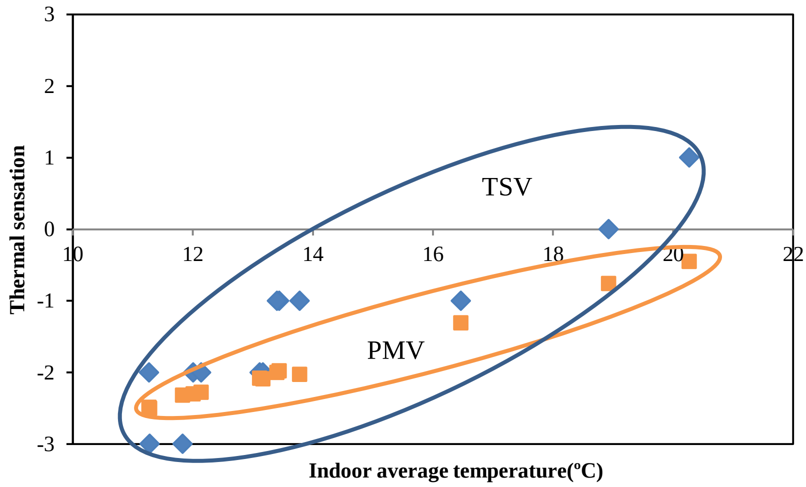



Figure 3-54 Comparison between TSV and PMV

(2) Thermal comfort vote (TCV)

1) TCV value

Figure 3-55 shows the results of thermal comfort vote of indoor environment in winter in Hangzhou. It can be seen that only the TCV value of living room in residence HSCW-1 presented 0, which means the occupants feel the indoor thermal environment of living room universality. The TCV values of living room in other residences mainly located in -2 which means uncomfortable because of the lower indoor temperatures. Compared with the living room, the thermal comfort condition of bedroom in most surveyed residences seems to move in the better direction by one level, but the comfort condition was still poor. In addition, due to the temperature of non-air conditioning room were almost same as that in living room in most surveyed residences, the evaluation of thermal comfort in non-air conditioning rooms differed little from that in living rooms, mainly concentrated in the -2~-3.

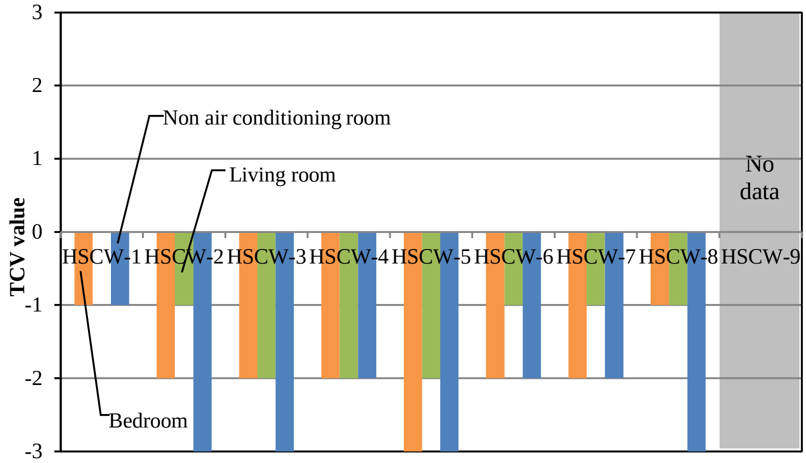



Figure 3-55 TCV value

2) Uncomfortable reason

The reasons of 「-1. Slightly uncomfortable」~「-3. Very uncomfortable」(Multiple choice)

| | |
|---|---|
| A | Room is cold overall |
| B | Feel hot, because of the very good effect of Air conditioning / district heating |
| C | Feet feel cold |
| D | Feel cold-blast air |
| E | The effect of air-conditioning is poor, it works after a long time with open |
| F | Indoor temperature drops rapidly after stopping the heating equipment |
| G | Feel flushed face with hot when using the air-conditioning |
| H | Feel sweaty |
| I | Feel dry |
| J | Others |

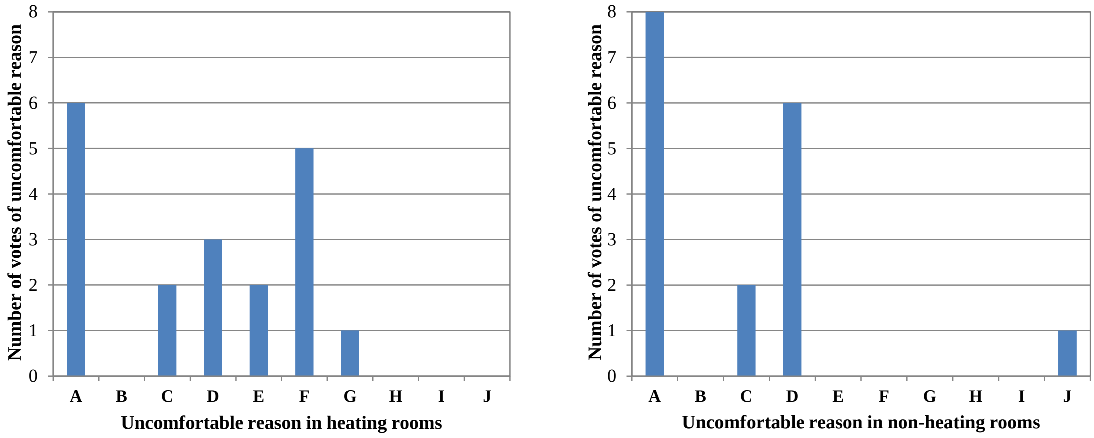



Figure 3-56 Uncomfortable reason

Figure 3-56 shows the uncomfortable reason in living room and bedroom as well as non-air conditioning room. It can be seen that the uncomfortable reason in living room and bedroom were mainly the residents feel cold and the indoor temperature dropped rapidly after stopping the heating equipment. And in residence HSCW-1, the temperature differences between human activity area (1.1m) and floor (0m) are large, the temperatures of floor were low. Thus the occupants felt feet cold and uncomfortable. In addition, due to the low outdoor temperature in winter, it will take some time for the air conditioning to operate. Therefore, some residents selected the "The effect of air-conditioning is poor, it works after a long time with open". There were also a few residents reflected the windows are not tight, they felt cold-blast air through the window seam. It is worth noting that there was 5.26% of residents felt flushed face with hot when used the air-conditioning. This may be because the setting temperature of the air conditioning was relatively higher and the air outlet of air conditioning was set to face to the residents' activity area. For the non-air conditioning room, the uncomfortable reason concentrated in "the room was cold overall", "residents felt feet cold" and "residents felt cold-blast air", respectively.

3. The schedule of heating equipment

| | | Capacity (kW) | Day | Setting temperature (℃) |
|---|---|---|---|---|
| HSCW-1 | Livingroom | 8.2 | 7 | 20 or 22 |
| | Mainbedroom | 3.5 | 7 | 22 |
| | Bedroom2 | 3.5 | 7 | 22 |
| HSCW-2 | Livingroom | 1.5 | 3~5 | — |
| | Mainbedroom | 2.3 | 3~5 | 20 |
| | Bedroom2 | 1.5 | 1~2 | — |
| HSCW-3 | Livingroom | 2.2 | 1~2 | — |
| | Mainbedroom | 3.55 | 1~2 | 20 |
| | Bedroom2 | 2.3 | 3~5 | 22 |
| HSCW-4 | Livingroom | 8.6 | 1~2 | 22 |
| | Mainbedroom | 4.15 | 6~7 | 22 |
| | Bedroom2 | 3.95 | 6~7 | 22 |
| HSCW-5 | Livingroom | 5.6 | 1~2 | 20 |
| | Mainbedroom | 3.8 | 1~2 | 22 |
| | Bedroom2 | 1.13 | 1~2 | 24 |
| HSCW-6 | Livingroom | 9.2 | 1~2 | 25 |
| | Mainbedroom | 3.85 | 0 | — |
| | Bedroom2 | 2.75 | 1~2 | 26 |
| HSCW-7 | Livingroom | 4.2 | 1~2 | 22 |
| | Mainbedroom | 2.75 | 3~5 | 22 |
| | Bedroom2 | 2.75 | 3~5 | 22 |
| HSCW-8 | Livingroom | 4.6 | 0 | — |
| | Mainbedroom | 3.2 | 1~2 | — |
| | Bedroom2 | 2.5 | 3 | 24 |
| HSCW-9 | Livingroom | | | |
| | Mainbedroom | | | |
| | Bedroom2 | | | |

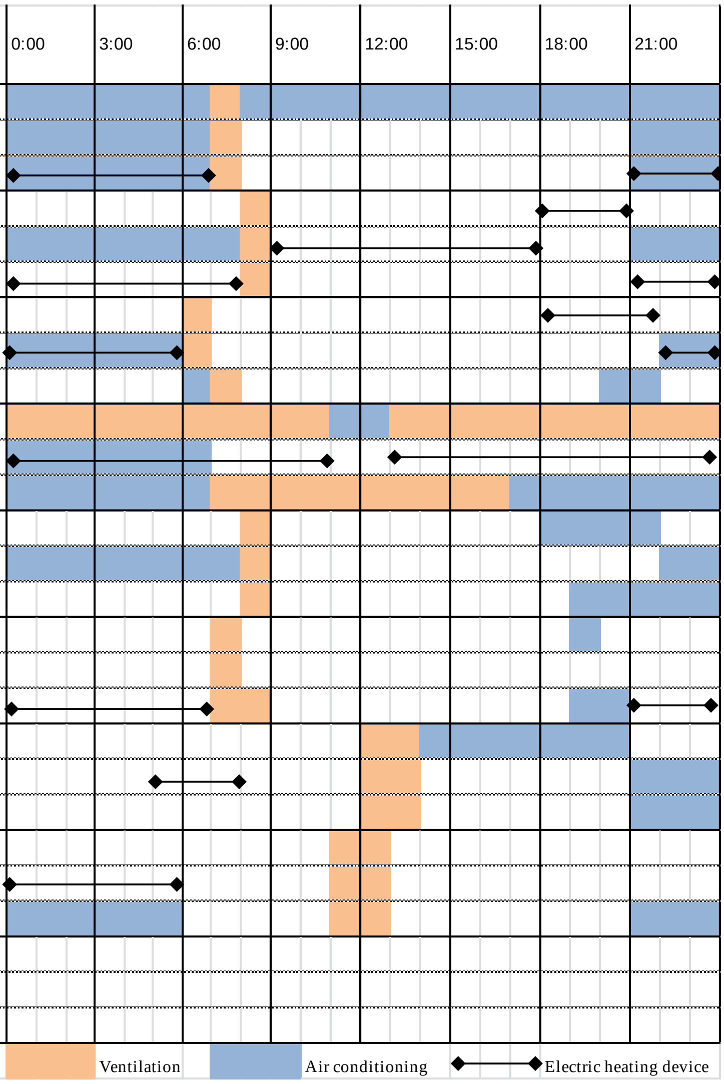



Figure 3-57 Heating equipment and natural ventilation schedule of each residence

By applying statistical analysis to the questionnaire data, the schedule of heating equipment in the nine residences including air conditioning and electric heating device were obtained, as shown in Figure 3-57.

The service time of air conditioning and electric fans as well as natural ventilation time of different residences varied from each other. Because there was a guest lodged in the living room of residence HSCW-1 during the measured period, leading to the almost full-time use of the air conditioning in the living room of residence HSCW-1. The setting temperature of air conditioning was 20ºC during the daytime and 22ºC at night. The air conditioning in bedroom was used for heating during the night (21:00~7:00), and oil filled electric heater was also used for auxiliary heating in bedroom2 at the same time. Meanwhile, the frequency of this air conditioning schedule implementation was set as 7 days a week in residence HSCW-1. Therefore, the indoor temperature remained at around 18ºC.

In addition to residence HSCW-1, the other residences hardly used the air conditioning or heater in the living room. Even if used, the using frequency was relatively low. The air conditioning was only used in the main bedroom during the night in residence HSCW-2, but the using frequency of air conditioning was less than that of residence HSCW-1. Electric heating device was mainly used for heating during the night in bedroom2 and entertainment time after dinner in the living room. The reflection-type electric heater was used in this residence, although this kind of the electric heater was less power and small energy consumption than the oil filled electric heater, it cannot improve the indoor overall temperature due to the locality and targeted heating. Although the residence HSCW-3 used the air conditioning in the main bedroom, the using frequency was rare with only 1~2 days a week, and relied more on the electric heater for heating. The service time of air conditioning in bedroom was less, only before getting up in the morning and before going to bed at night. The air conditionings were used frequently during the night in two bedrooms of residence HSCW-4. The other residences also rarely used the air conditioning in the bedroom, even if used, the using frequency was less with only 1~2 days a week. Just because the heating equipment was rarely used, resulting in the low indoor temperature distribution and poor indoor comfort.

Regarding the ventilation condition, most of the residences would open window for a short ventilation after getting up in the morning. There also were residence HSCW-4 opening window for ventilation in the living room all day long and in bedroom2 during the daytime (7:00~17:00). In addition, the residences HSCW-7 and HSCW-8 chose to open window for ventilation when the outdoor temperature was relatively higher at the noon.

4. The statistics of occupation condition

(1) Family members

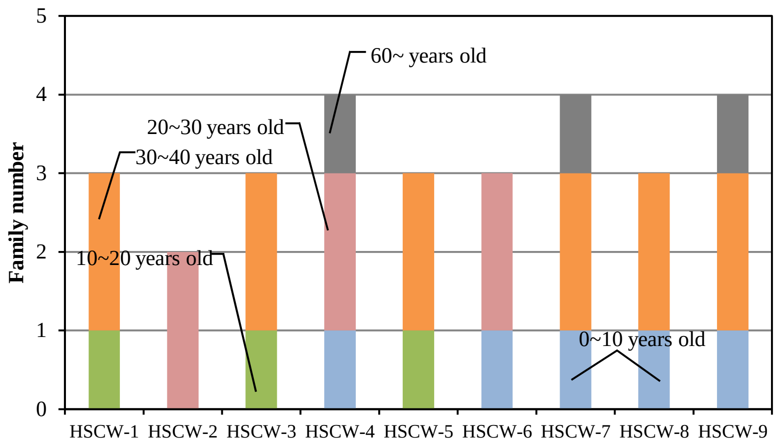


Figure 3-58 Family population and age distribution

Figure 3-58 shows the family population and age distribution in different residences Hangzhou. The same as the investigation in other cities, the overall number of family people in most of residence is 3. The family structure is a couple aged 30~50 years old and a child aged 0~20 years old. In addition, some residents chose to live with older parents together.

(2) Occupation time

Table 3-9 shows the occupation time schedule of residents in different residences of Hangzhou. Unlike the investigations in other cities, the investigated residents were not only university teachers but also housewives. For the residents as the teachers, due to the nature of university teachers’ job, the time at home in the daytime was relatively less, basically leave home for school in the morning (around 8:00) and return home in the early evening (about 18:00). Because the residence was near the university, some residents are accustomed to returning home for lunch and having a short break at noon (about 12:00~14:00). Most of the children are at school during the day, and return home in the evening. For the housewife and the old as well as children, they stay at home at most of the time all day long, such as the member 3 and member4 in residence HSCW-4 as well as member 1 and member3 in residence HSXW-6. Because these residents stay in the room for a long time, the demand for the air conditioning was greater. How much time staying in the room of residents will directly affect the service time of the air conditioning, which can indirectly lead to the difference of indoor thermal environment and different power consumption of air conditioning in winter. The accumulated use time of air conditioning by resident who stay in the room for a long time was longer, thus the indoor temperature was relatively high, but the energy consumption of air conditioning was larger.

Table 3-9 Occupation time schedule

| | | 0:00 | 3:00 | 6:00 | 9:00 | 12:00 | 15:00 | 18:00 | 21:00 |
|---|---|---|---|---|---|---|---|---|---|
| HSCW-1 | Member 1 | | | | | | | | |
| | Member 2 | | | | | | | | |
| | Member 3 | | | | | | | | |
| HSCW-2 | Member 1 | | | | | | | | |
| | Member 2 | | | | | | | | |
| HSCW-3 | Member 1 | | | | | | | | |
| | Member 2 | | | | | | | | |
| | Member 3 | | | | | | | | |
| HSCW-4 | Member 1 | | | | | | | | |
| | Member 2 | | | | | | | | |
| | Member 3 | | | | | | | | |
| | Member 4 | | | | | | | | |
| HSCW-5 | Member 1 | | | | | | | | |
| | Member 2 | | | | | | | | |
| | Member 3 | | | | | | | | |
| HSCW-6 | Member 1 | | | | | | | | |
| | Member 2 | | | | | | | | |
| | Member 3 | | | | | | | | |
| HSCW-7 | Member 1 | | | | | | | | |
| | Member 2 | | | | | | | | |
| | Member 3 | | | | | | | | |
| | Member 4 | | | | | | | | |
| HSCW-8 | Member 1 | | | | | | | | |
| | Member 2 | | | | | | | | |
| | Member 3 | | | | | | | | |
| HSCW-9 | Member 1 | | | | | | | | |
| | Member 2 | | | | | | | | |
| | Member 3 | | | | | | | | |
| | Member 4 | | | | | | | | |

4. Energy consumption

Table 3-10 Charging system in Hangzhou(yuan)

| Electricity/kWh | | | Annual electricity consumption | | |
|---|---|---|---|---|---|
| | | | ~2760kWh | 2761~4800kWh | 4801~kWh |
| | Current price | | 0.538 | 0.588 | 0.838 |
| | Peak time | 8:00~22:00 | 0.568 | 0.618 | 0.868 |
| | Valley time | 22:00~8:00 | 0.288 | 0.338 | 0.588 |

Table 3-10 shows the charging system of electricity consumption in Hangzhou. As can be seen, the electricity bill is divided into two methods of valuation with three-tiered pricing same as that in Hangzhou. According to the pilot program, based on the current tiered electricity pricing standards, plus 0.03 yuan per kilowatt hour during the peak period (8:00~22:00), cut 0.25 yuan per kilowatt hour during the valley period (22:00~8:00). In addition, according to the annual electricity consumption, the charging system was divided into three-tiered pricing. Based on the current tiered electricity pricing standards, plus 0.05 yuan per kilowatt hour when the annual electricity consumption exceed 2760kWh and less than 4800kWh, and plus 0.3 yuan per kilowatt hour when the annual electricity consumption exceed 4800kWh.

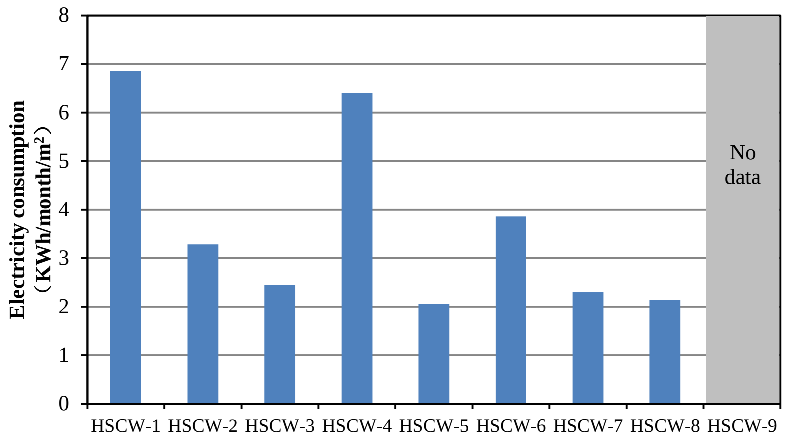


Figure 3-59Average monthly electricity consumption in winter

Figure 3-59 shows the average monthly electricity consumption in December and January. In this climate zone, the electricity consumption of using air conditioning or other heating equipment for heating in winter accounted for the major part. It can be seen from that residence HSCW-1 had the largest monthly total electricity consumption, which about 6.86 kWh/m$^2$. The habit of using of air conditioning during the whole day leaded to this result. It was followed by residence HSCW-4 mainly because of the long use time of air conditioning. Residence HSCW-6 had the relatively large energy consumption because of the using of electric heater and the large number of appliances. However, the monthly total consumption of the other surveyed residence had little difference, about 2~3 kWh/m$^2$. The monthly total energy consumption was far less than that of Harbin and Qingdao.

## 3.4 Conclusion

This chapter mainly researched the actual condition of thermal environments in winter in multi-unit residences in three colder climate zones of China through field measurement and questionnaire analysis. On such basis, rational improvement proposals and measures to improve the comfort of indoor thermal environments and energy conservation in Chinese multi-unit residences are discussed. The main conclusions are as follows:

(1) For the Severe Cold Zone:

1) Due to the better effect of district heating, the indoor temperature of heating rooms were over 24$^{o}$ C, and the indoor relative humidity were below 30% in most surveyed residences. The actual indoor temperature exceed the standard of district heating design temperature which were 18~22$^{o}$ C, also far beyond the indoor comfort temperature range in winter which is specified by ASHRAE.

2) PMV evaluation results also showed that the indoor thermal environment of most residences were in slightly hot state.

3) The clothing insulation value of most of surveyed residences in Harbin concentrated in about 0.5clo in winter benefitting from better effect of district heating.

4) Thermal sensation vote by residents in heating rooms mainly concentrated in 1~2 which corresponds to the thermal sensation of warm and slightly hot. And it can be obtained 22.1ºC as the thermal neutral temperature of human body in winter of this zone.

5) Thermal comfort vote of the living room and bedroom in most surveyed residences concentrated in -1~-2 which means the residents feel slightly uncomfortable or uncomfortable in heating rooms, and the uncomfortable reason was mainly residents feel hot and dry because of the better effect of district heating.

6) The energy consumption of district heating accounted for the main part of total energy consumption, and the monthly consumption of the most surveyed residences were about 10kWh/m$^2$.

Therefore, for the Severe Cold Zone, the heating temperature of district heating system is the temperature should be modified to achieve the actual indoor temperature maintain at approximately 22 ºC according to the thermal adaptation of local people. At the same time, the household heat-regulating system should be put into practice as soon as possible so as to avoid overheating phenomenon and energy waste. In addition, corresponding measures should be adopted for indoor humidification.

(2) For the Cold Zone:

1) The indoor temperature distribution of heating rooms were concentrated in 20~23$^{o}$C in most surveyed residences in Qingdao which also has the district heating system. Due to the vertical-pipe type hot water circulation heating method and roof heat dissipation, the indoor temperature of the residence which located in the top-level was lower. The indoor relative humidity was slightly higher than in Harbin, around 40% in most surveyed residences.

2) There was large temperature difference between upper and lower in some residences with common wall-type radiators. The vertical temperature difference between top and bottom even reached up to 9ºC, which would seriously result in the discomfort of hot head cold feet.

3) The indoor temperature and relative humidity data of most residences fell into the ASHRAE comfort zone.

4) PMV evaluation results showed that the indoor thermal environment of most residences were in neutral state, while in the cold state in the top-level residence.

5) The clothing insulation value of most of surveyed residences in Qingdao was higher than that of Harbin, distributed around 0.9clo in winter.

6) Thermal sensation vote by residents in the heating rooms mainly concentrated in 0 which means that these residents feel the rooms with district heating are a neutral thermal environment. And it can be obtained 20.6ºC as the thermal neutral temperature of human body in winter of this zone.

7) The energy consumption of district heating also accounted for the main part of total energy consumption same as that in Harbin, and the monthly consumption of the most surveyed residences were slightly lower than Harbin.

Therefore, for the Cold Zone, the heating temperature of district heating system is the temperature should be modified to achieve the actual indoor temperature maintain at approximately 20ºC according to the thermal adaptation of local people in this zone. Except for the household heat-regulating system, the original vertical-pipe type hot water circulation heating method should be changed as soon as possible so as to avoid the phenomenon of lower temperature in top-level residence. In addition, the radiant floor heating should be adopted to avoid the discomfort of hot head cold feet by the large vertical temperature difference between top and bottom.

(3) For the Hot Summer and Cold Winter Zone:

1) The indoor temperature were only distributed in 10~15$^{o}$C in most surveyed residences in Hangzhou, and even lower than limiting temperature in winter which is 12$^{o}$C specified by Chinese Hygiene Standard. The indoor relative humidity distributions in most of the surveyed residences were about 40%~60%.

2) Because of lower temperature, there was almost no data falling into the ASHRAE comfort zone.

3) The PMV values of indoor thermal environment in most residences located in the range of -3~-2 which means the indoor thermal environment is very cold.

4) The clothing insulation values of most of surveyed residences in Hangzhou mainly concentrated in about 1.5clo.

5) The TSV value concentrated in -2 in most surveyed residences which mean that these residents feel the indoor environment was in a slightly cold condition. And it can be obtained 18.1ºC as the thermal neutral temperature of human body in winter of this zone.

6) Thermal comfort vote of the living room and bedroom in most surveyed residences concentrated in -2 which means the residents feel uncomfortable, and the uncomfortable reason is mainly residents feel cold and indoor temperature drops rapidly after stopping the heating equipment.

7) Because of less using air conditioning for heating, the monthly electricity consumption of most surveyed residence were only about 2~3 kWh/m$^2$. It was far less than that of Harbin and Qingdao which have district heating system.

Therefore, for the Hot Summer and Cold Winter Zone, the indoor temperatures need to be improved urgently. On the one hand, envelope performance should be improved so as to reduce heat loss. On the other hand, the economy and comfort should be simultaneously taken into account to decide whether to adopt the district heating system.

## References

(1)Yi Wang, Study on the indoor thermal environment in summer for residential buildings in the Cold Zone, Doctoral thesis, Xi'an University of Architecture and Technology, pp7~8, 2003.6.

(2)China Academy of Building Research, Standard of climate regionalization for architecture(GB50178-93), Ministry of Construction of the PRC,1993

(3)Meinan Wang, Nobuyuki Sunaga, The effects of building performance and air-conditioning setting temperature on energy consumption and thermal comfort in multi-unit residences in China, Journal of Environmental Engineering, AIJ, Vol.82, No.734, pp.471-480, 2017.4.

(4)Weather Data: Energy-Plus weather database-International Weather for Energy Calculations, U.S. Departure of Energy, Energy Efficiency& Renewable Energy, [Online]. Available: https://energyplus.net/weather.

(5)ASHRAE Handbook-Fundamentals 2005, M. Atlanta: American Society of Heating Refrigeration and Air Conditioning Engineers, Inc.

(6)Design code for heating ventilation and air conditioning of civil buildings (GB50736-2012), China Architecture& Building Press, 2012.

(7)Tanabe Lab, PMV and PPD calculation software, available at: http://www.tanabe.arch.waseda.ac.jp.

# CHAPTER 4 FIELD INVESTIGATION OF INDOOR THERMAL ENVIRONMENT AND ENERGY CONSUMPTION IN MULTI-UNIT RESIDENCES IN SUMMER

## 4.1 Introduction

Due to the influence of global warming and urban heat island (UHI) phenomenon, the outdoor temperature in summer is on the increase, the high outdoor temperature in summer has obviously affected the indoor living environment. In addition, the service conditions and habits of indoor air conditioning and other cooling equipment in different climate zones can also lead to the differences in indoor thermal environment and cooling energy consumption. This chapter mainly researched the current status of indoor thermal environments and energy consumption in summer in multi-unit residences in three hotter climate zones of China through field measurement and questionnaire analysis. On such basis, rational improvement proposals and measures to improve the comfort of indoor thermal environments and energy conservation in summer are discussed.

## 4.2 Investigation Summary

4.2.1 Selection of investigation cities

Because generally there is no need to consider the heat protection in summer in the Severe Cold Zone as well as the Temperate Zone [(1)], and less cooling energy demand was proved in previous studies[(2)]. Therefore, the field measurement was not conducted in summer in these two zones. The residences under summer investigation in the Cold Zone as well as Hot Summer and Cold Winter Zone were selected same as that in winter. Guangzhou which is one of the most economically developed region in China and has a relatively high standard of living was taken as the research city in Hot Summer and Warm Winter Zone. The representative city of each climate zone were shown as Figure 4-1.

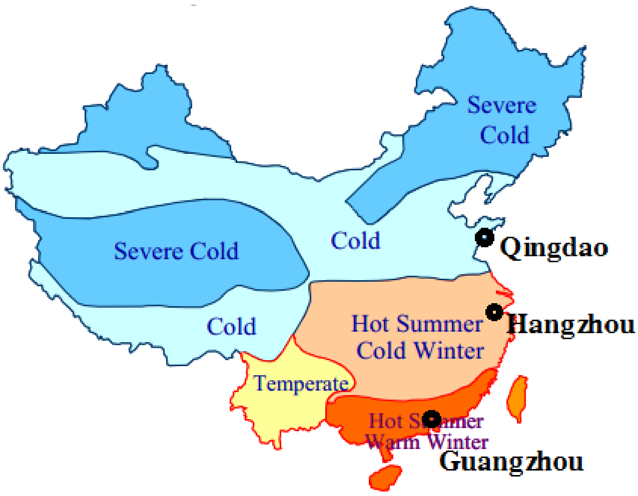



Figure 4-1 Selected cities in different climate zones

Figure 4-2 shows the summer climograph(Jun.~ Sep.)of representative cities for investigation in China. The climate of the different cities also has large disparities in summer. Qingdao is located in the Cold Zone that is cooler than Hangzhou in summer. It can be seen from the summer climograph of Qingdao, the average temperature of July is almost the same as in August. The average temperature of the hottest month of Qingdao is 25.1ºC with the relative humidity of 78.4%. Hangzhou is located in the Hot Summer and Cold Winter Zone which is hotter than Qingdao and cooler than Guangzhou in summer. The average temperature of the hottest month of Hangzhou is 28.2ºC with the relative humidity of 79.6%. The number of days that Daily Mean Temperature is higher than 25ºC accounts for 92. Guangzhou is located in the hottest climate zone, as shown in Figure 4-2, the average temperature of the hottest month of Guangzhou is 29ºC with the relative humidity of 83%. The highest outdoor temperature reached 35.9ºC. The number of days that Daily Mean Temperature is higher than 25ºC accounts for 189. The temperature difference between day and night is small.

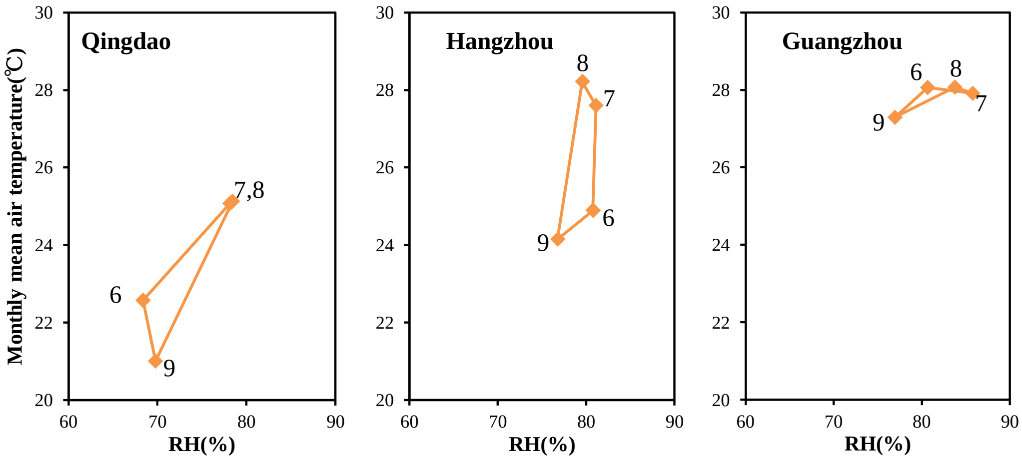
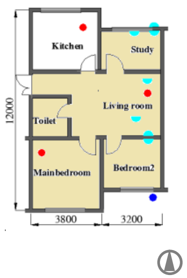
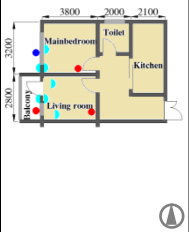
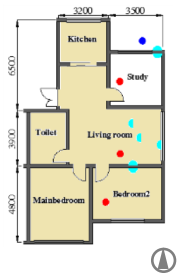
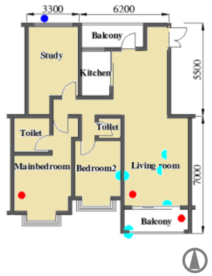
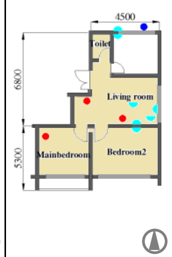
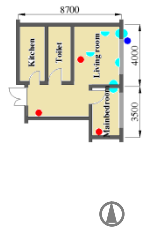



Figure 4-2 Climate characteristics of three representative cities

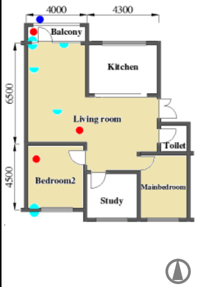
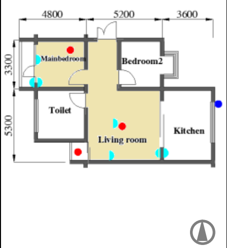
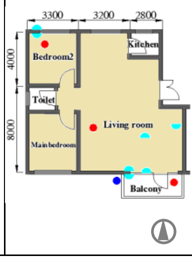
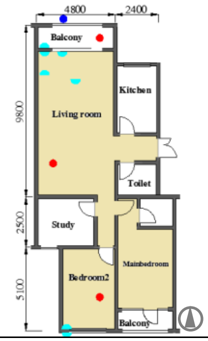
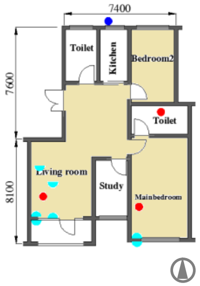
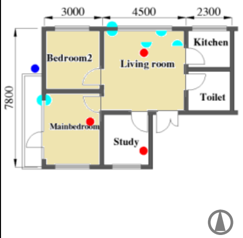
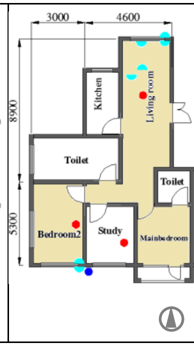
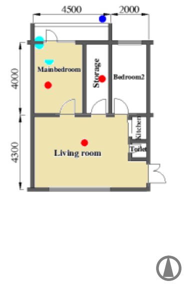
### 4.2.2 Field measurement summary

Same as the field measurement in winter, 9 participating residences were selected as the measured object by the local researchers. I undertook the field measurement in person in Qingdao, and assisted the local collaborative researchers to conduct the measurement in Hangzhou and Guangzhou throughout the survey. The field measurements in summer also lasted for about two weeks in each investigation city. The testing instrument and the monitoring points were almost the same as in winter. However, the surface temperature only included inside and outside surface of exterior wall as well as floor surface, and only measured in Qingdao and Hangzhou. Summary of measured residences and monitoring points in Qingdao and Hangzhou were almost the same as that in winter. Summary of measured residences and monitoring points is illustrated in Table 4-2.

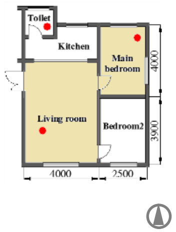
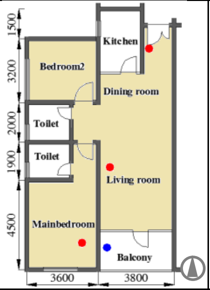
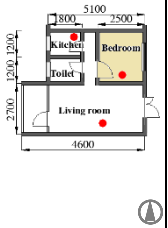
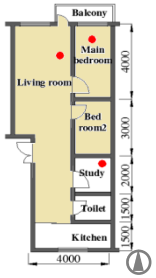
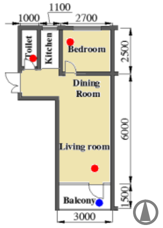
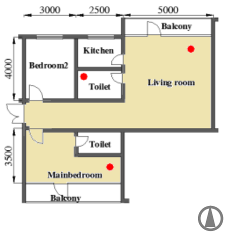
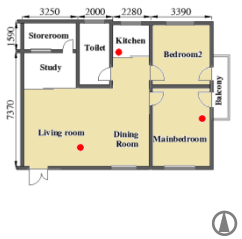
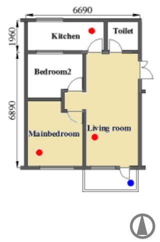
Table 4-2 Summary of measured residences and monitoring points

| | The Cold Zone(C)—Qingdao | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| NO. | C-1 | C-2 | C-3 | C-4 | C-5 | C-6 | C-7 | C-8 | C-9 |
| |  |  |  |  |  |  |  |  |  |
| Build/Repair year | 1998 | 1990 | 2007 | 2009 | 2004 | 2007 | 1996 | 2000 | 1987 |
| Structure | BC | BC | RC | RC | BC | RC | RC | RC | BC |
| Floor/Total | 1/7 | 1/6 | 3/8 | 6/21 | 3/6 | 6/8 | 7/7 | 3/7 | 3/8 |
| Construction area ($m^2$) | 92 | 49 | 128 | 135 | 113 | 128 | 80 | 70 | 56 |
| Position | Middle | North End | Middle | Middle | East End | Middle | East End | East End | Middle |
| Envelope* | Exterior window: k=3.4w/($m^2$ • °C) Exterior wall: k=1.20w/($m^2$ • °C) Roof: k=0.76w/( $m^2$ • °C) | Unknown | Exterior window: k=3.4w/($m^2$ • °C) Exterior wall: k=0.86w/($m^2$ • °C) Roof: k=0.41w/( $m^2$ • °C) | Exterior window: k=2.2w/($m^2$ • °C) Exterior wall: k=0.6w/($m^2$ • °C) Roof: k=0.36w/( $m^2$ • °C) | Exterior window: k=3.4w/($m^2$ • °C) Exterior wall: k=1.09w/($m^2$ • °C) Roof: k=0.46w/( $m^2$ • °C) | Exterior window: k=3.4w/($m^2$ • °C) Exterior wall: k=0.86w/($m^2$ • °C) Roof: k=0.41w/( $m^2$ • °C) | Unknown | Exterior window: k=3.4w/($m^2$ • °C) Exterior wall: k=1.09w/($m^2$ • °C) Roof: k=0.51w/( $m^2$ • °C) | Unknown |
| Units of AC | 1 | 0 | 2 | 2 | 2 | 2 | 2 | 2 | 1 |
| Family members — Age | 10~20 / 30~40 | ~10 / 30~40 | ~10 / 30~40 | ~10 / 30~40 / 60~ | 10~20 / 30~40 | 10~20 / 40~50 | 10~20 / 40~50 | ~10 / 30~40 | 20~30 |
| Family members — Number | 1 / 2 | 1 / 2 | 1 / 2 | 1 / 2 / 1 | 1 / 1 | 1 / 2 | 1 / 2 | 1 / 2 | 2 |
| Measured period | 2014.8.5~8.20 | | | 2014.8.20~9.4 | | | 2014.9.5~9.22 | | |
| Plan and monitoring points** |  |  |  |  |  |  |  |  |  |
| | ● Outdoor air temperature ● Indoor air temperature ● Surface temperature | | | | | | | | |

* Detailed materials of external envelope construction are shown in appendix.
** The fill color of the room represents the district heating area.

| | The Hot Summer and Cold Winter Zone(HSCW)—Hangzhou | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **NO.** | **HSCW-1** | **HSCW-2** | **HSCW-3** | **HSCW-4** | **HSCW-5** | **HSCW-6** | **HSCW-7** | **HSCW-8** | **HSCW-9** |
| |  |  |  |  |  |  |  |  |  |
| **Build year** | 2007 | | 2008 | 1999 | 2004 | 2007 | 1996 | 2004 | 1987 |
| **Structure** | RC | | F | RC | F | RC | BC | F | BC |
| **Floor/Total** | 5/6 | 5/6 | 14/23 | 6/6 | 10/23 | 2/15 | 5/6 | 10/23 | 5/6 |
| **Construction area ($m^2$)** | 130 | 130 | 120 | 109 | 180 | 155 | 80 | 130 | 56 |
| **Position** | Middle | Middle | Middle | West End | Middle | Middle | West End | West End | Middle |
| **Envelope*** | Exterior window: k=4.1w/($m^2$ • °C) Exterior wall: k=1.53w/( $m^2$ • °C) Roof: k=0.76 w/( $m^2$ • °C) | | Exterior window: k=3.2w/( $m^2$ • °C) Exterior wall: k=1.09w/( $m^2$ • °C) Roof: k=0.76w/( $m^2$ • °C) | Exterior window: k=4.7w/( $m^2$ • °C) Exterior wall: k=1.53w/( $m^2$ • °C) Roof: k=1.19w/( $m^2$ • °C) | Exterior window: k=3.4w/( $m^2$ • °C) Exterior wall: k=1.16w/( $m^2$ • °C) Roof: k=0.76w/( $m^2$ • °C) | Exterior window: k=4.1w/( $m^2$ • °C) Exterior wall: k=1.16w/( $m^2$ • °C) Roof: k=0.76w/( $m^2$ • °C) | Unknown | Exterior window: k=3.4w/( $m^2$ • °C) Exterior wall: k=1.16w/( $m^2$ • °C) Roof: k=0.76w/( $m^2$ • °C) | Exterior window: k=4.7w/( $m^2$ • °C) Exterior wall: k=2.03w/( $m^2$ • °C) Roof: k=1.47w/( $m^2$ • °C) |
| **Units of AC** | 3 | 3 | 2 | 3 | 3 | 3 | 3 | 3 | 2 |
| **Family members — Age** | 30~40, 10~20 | 20~30 | 10~20, 30~40 | ~10, 20~30, 60~ | 10~20, 30~40 | ~10, 20~30 | ~10, 30~40, 60~ | ~10, 30~40 | ~10, 30~40, 60~ |
| **Family members — Number** | 2, 1 | 2 | 1, 2 | 1, 2, 1 | 1, 2 | 1, 2 | 1, 2, 1 | 1, 2 | 1, 2, 1 |
| **Measured period** | 2014.7.27~8.9 | | | 2014.8.10~8.31 | | | 2014.8.31~9.13 | | |
| **Plan and monitoring points**** |  |  |  |  |  |  |  |  |  |
| | ● Outdoor air temperature ● Indoor air temperature ● Surface temperature | | | | | | | | |

* Detailed materials of external envelope construction are shown in appendix.
** The fill color of the room represents the rooms equipped with air conditioning.

| | The Hot Summer and Warm Winter Zone(HSWW)—Guangzhou | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **NO.** | **HSWW-1** | **HSWW-2** | **HSWW-3** | **HSWW-4** | **HSWW-5** | **HSWW-6** | **HSWW-7** | **HSWW-8** | **HSWW-9** |
| |  |  |  |  |  |  |  |  |  |
| **Build year** | 1998 | 1987 | 2015 | 1990 | 1996 | 1992 | 2003 | 2006 | 2001 |
| **Structure** | BC | RC | F | BC | RC | BC | RC | RC | RC |
| **Floor/Total** | 4/7 | 3/8 | 22/45 | 4/6 | 7/8 | 5/5 | 2/9 | 5/8 | 4/9 |
| **Construction area ($m^2$)** | 58 | 62 | 104 | 28 | 75 | 50 | 80 | 102 | 68 |
| **Position** | East End | East End | West End | South End | Middle | West End | Middle | East End | Middle |
| **Envelope*** | Exterior window: k=3.7w/( $m^2$ • °C) Exterior wall: k=2.03w/( $m^2$ • °C) Roof: k=0.76w/( $m^2$ • °C) | Exterior window: k=4.7w/( $m^2$ • °C) Exterior wall: k=3.03w/( $m^2$ • °C) Roof: k=1.47w/( $m^2$ • °C) | Exterior window: k=2.2w/( $m^2$ • °C) Exterior wall: k=0.85w/( $m^2$ • °C) Roof: k=0.46w/( $m^2$ • °C) | Unknown | Exterior window: k=4.7w/( $m^2$ • °C) Exterior wall: k=2.03w/( $m^2$ • °C) Roof: k=0.76w/( $m^2$ • °C) | Unknown | Exterior window: k=4.1w/( $m^2$ • °C) Exterior wall: k=2.03w/( $m^2$ • °C) Roof: k=0.76w/( $m^2$ • °C) | Exterior window: k=4.1w/( $m^2$ • °C) Exterior wall: k=1.09w/( $m^2$ • °C) Roof: k=0.76w/( $m^2$ • °C) | Exterior window: k=4.1w/( $m^2$ • °C) Exterior wall: k=2.03w/( $m^2$ • °C) Roof: k=0.76w/( $m^2$ • °C) |
| **Units of AC** | 2 | 2 | 3 | 1 | 3 | 2 | 2 | 3 | 2 |
| **Family members – Age** | 20~30 | ~10 / 30~40 / 50~60 | ~10 / 20~30 / 50~60 | 20~30 | 20~30 | 20~30 | 20~30 / 50~60 | ~10 / 20~30 / 50~60 | 20~30 |
| **Family members – Number** | 2 | 1 / 2 / 2 | 1 / 2 / 2 | 2 | 3 | 2 | 2 / 1 | 1 / 2 / 2 | 2 |
| **Measured period** | 2016.7.21~8.3 | | | 2016.8.4~8.17 | | | 2016.8.20~9.3 | | |
| **Plan and monitoring points**** |  |  |  |  |  |  |  |  |  |
| | ●Outdoor air temperature ● Indoor air temperature | | | | | | | | |

* Detailed materials of external envelope construction are shown in appendix.
** The fill color of the room represents the rooms equipped with air conditioning.

### 4.2.3 Questionnaire summary

Table 4-3 shows the survey period, distribution number, answer number and response rate in each city in summer. The questionnair survey was not conducted in summer of Qingdao.

Table 4-3 Questionnaire summary

| | Investigation city | Qingdao | Hangzhou | Guangzhou |
|---|---|---|---|---|
| Summer | Survey Period | - | 2014.7~9 | 2016.7~9 |
| | Distribution Number | - | 9 | 9 |
| | Answer Number | - | 9 | 9 |
| | Response Rate | - | 100% | 100% |

## 4.3 Investigation Results

### 4.3.1 Measured results in Qingdao

1. Indoor and outdoor temperature and relative humidity during the measured period

(1) Indoor and outdoor temperature

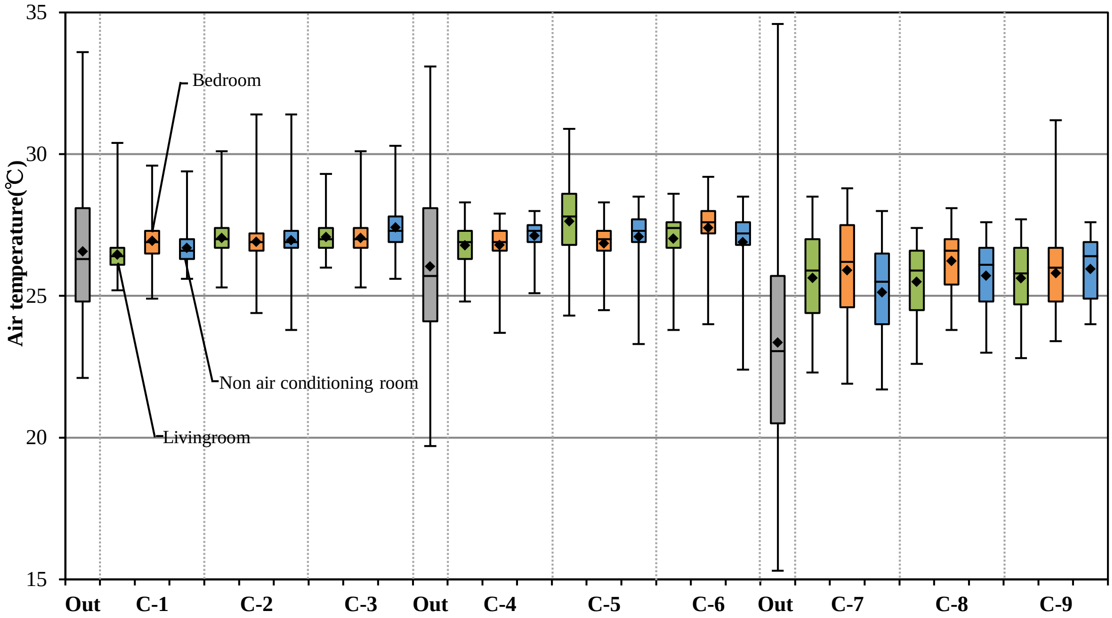



Figure 4-3 Temperature distributions during the summer measured period

Figure 4-3 shows the indoor and outdoor temperature distribution during the summer measured period in Qingdao. It can be seen that the variations of outdoor temperature in the three measured stages all were larger, (22.1~33.6ºC), (19.7~33.1ºC) and (15.3~34.6ºC), respectively. Outdoor temperature distribution was more dispersed, and the maximum temperature difference reached about 19.3ºC in the third measured period. It also shows that the temperature difference between day and night was larger. In addition, it is worth noting that as the measured time went by, the difference in outdoor temperature between day and night became larger and larger, and the average temperature became lower and lower. The average outdoor temperature of the first measured period was 26.5ºC, while 23.3ºC in the third measured period.

For the variations of indoor temperature, the average temperatures of nine residences were not much different. Because of the higher outdoor temperature in the first measured period, the indoor temperature was relatively higher than those of other periods. Indoor temperature distribution of the first period mainly concentrated in 25~30ºC, the average indoor temperature maintained at about 27ºC. However, the maximum indoor temperature of bedroom and non air conditioning room were far higher than 30ºC, about 2ºC higher than the maximum livingroom temperature. It may be because the residence C-2 was located in the East-West direction, the balcony and bedroom faced towards the west with windows. The solar radiation was strong in the afternoon in this climate region. The indoor temperatures of balcony and bedroom were higher affected by a western exposure. However, the indoor average temperature difference of different types of room was little, and even the indoor average temperature of non air conditioning room in residence C-1 was lower than that of bedroom. Therefore, it can be used to explain the less service time of air conditioning in summer in this climate zone.

The indoor temperature of the second period was mainly concentrated in 24~28ºC, the average indoor temperature also remained at about 27ºC. It is worth noting that the living room temperature of residence C-5 was higher than those of other rooms as well as other residences. This may be due to the residential plan is different from the other two residences, livingroom was located in the middle with a east window and no balcony. However, the dominant wind direction was south in summer. Direct solar radiation into the living room in the morning, and poor ventilation conditions led to higher indoor temperature.

Compared to the indoor temperature distributions of the first and second measured period, the indoor temperature of the third period was lower and more dispersed. The indoor temperature was mainly distributed in 22~28ºC, and the average indoor temperature in this period was also lower than those of other two measured period, which was about 26ºC in most rooms.

(2) Indoor and outdoor relative humidity

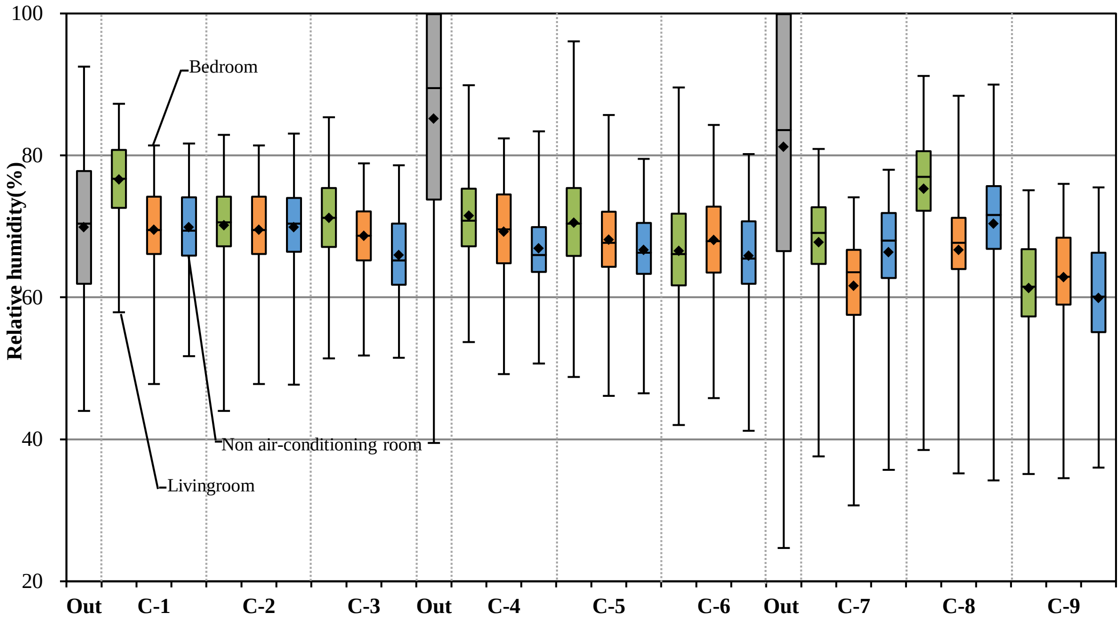



Figure 4-4 Relative humidity distributions during the summer measured period

Figure 4-4 shows the indoor and outdoor relative humidity distributions during the summer measured period in Qingdao. The outdoor relative humidity was suitable in the first measured period as shown in Figure 4-4. However, the outdoor relative humidity of the second and third measured period were both higher, even reached 100% for 25% of the time. This is because August and September were rainy seasons, the relative humidity was higher. The distribution of relative humidity of most residences in most of the time concentrated in about 65~75%. According to Chinese specification <Design code for heating ventilation and air conditioning of civil building>, the comfortable indoor relative humidity range was 40%~65%. Therefore, the relative humidity in summer was slightly higher than the comfortable humidity range. At relatively high humidity, too much skin moisture tended to increase discomfort.

2. Variation curve of indoor and outdoor temperature and humidity in a typical day

According to the climatic characteristics of different zones in summer, one day had been selected as the representative to analyse the hourly thermal environment. It benefits to analysis the character of indoor thermal environment, the current cooling mode and time of using mechanical cooling equipment.

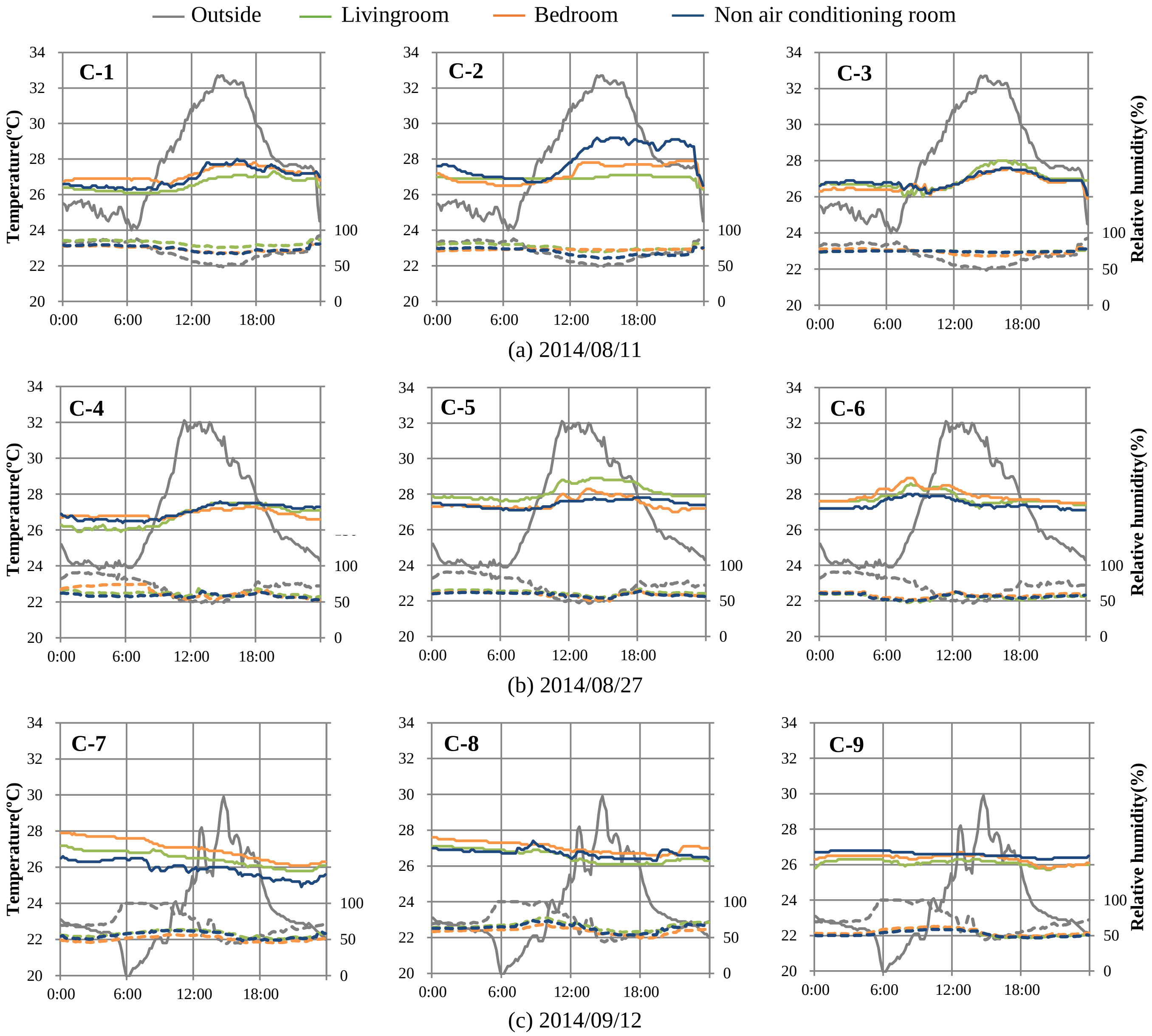



Figure 4-5 Variation curve of indoor and outdoor temperature and humidity in a typical day

Figure 4-5 shows the variation curve of indoor and outdoor temperature and humidity. It can be seen that all the room temperatures of most surveyed residences in a different day were changing gently, basically unchanged along with outdoor temperature, and the temperature difference of non-air-conditioning room with the living room and bedroom was not too much.

This is mainly because the summer in Qingdao was not intensely hot during the day, cool at night. Not only cooling equipment was seldom used but also the windows were usually closed in the daytime, so the effect of outdoor temperature variation on indoor thermal environment was relatively less.

In addition, it can be seen from the Fig. (a), the outdoor temperature reached the minimum at 6:00 am, and reached the highest value around 2:30 in the afternoon, the temperature fluctuation range within 1 day was between 24.1~32.7ºC. The outdoor temperature dropped sharply at about 23:00 in the evening, combined with the outdoor relative humidity fluctuation value, it can be inferred that this may be due to the decrease of temperature caused by thunderstorm weather. Compared with the residence C-2, the room temperatures in residence C-1 and C-3 were both changing gently, the indoor temperature differences between day and night remained within 2ºC, changed little with the outdoor temperature, and the temperature difference of non-air-conditioning room with the living room and bedroom was not much. However, the variation curve of indoor and outdoor temperature and humidity of residence C-2 shows that the indoor temperature of non-air conditioning room had a large rise along with the increase of outdoor temperature in the afternoon. At the same time, it had a large difference with the temperature of living room and bedroom in the afternoon. The temperature of non-air conditioning room was the highest, about 1.5ºC higher than that of bedroom and about 2 ºC higher than that of living room. This may be due to the relatively strong solar radiation of this area in the afternoon, the pattern of residence C-2 was east-west orientation, there both were windows towards the west in the balcony and bedroom, but the window in the balcony was far bigger than that in the bedroom, thus the temperature of balcony in the afternoon was higher affected by a western exposure.

It can be seen from the Fig. (b), the outdoor temperature fluctuation range of the second testing stage was lower than that of the first testing stage, basically stabilised at around 24 ºC at night, but reached up to 32 ºC in the daytime. However, it can be seen from the variation curve of outdoor relative humidity, it was damp at night and the relative humidity was still close to 90% even if there was no rain. As a result, it is often possible to see dew on the leaves of grass in the morning in summer of this area. It can be seen from the indoor temperature distribution curve that the indoor temperature change between day and night was small. And there was no significant difference in temperature of non-air conditioning room with the living room and bedroom, which also indicated that during the second testing period, the three surveyed residences basically did not use the air conditioning. In addition, due to the impact of living room pattern of residence C-5, the indoor temperature was slightly higher than that of the bedroom and non-air conditioning room, it was more significant in the daytime and approximately 1 ºC higher.

It can be seen from the Fig. (c) that the outdoor temperature fluctuation range was lower than those of the first two measured periods, the highest temperature reached only 30 ºC at noon. In addition, due to the rainfall, the outdoor temperature had a larger decrease twice, while the relative humidity had a greater increase and the humidity even reached 100% between 5:30~10:00. This also proves that the rainy weather often occurred during this testing period. It can be seen from the indoor temperature distribution curve that the indoor temperature almost unchanged along with the outdoor temperature. There was also almost no difference in temperatures of different types of rooms in residence C-8 and C-9, there was a smaller temperature difference in the indoor different rooms of only residence C-7. the indoor temperature of bedroom was about 0.7ºC higher than that of living room in the early hours of the morning, and about 1.5ºC higher than that of non-air conditioning room, the temperature difference was narrowed gradually in the afternoon. This may be due to the overcast and rainy weather, the sunlight was weak, there both were windows for ventilation in the non-air conditioning rooms and living rooms, while the bedroom without the window was located in the middle and relatively sultry.

3. Indoor temperature distributions at different heights

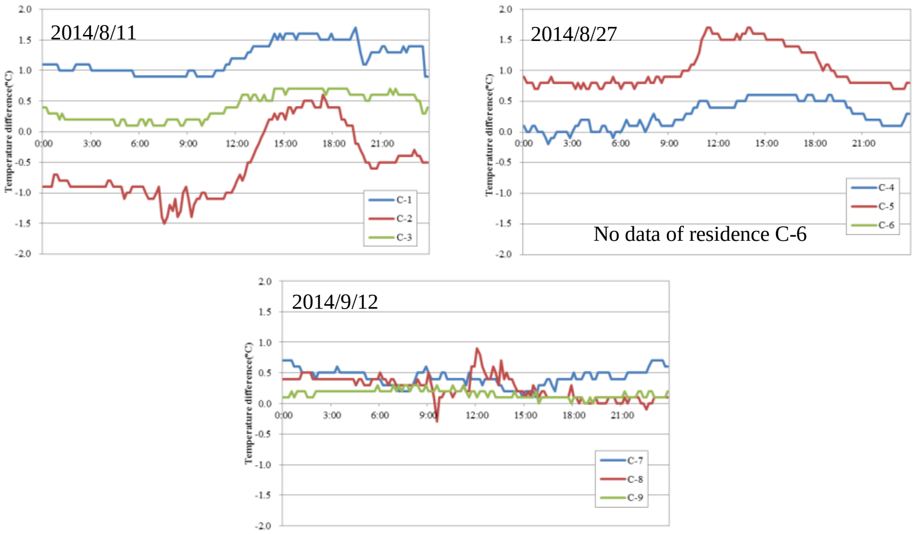
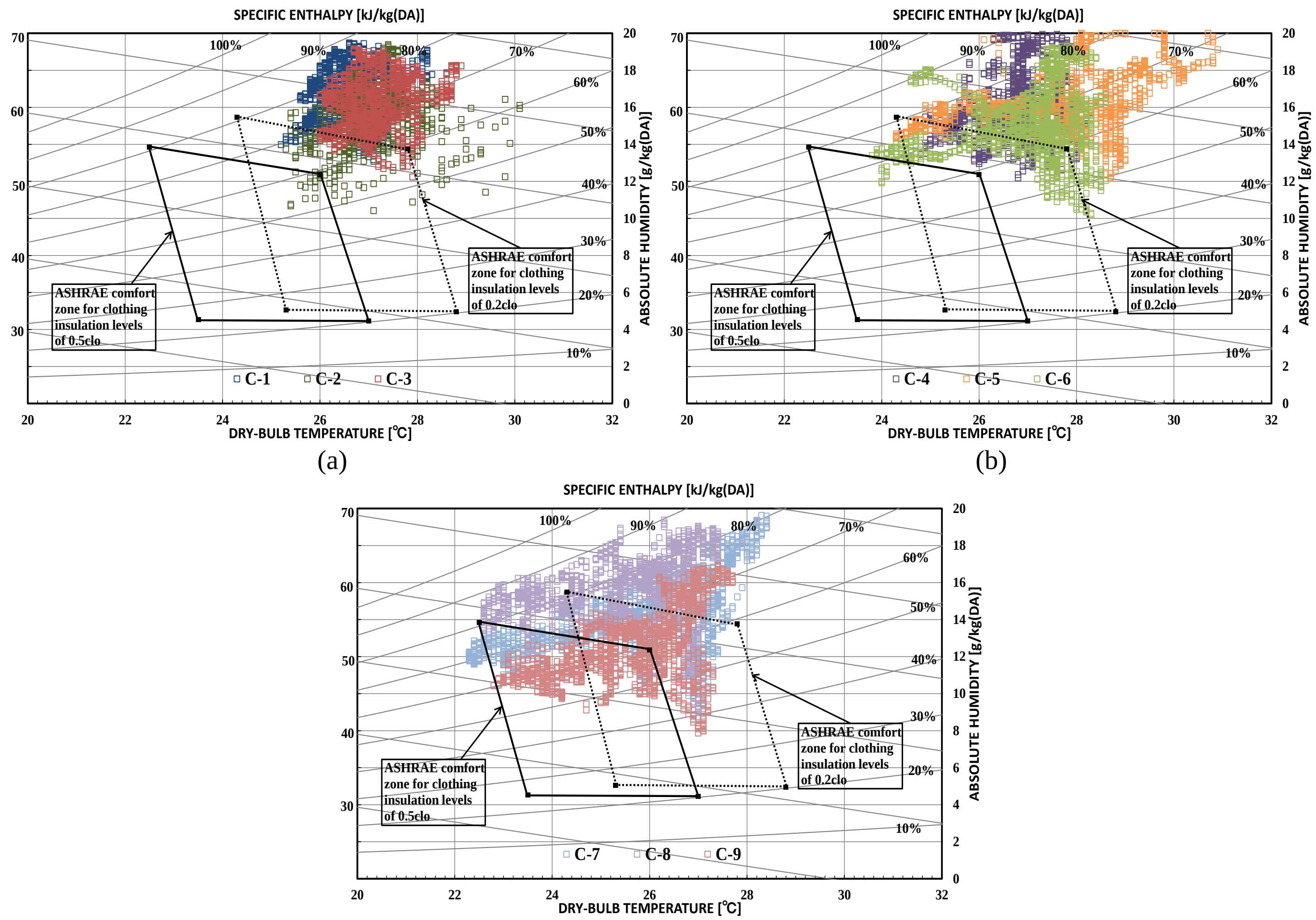



Figure 4-6 Temperature distribution at different height in the living room

The temperatures at different heights in summer measurement in Qingdao only carried out on the floor (0m) and human activity area (1.1m). The temperature difference between floor and human activity area was also believed to have a significant impact on human thermal sensation. Figure 4-6 shows the temperature difference between human activity area and floor. The difference was relatively small in residence C-3 than those of other two residences during the same measured period, less than 1ºC. It demonstrates the indoor temperature had a better uniformity in different height. Different from other residences, the difference between human activity area and floor found in residence C-2 had a negative value in addition to the afternoon. This may be because the residence C-2 was located at the bottom of the residential building with poor thermal insulation of floor. The earth's surface heat was transferred to floor surface. Therefore, the temperature of floor surface was higher than that of human activity area before 2:00 p.m. In addition, the indoor temperature uniformity of three residences in the second measured period was compared. The difference between human activity area and floor of residence C-4 was relatively smaller than residence C-5 during the same measured period, about 0.6ºC in the daytime and less than 0.5ºC at night. However, the difference in residence C-5 ran up to 1.7ºC at about 12:00. Therefore, the temperature uniformity was poor in residence C-5 than that of residence C-4. It can be seen from the indoor temperature difference of three residences in the third measured period, the differences were all less than 1ºC, and there was no significant difference among these three residences. This may be due to the outdoor air temperature was not high in the rainy day, the room temperatures were also lower and changed smaller along with outdoor temperature. Therefore, the temperature difference between human activity area and floor were all smaller.

4. ASHRAE comfort zone




(c)

Figure 4-7 Indoor temperature and relative humidity distribution and ASHRAE comfort zone in summer

Figure 4-7 shows the indoor temperature and relative humidity distribution as well as the location of ASHRAE comfort zone in summer. It can be seen that the indoor temperature and humidity distribution of residential during the first measured period was relatively concentrated, the temperature was mainly distributed between 25~29ºC, and the relative humidity was mainly distributed between 60%~90%. Considering the temperature and relative humidity comprehensively, there was little data falling into the ASHRAE comfort zone for clothing insulation levels of 0.5clo. Similarly, the ASHRAE comfort zones for less clothing levels can be approximated by increasing the temperature borders of this zone by 0.6K for each 0.1clo increase of clothing insulation, the comfort zone moved to the right side along with the reduction of clothing insulation. After moving, most of the temperature data was distributed in the range of comfort zone requirement, but due to the higher relative humidity, only a portion of the indoor temperature and humidity data of residence C-2 and C-3 fell into the ASHRAE comfort zone for clothing insulation levels of 0.2clo.

Compared with the first measured period, the indoor temperature and humidity distribution of residences during the second measured period was relatively dispersed, especially for the residence C-5, the lowest indoor temperature was around 24ºC, the highest temperature can reach up to 31ºC. Due to the higher temperature and relative humidity, there was little data of these three residences falling into the ASHRAE comfort zone for clothing insulation levels of 0.5clo. After moving with the reduction of clothing insulation, the portions of the data of residence C-4 and C-6 fell into the comfort zone.

Compared the first two measured periods, because of the effect of indoor temperature and humidity, the indoor temperature and humidity distribution of residential during the third measured period was improved, but most of the relative humidity was still over 50%. Residential indoor temperature was mainly distributed between 22~28ºC, the relative humidity was mainly distributed between 40%~90%. A portion of the indoor temperature and humidity data of residence C-7 and C-9 fell into the ASHRAE comfort zone for clothing insulation levels of 0.5clo profiting from the lower indoor temperature distribution. After moving with the reduction of clothing insulation, the data fell into the comfort zone was more. Although the temperature was within the range specified in the ASHRAE comfort zone, the relative humidity of residence C-8 at most of the time was between 70%~90%, so most of the time was outside the comfort zone.

5. Predicted Mean Vote (PMV)

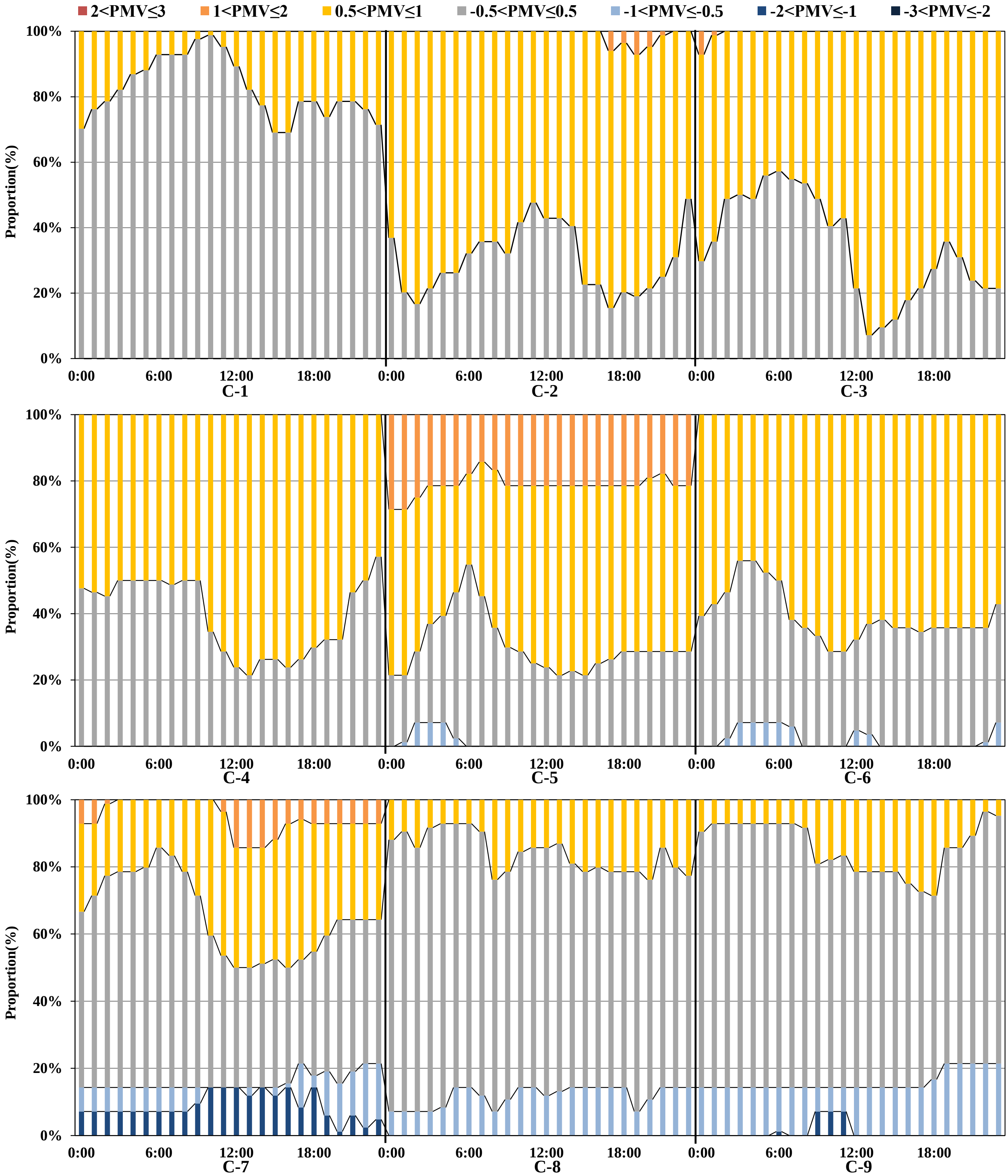



Figure 4-8 Proportion of PMV in summer of Qingdao

（Annotation: PMV's calculation condition: M=1.2met, v=0.25m/s）

Figure 4-8 shows the proportion of PMV value of the living room in summer of Qingdao. Compared to the PMV values and its proportions of indoor thermal environment of the three residences during the first measured period, it can be seen that the PMV value evaluation results were seemed to be different from those of ASHRAE comfort zone evaluation and heat stroke risk evaluation. The ASHRAE comfort zone evaluation results indicated that due to the higher indoor temperature and humidity of these three residences during the first measured period, there was almost no data falling into the comfort zone. However, the comfort proportion of PMV value evaluation results was improved. Heat stroke risk evaluation results indicated that the heat stroke risk of indoor thermal environment in residence C-2 was the lowest. However, the PMV evaluation results indicated that the comfort proportion of the PMV value of indoor thermal environment in residence C-1 in the range of -0.5~0.5 which meant the residents felt the neutral was the highest, was up to about 80%. The comfort proportion even reached 99% at about 11:00. In addition, from the point of view of the time, the highest comfort proportion of the PMV values of indoor thermal environment in residence C-1 and C-2 in the range of -0.5~0.5 occurred in the noon, but the comfort proportion in residential C-3 was the lowest at about 1:00 in the noon. This is due to the different location of the living room, the living rooms of former were located in the middle of residence, while the latter was located in the south where the impact of solar radiation was more significant.

It can be seen that the comfort proportions of the PMV value of indoor thermal environment in the three residences during the second measured period in the range of -0.5~0.5 which meant the residents felt the neutral differed little, all accounted for around 30~40%. However, it is worth noting that the proportion of the PMV value in residence C-5 in the range of 1~2 which meant the residents felt slightly hot accounted for about 20%. This result seemed to be consistent with the heat stroke risk evaluation. In addition, compared with the comfort proportions in different time, it can be seen that the comfort proportions of these three residences all reduced at 12:00 in the noon, all increased at about 6:00 in the morning.

Compared to the PMV values and its proportions of indoor thermal environment of these three residences during the third measured period, it can be seen that the indoor comfort proportions of residence C-8 and C-9 were slightly higher than that of residence C-7. Moreover, unlike the residence C-7, there was no significant reduction in the comfort proportions of these two residences when the solar radiation was relatively strong in the noon. In addition, it is worth noting that the PMV values of these three residences were all located in the range of -1~-0.5 which meant the residents felt cool for part of the time, this is because that the outdoor temperature at night was low, the temperature difference between day and night was larger and it often rains in the daytime during the third measured period, leading to the reduction of indoor temperature.

6. WBGT and Heat stroke

(1)WBGT

The WBGT is an environmental heat stress index that combines dry-bulb temperature($t_{db}$), wet-bulb temperature ($t_{wb}$), and black globe temperature ($t_g$), according to the following relation:

Indoor: $WBGT=0.7t_{wb}+0.3t_g$

Outdoor: $WBGT=0.7t_{wb}+0.2tg+0.1t_{db}$

The WBGT index has been widely used for estimating the heat stress potential of industrial environments. In the United States, the National Institute of Occupational Safety and Health developed criteria for a heat-stress-limiting standard ISO Standard 7243 also uses the WBGT. This study tried to use WBGT to evaluate the risk of heat stroke of indoor thermal environment.

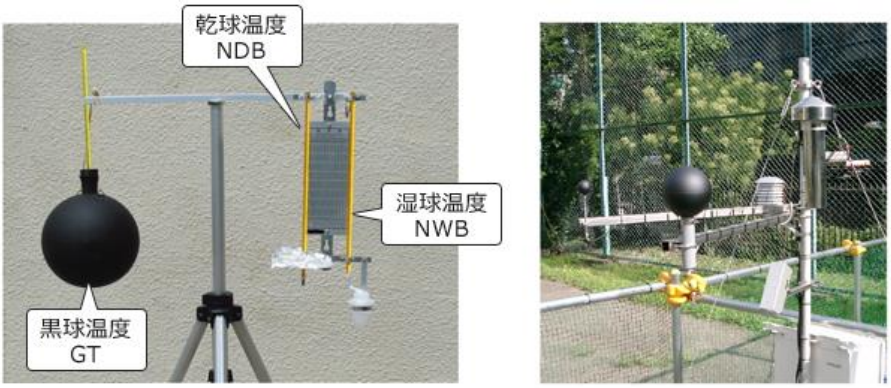



Figure 4-9 WBGT measuring instrument

Figure 4-9 shows the WBGT measuring instrument that composed of psychrometer and black-bulb thermometer. Because the measured process of globe temperature and wet bulb temperature are relatively complicated, WBGT is usually estimated by air temperature and relative humidity according to the “Heatstroke Prevention Guidelines in Daily Life” which published by the Japanese Society of Biometeorology. The relationship between the WBGT, air temperature and relative humidity is shown in Figure 4-10.

In this guideline, the heat stroke risk in WBGT is divided into four temperature standard stages which are “Danger”, “Serious warning”, “Warning” and “Caution”, respectively. Table 4-4 shows the heat stroke risk and WBGT. In the “Danger” and “Serious warning” zones, all the activities in living life are likely to cause the occurrence of heat stroke, especially the elders during rest in the dangerous zones are also very possible to cause the heat stroke.

Relative humidity (%)

| Air temperature(ºC) | 20 | 25 | 30 | 35 | 40 | 45 | 50 | 55 | 60 | 65 | 70 | 75 | 80 | 85 | 90 | 95 | 100 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 40 | 29 | 30 | 31 | 32 | 33 | 34 | 35 | 35 | 36 | 37 | 38 | 39 | 40 | 41 | 42 | 43 | 44 |
| 39 | 28 | 29 | 30 | 31 | 32 | 33 | 34 | 35 | 35 | 36 | 37 | 38 | 39 | 40 | 41 | 42 | 43 |
| 38 | 28 | 28 | 29 | 30 | 31 | 32 | 33 | 34 | 35 | 35 | 36 | 37 | 38 | 39 | 40 | 41 | 42 |
| 37 | 27 | 28 | 29 | 29 | 30 | 31 | 32 | 33 | 34 | 35 | 35 | 36 | 37 | 38 | 39 | 40 | 41 |
| 36 | 26 | 27 | 28 | 29 | 29 | 30 | 31 | 32 | 33 | 34 | 34 | 35 | 36 | 37 | 38 | 39 | 39 |
| 35 | 25 | 26 | 27 | 28 | 29 | 29 | 30 | 31 | 32 | 33 | 33 | 34 | 35 | 36 | 37 | 38 | 38 |
| 34 | 25 | 25 | 26 | 27 | 28 | 29 | 29 | 30 | 31 | 32 | 33 | 33 | 34 | 35 | 36 | 37 | 37 |
| 33 | 24 | 25 | 25 | 26 | 27 | 28 | 28 | 29 | 30 | 31 | 32 | 32 | 33 | 34 | 35 | 35 | 36 |
| 32 | 23 | 24 | 25 | 25 | 26 | 27 | 28 | 28 | 29 | 30 | 31 | 31 | 32 | 33 | 34 | 34 | 35 |
| 31 | 22 | 23 | 24 | 24 | 25 | 26 | 27 | 27 | 28 | 29 | 30 | 30 | 31 | 32 | 33 | 33 | 34 |
| 30 | 21 | 22 | 23 | 24 | 24 | 25 | 26 | 27 | 27 | 28 | 29 | 29 | 30 | 31 | 32 | 32 | 33 |
| 29 | 21 | 21 | 22 | 23 | 24 | 24 | 25 | 26 | 26 | 27 | 28 | 29 | 29 | 30 | 31 | 31 | 32 |
| 28 | 20 | 21 | 21 | 22 | 23 | 23 | 24 | 25 | 25 | 26 | 27 | 28 | 28 | 29 | 30 | 30 | 31 |
| 27 | 19 | 20 | 21 | 21 | 22 | 23 | 23 | 24 | 25 | 25 | 26 | 27 | 27 | 28 | 29 | 29 | 30 |
| 26 | 18 | 19 | 20 | 20 | 21 | 22 | 22 | 23 | 24 | 24 | 25 | 26 | 26 | 27 | 28 | 28 | 229 |
| 25 | 18 | 18 | 19 | 20 | 20 | 21 | 22 | 22 | 23 | 23 | 24 | 25 | 25 | 26 | 27 | 27 | 28 |
| 24 | 17 | 18 | 18 | 19 | 19 | 20 | 21 | 21 | 22 | 22 | 23 | 24 | 24 | 25 | 26 | 26 | 27 |
| 23 | 16 | 17 | 17 | 18 | 19 | 19 | 20 | 20 | 21 | 22 | 22 | 23 | 23 | 24 | 25 | 25 | 26 |
| 22 | 15 | 16 | 17 | 17 | 18 | 18 | 19 | 19 | 20 | 21 | 21 | 22 | 22 | 23 | 24 | 24 | 25 |
| 21 | 15 | 15 | 16 | 16 | 17 | 17 | 18 | 19 | 19 | 20 | 20 | 21 | 21 | 22 | 23 | 23 | 24 |

| WBGT Value |
|---|
| Danger<br>Above 31ºC |
| Serious Warning<br>28~31ºC |
| Warning<br>25~28ºC |
| Caution<br>Below 25ºC |

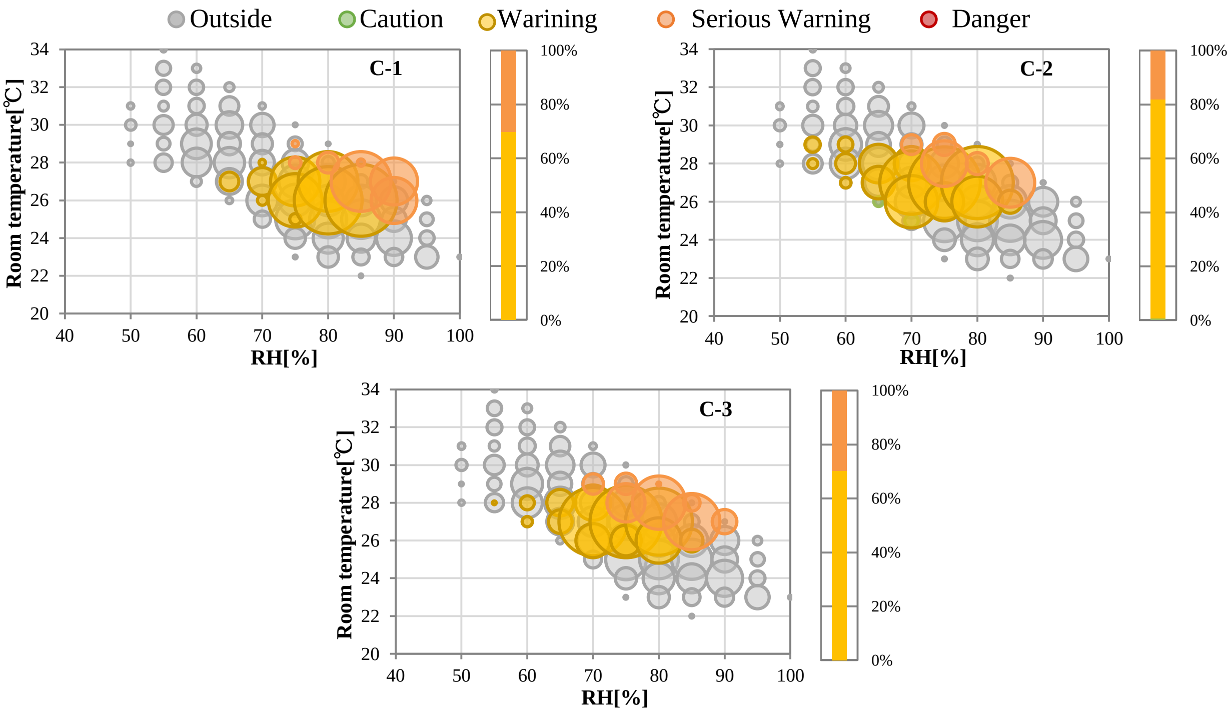
Figure 4-10 The estimated value of WBGT by air temperature and relative humidity

Table 4-4 Heatstroke Prevention Guidelines in Daily Life

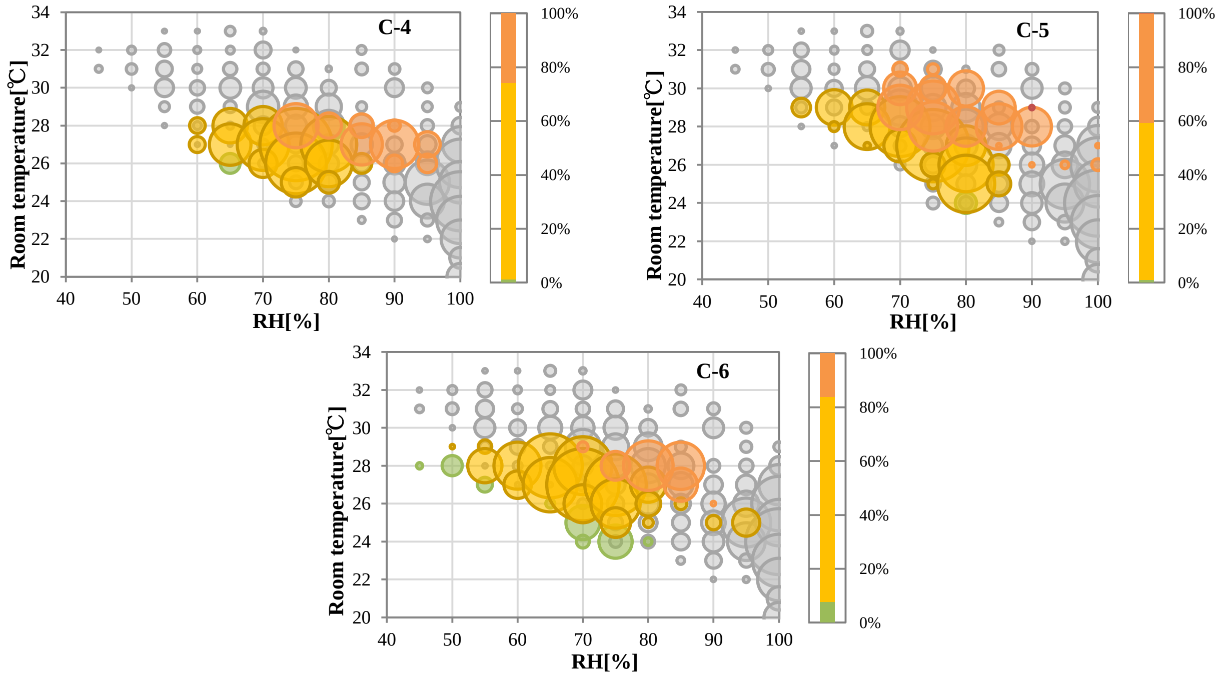
| Reference temperature of WBGT | Guide of all the life activities needing attention | Matters needing attention |
|---|---|---|
| Danger<br>Above 31ºC | The risk caused by all the life activities | The elders during rest in the dangerous zones are also very possible to cause the heat stroke, the risk is high. Try not to go out and stay in the cool room |
| Serious Warning<br>28~31ºC | | Avoid staying under the blazing sun outside, note the rise of room temperature in the room |
| Warning<br>25~28ºC | The risk caused by over the moderate life activities | During sports and high strength work, taking adequate rest on a regular basis |
| Caution<br>Below 25ºC | The risk caused by the strong life activities | Generally the risk is low, but there is heat stroke risk when doing intense sports and high strength work |

(2) Heatstroke possibility evaluation by WBGT

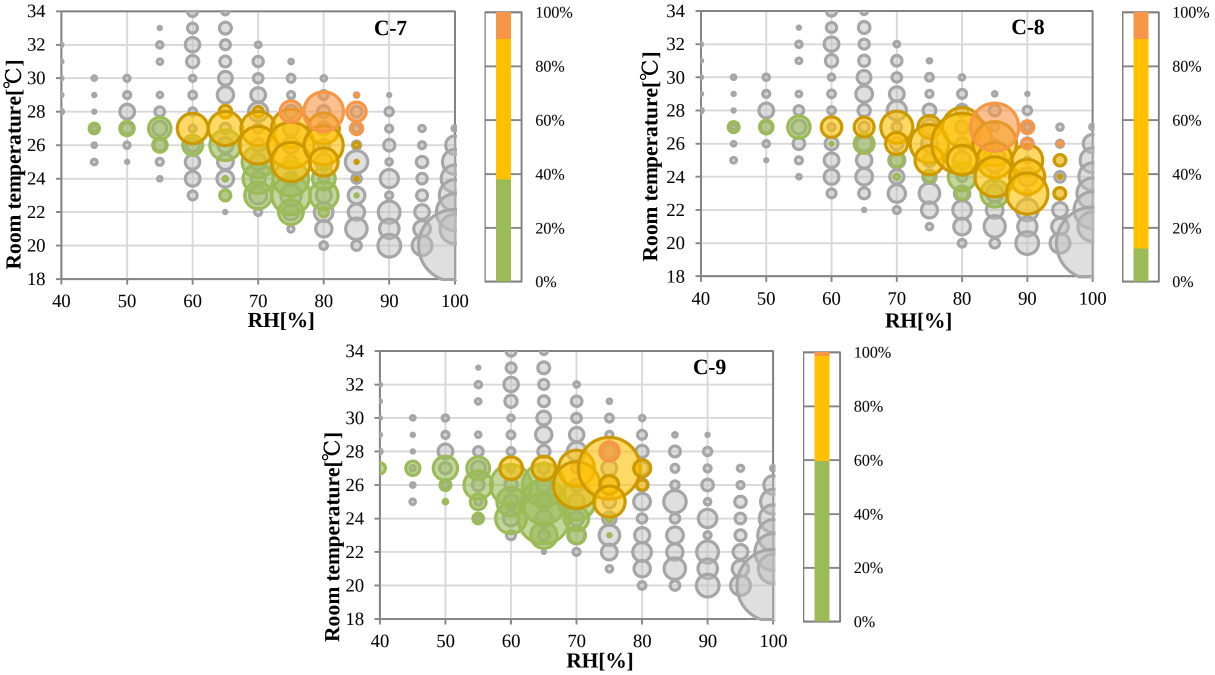
This study tried to use WBGT to evaluate the risk of heat stroke of indoor thermal environment. WBGT was estimated by the living room temperature and relative humidity.



(a)



(b)




(c)

Figure 4-11 Temperature and humidity distribution and heatstroke

Figure 4-11 shows the living room temperature and relative humidity distribution and heat stroke risk as well as its proportion. Compared to the temperature and relative humidity distribution conditions of three residences during the first measured period, it can be seen that because the summer in this climate zone was not particularly hot, the indoor thermal environments of these three residences were all not located in the danger zone of heat stroke, but located in the warning and serious warning zone of heat stroke for almost all the time. Residence C-1 and C-3 were located in the warning zone for around 70% of the time, in the serious warning zone for about 30% of the time. Although the temperature distributions of these two residences were between 25~28ºC for most of the time, due to the higher relative humidity which was mainly concentrated in 70~90%, leading to the warning and serious warning of heat stroke, so these two residences should focus on reducing the indoor relative humidity in summer. For example, using the desiccant in the room and other measures to reduce the risk of heat stroke that caused by the higher relative humidity. Compared with residence C-1 and C-3, the indoor humidity of residence C-2 with east-west orientation pattern had an about 10% reduction, thus the proportion of serious warning was reduced to less than 20%, even there was a small part of the time that the risk of heat stroke was reduced to "Caution". However, it is worth noting that the indoor temperature of residence C-2 was not low and even more than 28ºC for a portion of time. Therefore, the residence C-2 should not only decrease the indoor humidity but also pay attention to reduce the indoor temperature.

Compared to the temperature and humidity distributions of these three residences during the second measured period, it can be seen that the heat stroke risk of indoor thermal environment in residence C-6 was the lowest, located in the "Serious warning" zone of heat stroke for only 16% of the time, located in the "Warning" zone for 76% of the time, and even located in the low risk zone of "Caution" for 8% of the time. It was followed by the residence C-4, the "Serious warning", "Warning" and "Caution" heat stroke zones of indoor thermal environment accounted for 25%, 73% and 2%, respectively. Compared with the residence C-4 and C-6, the heat stroke risk of indoor thermal environment in residence C-5 was relatively higher, located in the "Serious warning" zone for about 42% of the time, and even located in the "Danger" zone for a little part of the time. This is because the indoor temperature of residence C-5 was about 1ºC higher than those of the other two residences. Therefore, the residence C-5 should pay more attention to the indoor cooling and avoid the heat stroke.

During the third measured period, because of the reduction in outdoor temperature and larger temperature difference between day and night, the heat stroke risk of indoor thermal environment was also reduced. Especially for the residence C-9, there was almost no time that the indoor thermal environment of living room was located in the "Serious warning" zone, but located in "Caution" zone of low heat stroke risk for about 60% of the time. Although the indoor temperature was not high, due to the larger indoor relative humidity, the residence C-8 still was located in the "Serious warning" and "Warning" zone for most of the time, a lower humidity can greatly reduce the risk of heat stroke under the condition of same temperature. Therefore, the residence C-8 should take the necessary measures to reduce indoor humidity accordingly.

### 4.3.2 Measured results in Hangzhou

#### 4.3.2.1 Field measurement results

1. Indoor and outdoor temperature and relative humidity during the measured period

(1) Indoor and outdoor temperature

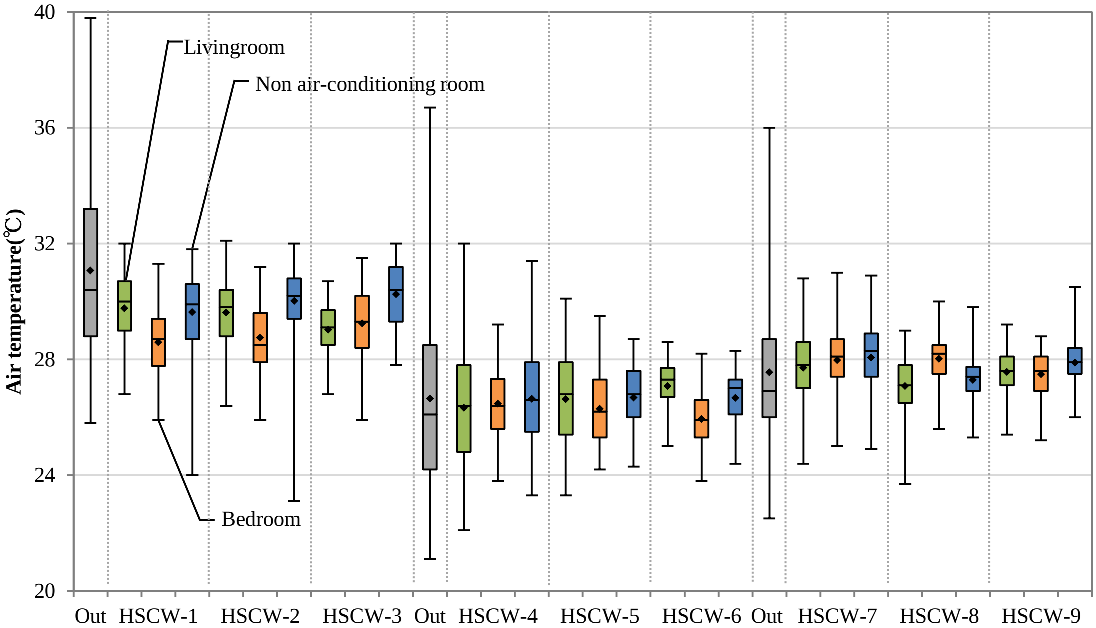



Figure 4-12 Temperature distribution during the measured period

Figure 4-12 shows the indoor and outdoor temperature distribution during the summer measured period in Hangzhou. It can be seen that the variations of outdoor temperatures during the three measured periods were all dispersed, were at (26.1~39.5ºC), (22.5~36.7ºC) and (23~36ºC), respectively. Compared to the first measured period, because of the abnormal weather during the later two measured periods (consecutive overcast and rainy weather for 10 days during the second measured period), the outdoor temperatures were not so hot like that during the first measured period, on the contrary, the temperatures were relatively comfortable and pleasant for a few days in summer. The average outdoor temperature of the first measured period was about 3ºC higher than those of the other two measured periods. The outside temperature distribution affected the indoor temperature distribution of building directly or indirectly. Due to the higher outdoor temperature, the variations of indoor temperature of these three residences during the first measured period were correspondingly higher than those of the other residences. Compare with the residences of the first measured period, it can be seen that the tempeartures of living rooms and bedrooms in different residences were all distributed between 28~30ºC. The temperatures of bedrooms in residence HSCW-1 and HSCW-2 were both relatively low, the temperature distribution of the living room was significantly higher than that of the bedroom. Even the average temperature of the living room in residence HSCW-1 was higher than that of non air-conditioning room, which was about 29.7ºC. This may be because the living rooms in residence HSCW-1 and HSCW-2 were located in the middle, and the north and south was not disconnected, resulting in the relatively poor ventilation conditions. On the other hand, it is likely to be that these two residents were not accustomed to using the air-conditioning in the living room, only using the air-conditioning in the bedroom, leading to a higher temperature of living room. The temperature distributions of the living rooms and bedrooms in residence HSCW-3 were both relatively low, the average temperatures were about 1.2ºC lower than those of non air-conditioning rooms. It can be found that the living room in residence HSCW-3 was located in the south, but there were no windows and no other residences shading in the south, and was not subject to be exposed to the direct sunlight. The residence was east-west orientation, opening the doors and windows of each room will enable to form the draught. In addition, the residence HSCW-3 was the latest one and may have a better insulation structure, leading to the lower indoor temperature distribution.

Because of consecutive rainfall for a few days during the measured period 8/11~8/21 (excluding 8/13), in order to understand the residential indoor thermal environment under the condition of normal weather more accurately, the measured period in the original two weeks was extended to 8/31. It can be seen that due to the lower outdoor temperature distribution, the indoor temperature was reduced as well. There was little difference in indoor temperatures between the air conditioning rooms and non air-conditioning rooms in residence HSCW-4 and HSCW-5, basically remained at around 26.5ºC. This also indirectly indicated that during this measured period, the residence rarely used the air-conditioning to conduct the cooling in the room. The temperature of living room in residence HSCW-6 was slightly higher than those of the other rooms.

Compared to the outdoor temperature during the first measured period, there was also a rainfall weather between 9/9~9/12 during the measured period, so the average outdoor temperature was only 27.55ºC. There was relatively small difference in indoor temperatures between the air conditioning rooms and non air-conditioning rooms, basically remained at 27~28ºC. In addition, it can be observed that compared to the temperature of the living room and non air-conditioning room, the temperature distribution of bedroom in residence HSCW-8 was slightly higher. This may be because not only there was window in the south of bedroom, the solar radiation in the south can be received, but there also was the window in the west, the solar exposure in the west was relatively strong, resulting in a higher temperature of bedroom.

(2) Indoor and outdoor relative humidity

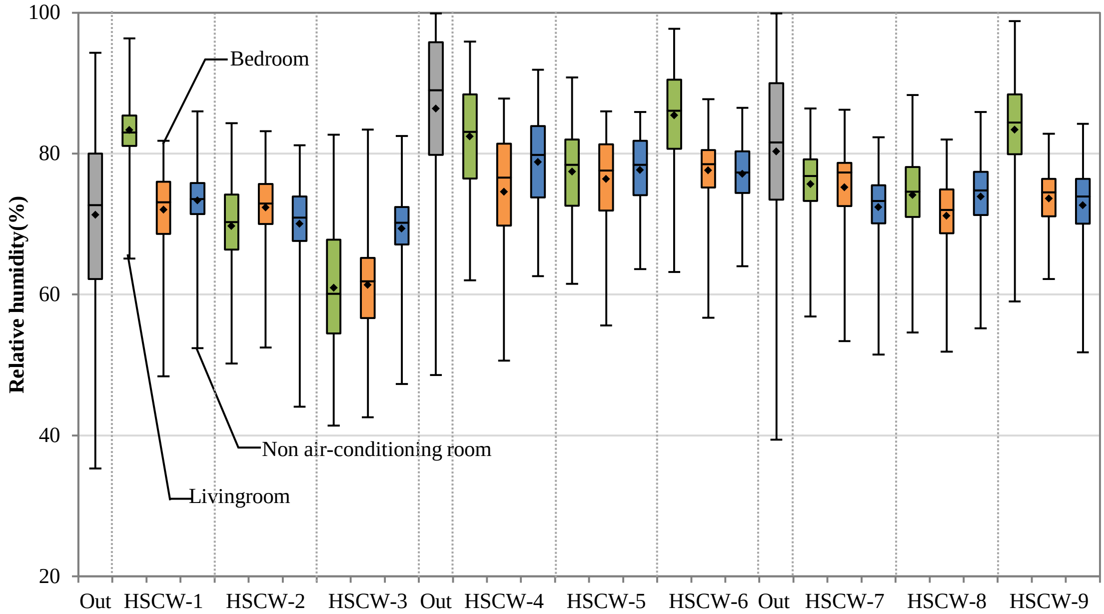



Figure 4-13 Relative humidity distribution during the measured period

Figure 4-13 shows the indoor and outdoor relative humidity distribution during the summer measured period in Hangzhou. The outdoor relative humidity of the first measured period was relatively lower than other two measured period. The average values of three period were about 71%, 86% and 80%, respectively. Due to the reasons for the rainy weather, the part time of relative humidity in the latter two measured period reached 99%.

The distribution of relative humidity of most residences for most of the time was concentrated in about 60~80%. However, the average relative humidity in the living rooms of some residences were higher than 80%. This may be because these several residents were accustomed to having dinner in the living room, and the measuring points were just located in the vicinity, leading to the larger relative humidity. According to Chinese specification <Design code for heating ventilation and air conditioning of civil building>, the comfortable indoor relative humidity range was 40%~65%. Therefore, the relative humidity in summer was slightly higher than the comfortable humidity range.

2. Variation curve of indoor and outdoor temperature and humidity in a typical day

In order to well understand the impact of overcast and rainy weather as well as fine weather on the indoor thermal environment, the two days which were rainfall weather and fine weather were selected as the analysis objects during the second measured period.

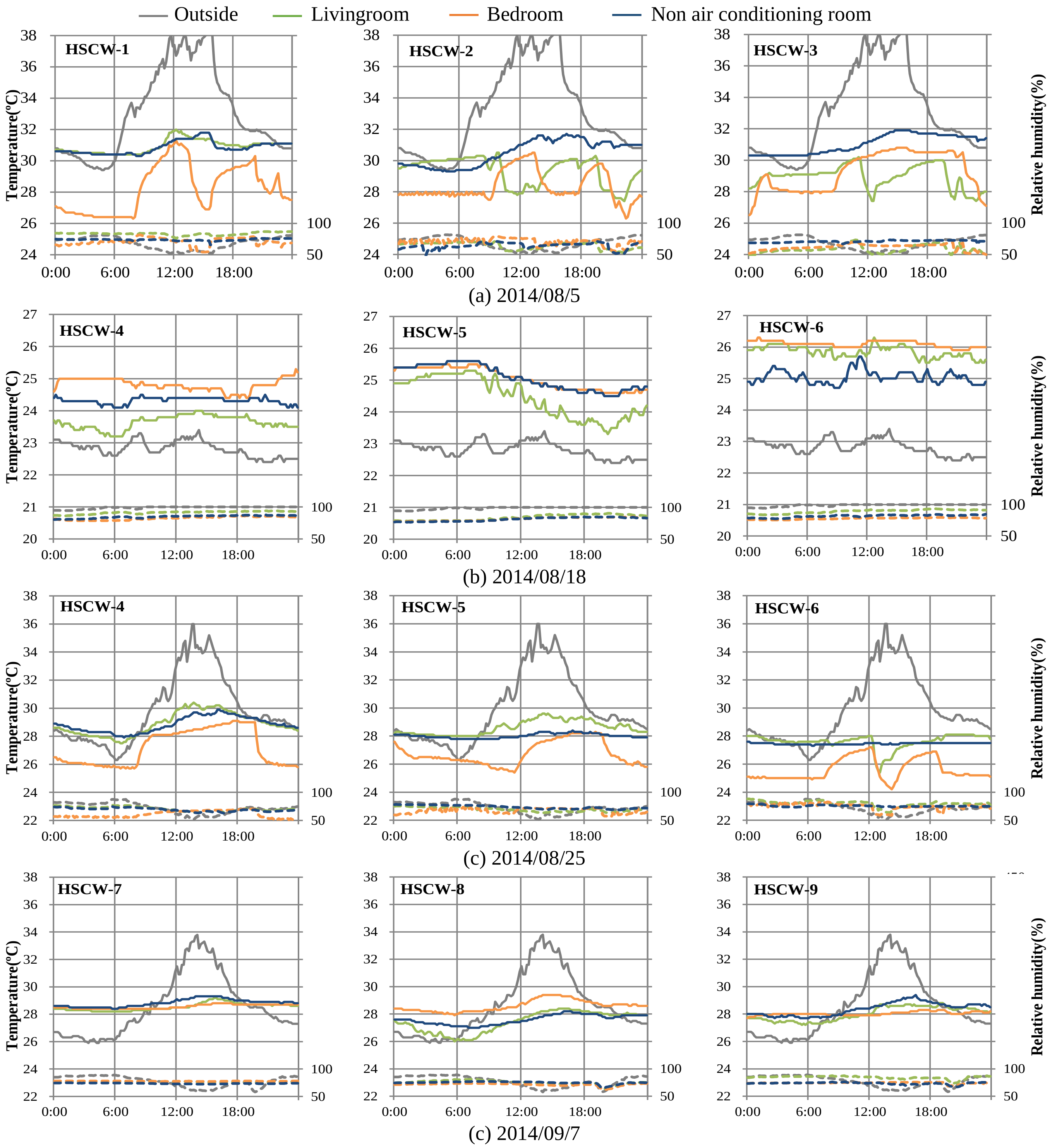



Figure 4-14 Variation curve of indoor and outdoor temperature and humidity in a typical day

Figure 4-14 shows the variation curves of indoor and outdoor temperature as well as humidity, which clarified the change trends of indoor temperature and the schedules of using the air conditioning in different residences.

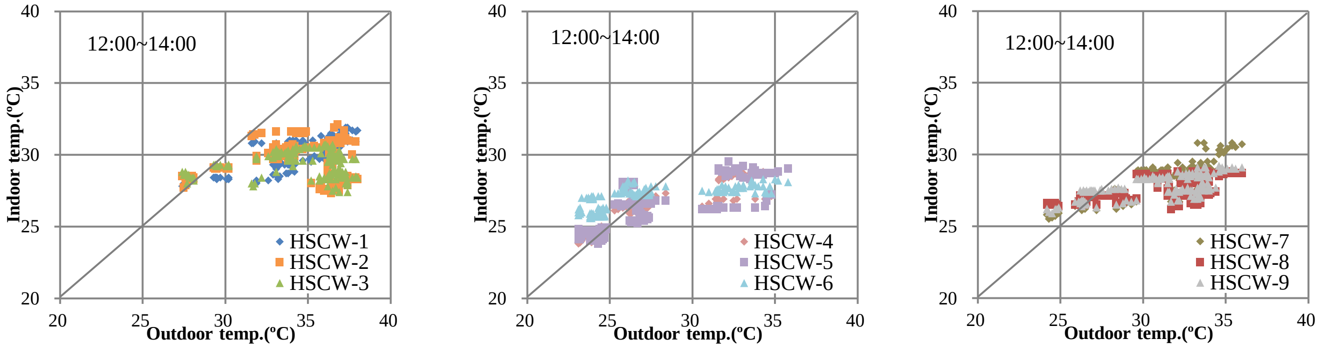
Fig. (a) shows the variation curves of indoor and outdoor temperature as well as humidity in a typical day during the first measured period. It can be seen that the outdoor temperature was higher, and the variation range was relatively smaller which was between about 29.4~38.3ºC. The indoor temperature of non-air conditioning room changed significantly along with the outdoor temperature, the temperature distribution was between 30~32º C at most of the time. Compared to the indoor temperature variation of non-air conditioning room, the temperature change range of air conditioning room was relatively larger, and the service time of air conditioning of living rooms and bedrooms in different residences was not the same. For example, the air conditioning of living room was basically not used in residence HSCW-1, while the service time of air conditioning in the bedroom was relatively longer, including the night rest (19:50~7:40) and lunch break (13:00~15:30). However, the air conditionings of living room and bedroom were both used in residence HSCW-2 and HSCW-3; the service time of air conditioning in the living room was the lunch time in the noon and dinner as well as entertainment after dinner. The service time of air conditioning in the living room of residence HSCW-2 was longer than that of residence HSCW-3. The service time of air conditioning in the bedroom of residence HSCW-2 was almost the same as HSCW-1, including the night and lunch break. However, the air conditioning of bedroom in residence HSCW-3 was only used in the evening. In addition, the indoor temperatures of different residences when using the air conditioning were not the same, the indoor temperatures of residence HSCW-2 and HSCW-3 were about 28ºC when using the air conditioning, while the indoor temperature of residence HSCW-1 was relatively low and about 26.5ºC.

Fig. (b) shows the variation curves of indoor and outdoor temperature as well as humidity in a rainfall weather during the second measured period. It can be seen that the outdoor temperature was very low, and the variation range was relatively smaller which was between about 22~23ºC. The indoor temperature distribution was higher than the outdoor temperature, but the fluctuation range was also relatively smaller. The air-conditionings of three residences were all not used in the room. However, the ventilation conditions and the open of the windows were different due to the different patterns of different residences, resulting in the different indoor temperature distributions. The indoor temperature of residence HSCW-5 was relatively higher in the night, but lower during the day, which was probably due to the closed windows in the relatively cool night and the open of windows for natural ventilation during the day. The difference in the indoor and outdoor temperature was the largest in residence HSCW-6 which indicated that the indoor ventilation conditions of residence HSCW-6 were relatively poor.

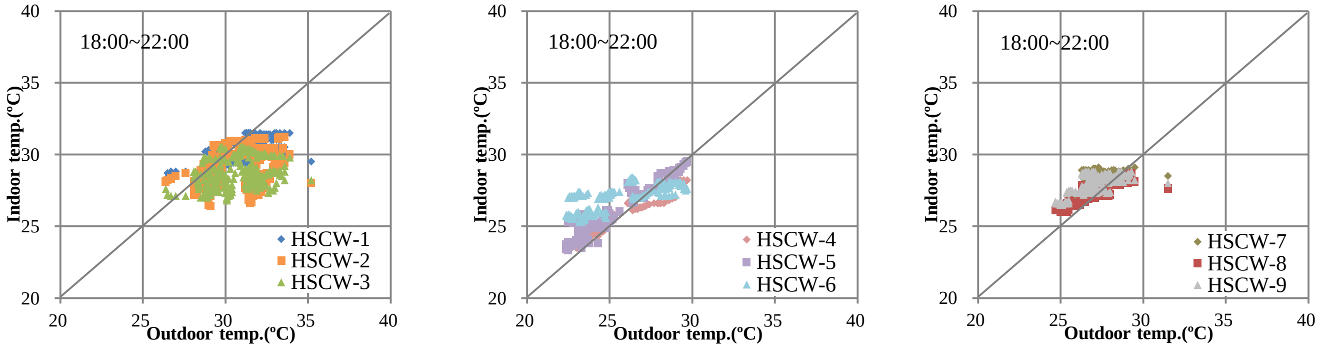
Fig. (c) shows the variation curves of indoor and outdoor temperature as well as humidity in a fine weather during the second measured period. It can be seen that compared to the first measured period, the outdoor temperature of the second measured period was decreased by more than 2ºC. The temperature fluctuation range within 1 day was between 26.3~36ºC. Therefore, the indoor temperature was decreased as well. Because the measuring points of non-air conditioning room in residence HSCW-4 were located in the balcony to the south, the influence of the solar radiation was more significant, so the change along with the outdoor temperature was obvious. However, the measuring points of non-air conditioning rooms in residence HSCW-5 and HSCW-6 were located in the balcony to the north and the bathroom in the middle respectively, hardly affected by the solar radiation, so there were almost no fluctuations in the indoor temperature of non-air conditioning within a day, remained at 28ºC and 27ºC respectively. Without the use of air-conditioning in the living rooms of residence HSCW-4 and HSCW-5, the temperature fluctuations were in the range of 28~30ºC; the air-conditioning of the bedroom was only used at night rest, the temperature were all distributed at around 26ºC. However, the air conditioning of living room in residence HSCW-6 was used at lunch time (12:00~12:40). The service time of air conditioning in the bedroom was relatively longer, including not only from the dinner (about 18:20) to the morning of the second day (about 7:40) but also the lunch time (12:40~14:40). In addition, the indoor temperature of residence HSCW-5 when using the air conditioning was lower than those of the other two residences and remained at around 25ºC.

Fig. (d) shows the variation curves of indoor and outdoor temperature as well as humidity in a typical day during the third measured period. Entering into September, the weather of Hangzhou city was not so hot. It can be seen that compared to the second measured period, the maximum outdoor temperature of the third measured period was decreased by about 2ºC again. The temperature fluctuation range within 1 day was between 25.9~33.8ºC. Therefore, all the indoor temperatures of surveyed residences during the third measured period changed gently. Moreover, the indoor temperatures of residences HSCW-7 and HSCW-9 changed little along with the outdoor temperature, and the temperature difference of non-air conditioning room of the living room and bedroom was not much in these two residences, basically remained at 28~29ºC. However, the indoor temperature fluctuation of residence HSCW-8 along with the outdoor temperature was relatively obvious, the highest temperature of the bedroom at noon was about 29.5ºC. Meanwhile, it can be observed that the temperature of the bedroom was about 1ºC higher than those of the other rooms, which was probably because that the bedroom in the south was not only affected significantly by the solar radiation, but also had a poor ventilation condition. In addition, based on the indoor temperature fluctuation trends, the air-conditionings of these three residences all were not used indoor.

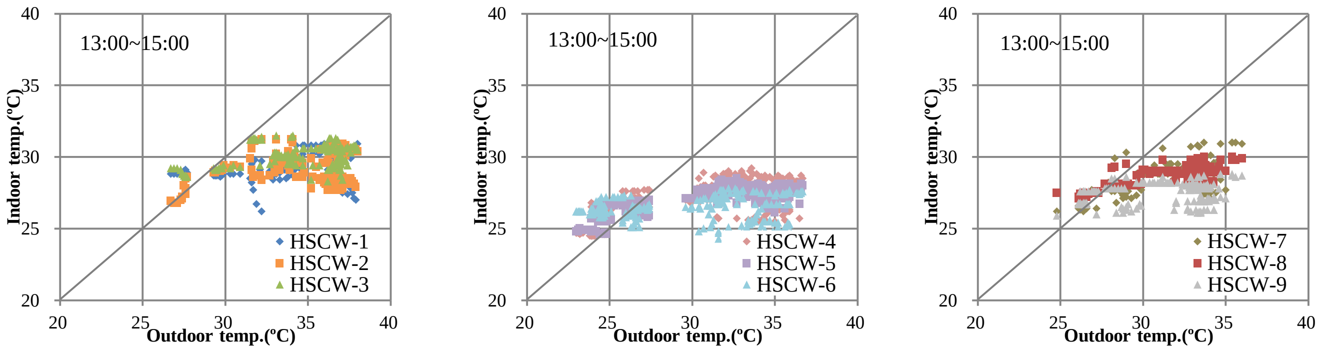
3. Relationship between the indoor and outdoor temperatures



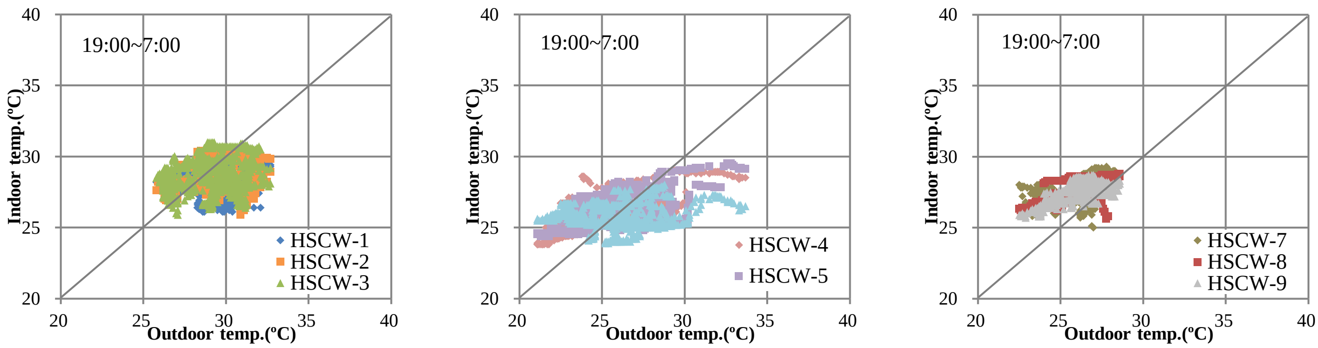

(a) Relationship between the indoor and outdoor temperatures in the daytime in livingroom




(b) Relationship between the indoor and outdoor temperatures in the evening in livingroom




(c) Relationship between the indoor and outdoor temperatures in the daytime in bedroom




(d) Relationship between the indoor and outdoor temperatures at night in bedroom

Figure 4-15 Relationship between the indoor and outdoor temperatures

Figure 4-15 shows the relationship between the outdoor temperatures and the temperatures of living room and bedroom at different time, which was not only conductive to understand the indoor ventilation condition and the service condition of air conditioning, but also can more reflect the thermal insulation performance of residential envelope structure from indirect perspectives.

Fig. (a) shows the relationship between the indoor and outdoor temperatures at noon in the living room. It can be found that due to the higher outdoor temperature at noon, the indoor temperature was all lower that the outdoor temperature at most of the time. The indoor and outdoor temperature data of the second measured period were divided into two parts obviously, this was due to the consecutive overcast and rainy weather during the measured period, the outdoor temperature was relatively low and the indoor temperature was higher than outdoor temperature. In addition, the indoor and outdoor temperature difference at noon was different depend on the different residences, the indoor and outdoor temperature differences of residence HSCW-2 and HSCW-3 were relatively larger, the maximum value was up to 10ºC. On the one hand, this is because that these two residences were accustomed to using the air conditioning in the living room at noon; on the other hand, this also reflected the better thermal insulation effect of envelope structure of residence HSCW-2 and HSCW-3.

Fig. (b) shows the relationship between the indoor and outdoor temperatures in the evening in the living room. The indoor temperatures of residential living rooms of later two measured periods were almost same as the outdoor temperature in the evening. This is because the outdoor temperatures in the late afternoon were relatively cool during these two measured periods, the residences were in the natural ventilation state and the air conditioning was hardly used to conduct the cooling, so the indoor and outdoor temperature difference was smaller. However, the indoor temperatures of living rooms in the three residences during the first measured period were still lower than the outdoor temperature, but the indoor and outdoor temperature difference in the late afternoon was reduced compared to that at noon. This is likely to be the higher temperature in the late afternoon during the first measured period, the air conditioning was still used to conduct the cooling when the entertainment in the living room after dinner.

Fig. (c) shows the relationship between the indoor and outdoor temperatures at noon in the bedroom. The bedroom temperature was slightly higher than the outdoor temperature in the rainfall weather. Beyond that, the indoor temperatures at noon of bedrooms of all the residences were lower than the outdoor temperature at the other time. The indoor and outdoor temperature difference of residence HSCW-6 was the largest, the maximum value was about 11ºC. The use of air conditioning in the bedroom at noon break and the lower setting temperature of air conditioning were the main reason why the indoor and outdoor temperature difference of bedroom in this residence was relatively larger. Fig. (d) shows the relationship between the indoor and outdoor temperatures at noon in bedroom. The bedroom temperatures of residences in the evening at about half the time during the first two measured periods were lower than the outdoor temperature. This indicates that these residences were accustomed to using the air conditioning for cooling when sleeping in the bedroom at night. However, the bedroom indoor temperatures of the three residences during the third measured period were almost all higher than the outdoor temperature. This may be mainly due to the lower outdoor temperature in the evening during this measured period, while there was usually a lot of waste heat in the residence, and the poor ventilation condition resulted in the higher indoor temperature than outdoor temperature. In contrast, the bedroom indoor temperature of residence HSCW-9 was slightly lower, this benefited from the good south-north exposure of bedroom in which the natural ventilation condition was better than the other residences.

4. ASHRAE comfort zone

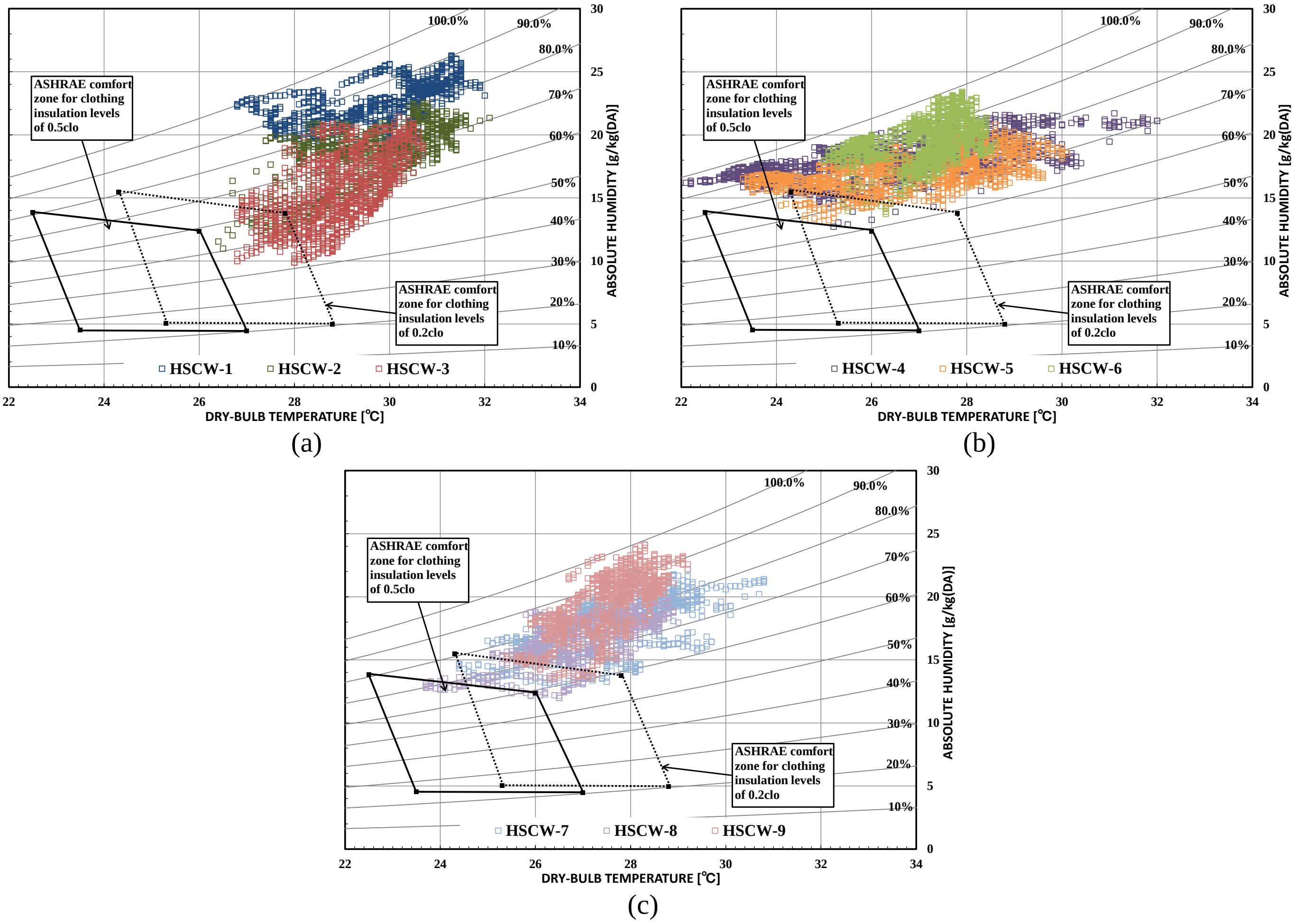


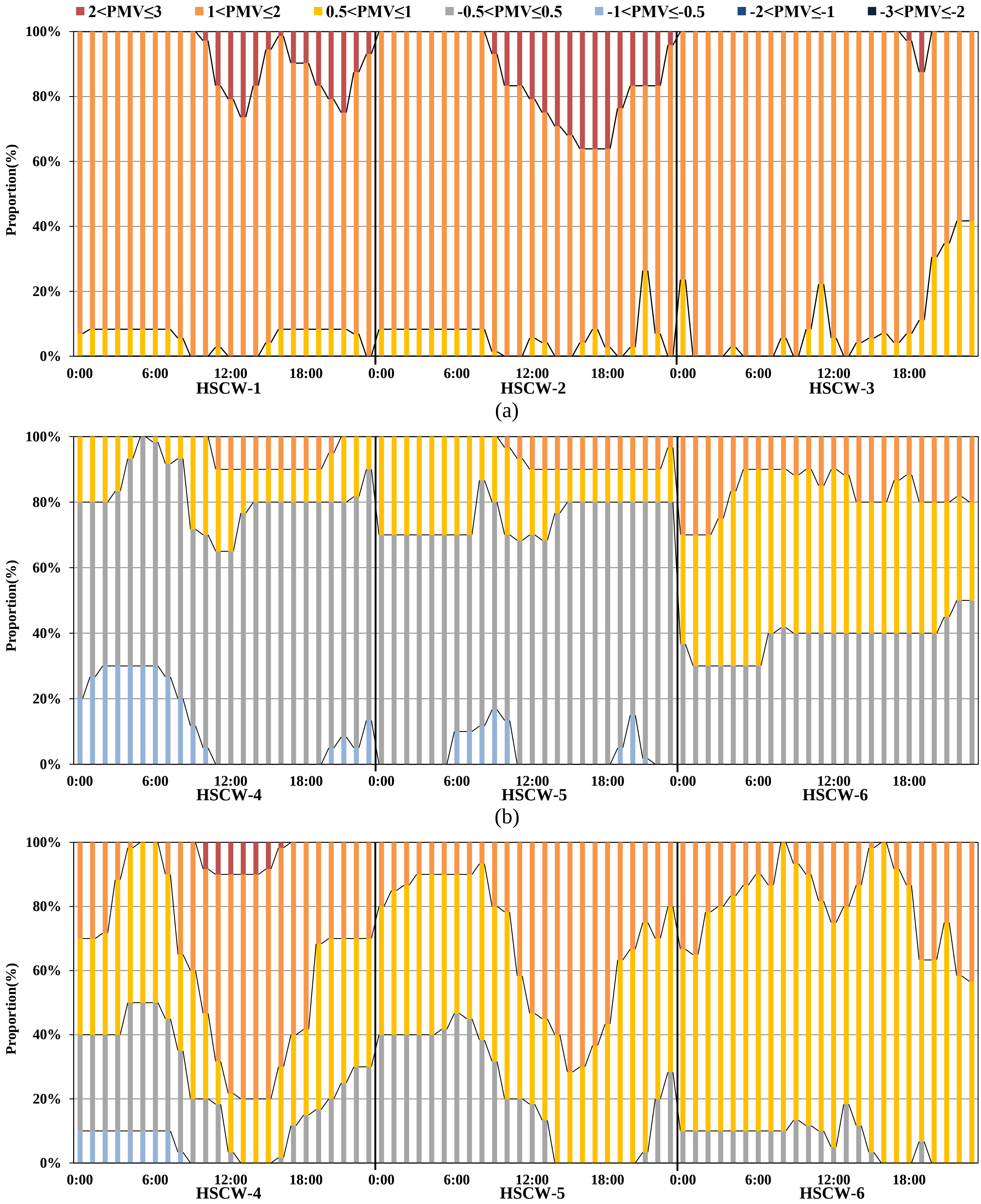

Figure 4-16 Indoor temperature and relative humidity distribution and ASHRAE comfort zone in summer

Figure 4-16 shows the indoor temperature and relative humidity distribution as well as the location of ASHRAE comfort zone in summer in Hangzhou. It can be seen that the indoor temperature of three residences during the first measured period was relatively high, mainly distributed between 27~32ºC. The relative humidity in residence HSCW-3 was slightly low compared with the other residences, mainly distributed between 40%~80%, while mainly distributed between 60%~90% in other residences. Even part of relative humidity data of residence HSCW-1 reached 99%. Because of this high temperature and relative humidity, there was no data falling into the ASHRAE comfort zone for clothing insulation levels of 0.5clo. Similarly, the ASHRAE comfort zones for less clothing levels can be approximated by increasing the temperature borders of this zone by 0.6K for each 0.1clo increase of clothing insulation, the comfort zone moved to the right along with the reduction of clothing insulation. After moving, only a portion of the indoor temperature and humidity data of residence HSCW-3 fell into the ASHRAE comfort zone for clothing insulation levels of 0.2clo.

Due to the rainy weather for several days, the indoor temperature of three residences during the second measured period was relatively low and dispersed, especially for the residence HSCW-4, the lowest indoor temperature was around 22ºC, the highest temperature can reach up to 32ºC. The indoor relative humidity of three residences all concentrated in the range of 65%~95%. Due to the higher relative humidity, there was no any data of these three residences falling into the ASHRAE comfort zone for clothing insulation levels of 0.5clo. After moving with the reduction of clothing insulation, a few data of residence HSCW-5 fell into the comfort zone.

The indoor relative humidity distributions of three residences during the third measured period were still over 60%. Residential indoor temperature was mainly distributed between 24~30ºC. There was also little data falling into the ASHRAE comfort zone for clothing insulation levels of 0.5clo. After moving with the reduction of clothing insulation, a few data of residence HSCW-7 and HSCW-8 fell into the comfort zone.

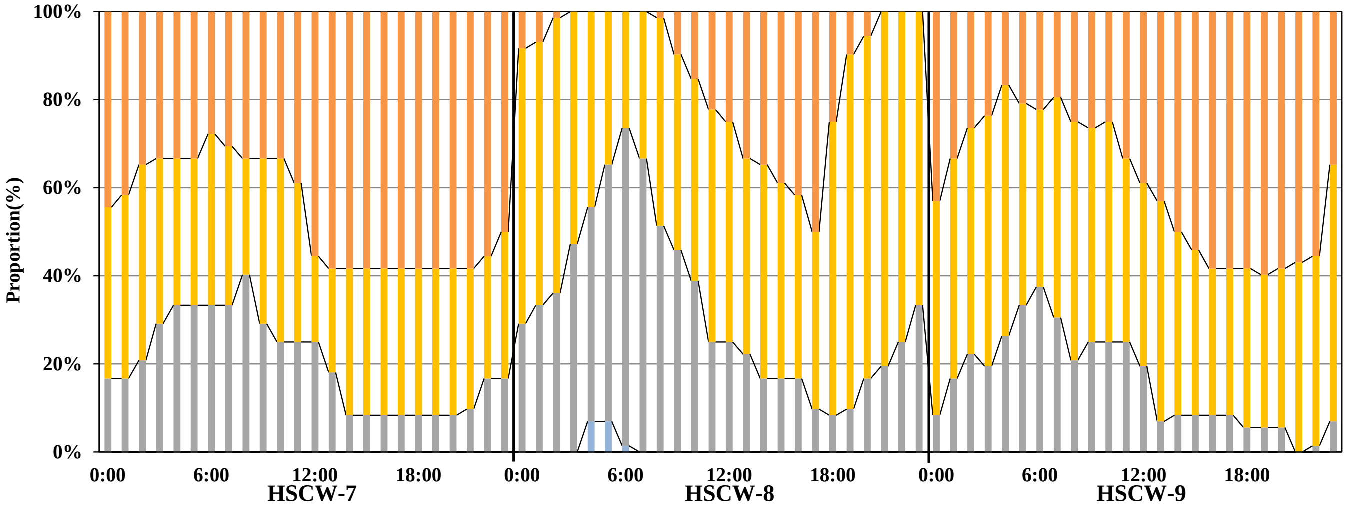
5. Predicted Mean Vote (PMV)




(a)

(b)

(c)




(d)

Figure 4-17 Proportion of PMV in summer of Hangzhou

（Annotation: PMV’s calculation condition: M=1.2met, v=0.25m/s）

Figure 4-17 shows the proportions of PMV value of the living room in summer of Hangzhou in different measured periods. Compared with the PMV values and its proportions of indoor thermal environment of the three residences during the first measured period, it can be seen that the PMV value evaluation results were almost consistent with those of ASHRAE comfort zone evaluation. The ASHRAE comfort zone evaluation results indicated that due to the higher indoor temperatures and humidity of these three residences during the first measured period, there was almost no data falling into the comfort zone. The PMV evaluation results also showed that the comfort proportions of indoor thermal environment in these three residences in the range of -0.5~0.5 which meant the residents felt the neutral were 0. The PMV values of these three residences were all located in the range of more than 0.5 which meant the residents felt slightly hot or hot for most of the time. However, the PMV value evaluation results were seemed to be a little different from those of heat stroke risk evaluation. Heat stroke risk evaluation results indicated that the heat stroke risk of indoor thermal environment in residence HSCW-1 was the highest. In contrast, the PMV evaluation results indicated that the uncomfort proportion of the PMV value of indoor thermal environment in residence HSCW-2 in the range of 2~3 which meant the residents felt hot was the highest, was up to about 36% at about 18:00. The uncomfort proportion of in residence HSCW-1 in the range of 2~3 was around 28% at about 13:00. The highest uncomfort proportion of the PMV value of indoor thermal environment in the range of 2~3 was different depend on the residence. In addition, from the point of view of the time, the highest uncomfort proportions of the PMV values of indoor thermal environment in residence HSCW-2 and HSCW-3 which were in the range of 2~3 both occurred in the evening, while the uncomfort proportion in residence HSCW-1 presented two peaks at 13:00 and 21:00, respectively. This may be due to the different occupancy schedule of the living rooms, the living rooms of the former were only used at dinner time, the heat radiation of personnel resulted in the rise of indoor temperature and humidity, leading to the increase of PMV value. In contrast, the living rooms of the latter were only occupied at noon break and entertainment after dinner in the evening.

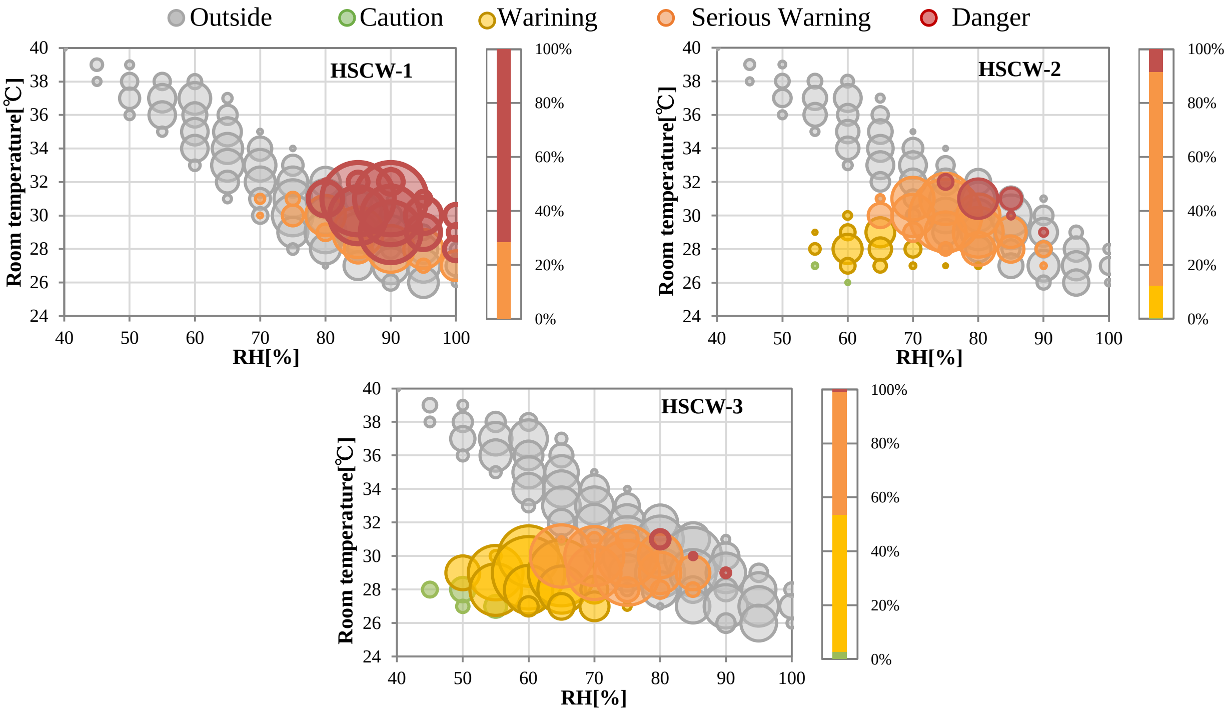
Because there was a large difference between the PMV values of rainfall and fine weather, the PMV comfort evaluation of the second measured period was divided into two parts to respectively calculate the PMV values of rainfall and fine weather as well as their respective proportions. Compared with the PMV values and its proportions of indoor thermal environment of the three residences in rainny days during the second measured period, it can be seen that the comfort proportions of the PMV value of indoor thermal environment in HSCW-4 and HSCW-5 in the range of -0.5~0.5 which meant the residents felt the neutral differed little, both accounted for around 80%. However, the comfort proportion of the PMV value in residence HSCW-6 only accounted for about 40%. As a result of the higher indoor temperature of HSCW-6 which caused by that the poor indoor ventilation conditions of residence. In addition, the PMV value in different time varied little in the rainfall day.

Compared with the PMV values and its proportions of indoor thermal environment of these three residences in fine day during the second measured period, it can be seen that the indoor comfort proportions of residence HSCW-5 were slightly higher than that of other two residences. The comfort proportion of the PMV value of indoor thermal environment in residence HSCW-4 and HSCW-5 reached the highest value at about 6:00. Moreover, due to the solar radiation was relatively strong at noon in residence HSCW-4, the proportions of the PMV values of indoor thermal environment which were in the range of 2~3 accounted for 10%.

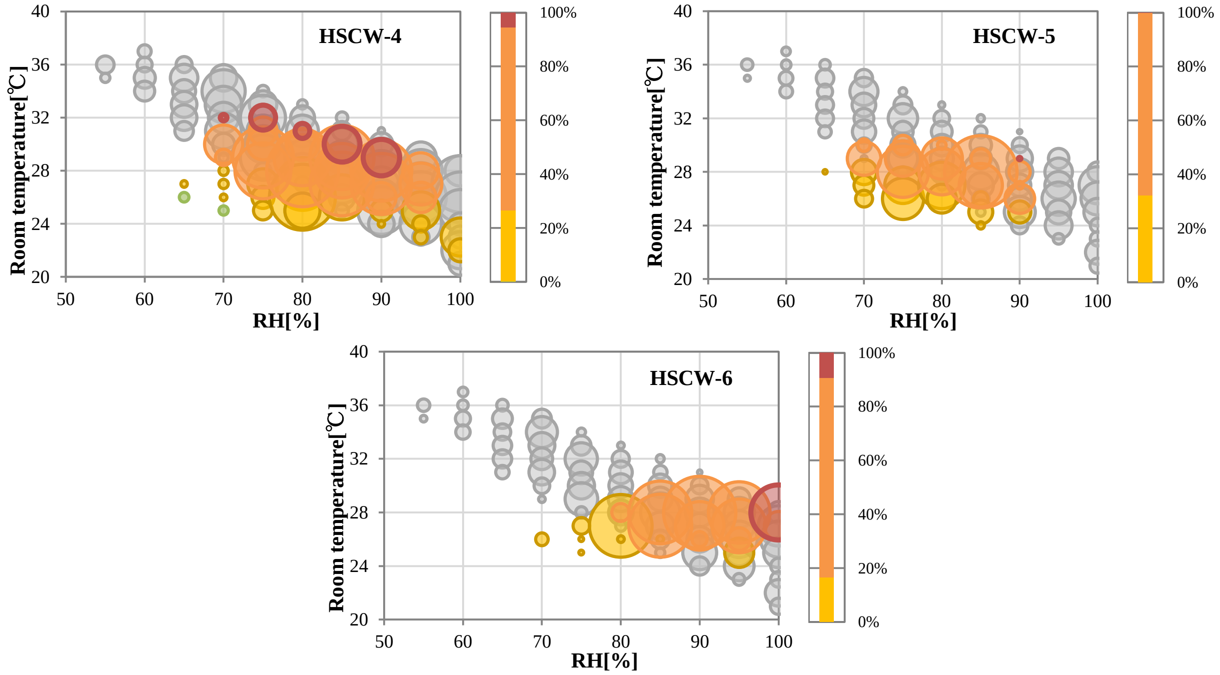
In addition, compared with the PMV values and its proportions of indoor thermal environment of the three residences during the third measured period, it can be seen that the PMV value evaluation results were almost consistent with those of heat stroke evaluation. The comfort proportion of the PMV value of indoor thermal environment in residence HSCW-8 was the highest, and even up to around 70% at about 6:00.

6. Heatstroke possibility evaluation by WBGT

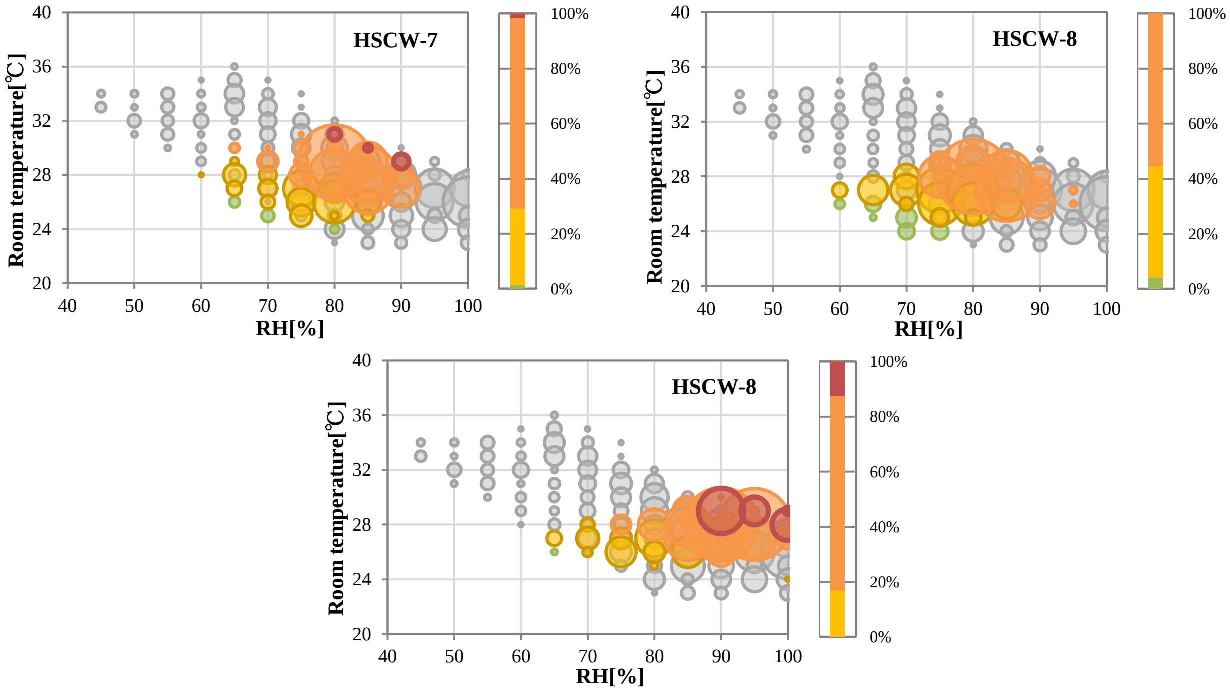
Figure 4-18 shows the temperature and relative humidity distributions of living room and heat stroke risk as well as its proportion in Hangzhou during different measured periods. Compared with that in Qingdao, the risk of heat stroke in summer of Hangzhou was relatively high, the risk assessment of heat stroke of indoor thermal environment in some residences was dangerous.




(a)




(b)




(c)

Figure 4-18 Temperature and humidity distribution and heatstroke

Based on the results, it can be seen that there was a significant difference in the risk of heat stroke among the three residences in the first measured period. Residence HSCW-1 was located in the danger zone of heat stroke for around 70% of the time, in the serious warning zone for about 30% of the time, which indicated a high probability of heat stroke in residence HSCW-1. This is not only due to the high indoor temperature, but more importantly, most of the relative humidity was in the range of 75%~100%. Such a high relative humidity would increase the risk of heat stroke. As a result, the residence HSCW-1 should pay more attention to the indoor humidity elimination so as to avoid the heat stroke. Although the temperature distributions of residence HSCW-2 was almost as high as residence HSCW-1 and mainly between 28~32ºC for most of the time, due to the low relative humidity which was mainly concentrated in 60~85%, leading to the less risk of heat stroke, only less than 9% in the the danger zone. Compared with residence HSCW-1 and HSCW-2, the indoor humidity of residence HSCW-3 with east-west orientation pattern had a greater improvement, but the tempearture distribution range differed little. Almost no data fell into the danger zone of heat stroke risk. The proportion of serious warning was reduced to less than 45%, and about 50% located in the warning zone, even there was a small part of the time that the risk of heat stroke was reduced to "Caution". Therefore, it can be concluded that the residence HSCW-3 had the lowest risk of heat stroke among the three residences in the first measured period.

Because of the relatively cool in the rainfall day, the risk assessment of heat stroke only used the data of fine day from 8/21 to 8/30 in the second measured period. It can be seen the out temperature was relatively lower than that in the first measured period, while the relative humidity increased by about 10%. Compared with the temperature and humidity distributions of the three residences during the second measured period, it can be seen that the heat stroke risk of indoor thermal environment in residence HSCW-5 was the lowest. There was no data falling into the danger zone of heat stroke. The indoor temperature of HSCW-5 was relatively lower. The proportion of serious warning covered 67%, and about 33% was located in the warning zone. The "danger" proportions of heat stroke in residence HSCW-4 and HSCW-6 were approximately same and both around 95%, but the reasons for the danger of heat stroke were different. The temperature distribution of residence HSCW-4 in the danger zones was 29~32ºC, and the relative humidity was distributed between 70%~90%. The higher temperature combined with relative humidity caused the danger of heat stroke in residence HSCW-4. However, for the residence HSCW-6, the indoor temperature was about 28ºC, but the relative humidity was up to 99%, so the risk of heat stroke was mainly caused by the high relative humidity.

Compared with the temperature and humidity distributions of the three residences during the third measured period, it can be seen that the heat stroke risk of indoor thermal environment in residence HSCW-8 was the lowest. There was no data located in the danger zone, and located in the "Serious warning" zone of heat stroke for about 52% of the time, located in the "Warning" zone for 40% of the time, and even located in the low risk zone of "Caution" for 8% of the time. It was followed by the residence HSCW-7, the "Danger", "Serious warning", "Warning" and "Caution" heat stroke zones of indoor thermal environment accounted for 2%, 69%, 27% and 2%, respectively. Compared to the residence HSCW-7 and HSCW-8, the heat stroke risk of indoor thermal environment in residence HSCW-9 was relatively higher, located in the "Serious warning" zone for about 71% of the time, and even located in the "Danger" zone for 13% of the time. However, it is worth noting that the indoor temperature was not higher than the other two residences, but the higher relative humidity of residence HSCW-9 caused the high risk of heat stroke. Therefore, the residence HSCW-9 should also pay more attention to the indoor humidity elimination so as to reduce the possibility of heat stroke.

4.3.2.2 Questionnaire survey results

1. Clothing insulation

(1) Clothing insulation value

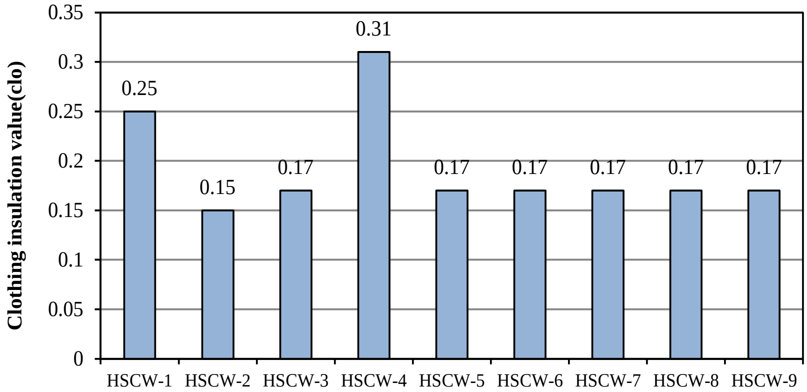



Figure 4-19 Clothing insulation value in summer in Hangzhou

Figure 4-19 gives clothing insulation values for typical indoor clothing of the surveyed residences during summer measurement in Hangzhou. It can be seen that clothing insulation levels was relatively lower than the ASHRAE recommended value in summer which was 0.5clo. The clothing insulation value of most of surveyed residences in Hangzhou was concentrated in about 0.17clo. It meant that residents usually wear short sleeved T-shirt and shorts when at home. In addition, the clothing insulation values of residence HSCW-1 and HSCW-4 were slightly high, about 0.25clo and 0.31clo, respectively.

(2) Relationship between clothing insulation value and living room temperature

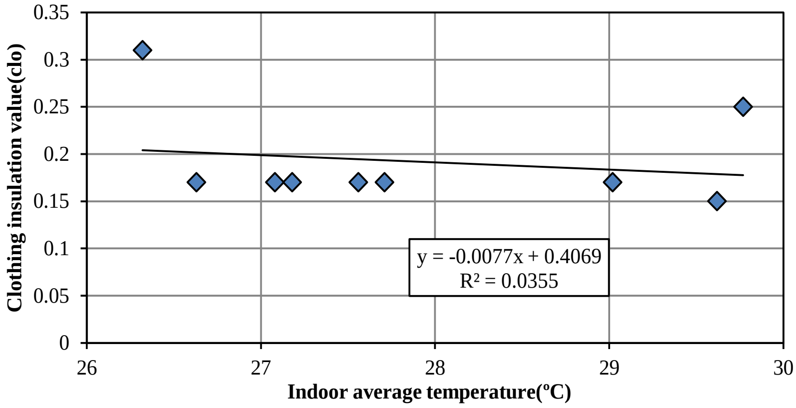



Figure 4-20 Relationship between clothing insulation value and indoor average temperature

In general, the indoor temperature and residents' condition were the factors for the selection of clothing. Figure 4-20 shows the relationship between the clothing insulation and indoor average temperature. Unlike in winter, the clothing insulation showed almost no linear relationship with indoor temperature in summer of Hangzhou. This is because the clothing insulation in summer was already less. The residents cannot adjust the amount of clothing according to the indoor temperature in summer.

2. The schedule of air conditioning and natural ventilation

By applying statistical analysis to the questionnaire data, the schedule of cooling equipment in the nine residences including air conditioning and electric fan as well as natural ventilation by opening windows were obtained, as shown in Figure 4-21.

| | | Area ($m^2$) | Capacity (kW) | Day | Setting temperature (℃) |
|---|---|---|---|---|---|
| HSCW-1 | Livingroom | 40 | 8.2 | 0 | — |
| | Mainbedroom | 15 | 3.5 | 5 | 28 |
| | Bedroom2 | 15 | 3.5 | 5 | 27 |
| HSCW-2 | Livingroom | 20 | 1.5 | 4 | 28 |
| | Mainbedroom | 20 | 1.16 | 7 | 28 |
| | Bedroom2 | 16 | 0.755 | 2 | 28 |
| HSCW-3 | Livingroom | 16 | 5.2 | 0 | — |
| | Mainbedroom | 14 | 3.55 | 2 | 28 |
| | Bedroom2 | 10 | 2.3 | 2 | 24 |
| HSCW-4 | Livingroom | 50 | 7.2 | 1 | 26 |
| | Mainbedroom | 15 | 3.3 | 3 | 26 |
| | Bedroom2 | 12 | 2.3 | 4 | 26 |
| HSCW-5 | Livingroom | 20 | 5 | 0 | — |
| | Mainbedroom | 20 | 3.2 | 3 | 26 |
| | Bedroom2 | 12 | 2.6 | 4 | 26 |
| HSCW-6 | Livingroom | 30 | 7 | 3 | 25 or 26 |
| | Mainbedroom | 20 | 3.5 | 4 | 25 |
| | Bedroom2 | 10 | 2.5 | 4 | 25 |
| HSCW-7 | Livingroom | 12 | 3.52 | 2 | 27 |
| | Mainbedroom | 11 | 2.3 | 7 | 27 |
| | Bedroom2 | 10 | 2.3 | 5 | 27 |
| HSCW-8 | Livingroom | 30 | 4.6 | 1 | 27 |
| | Mainbedroom | 12 | 3.2 | 5 | 27 |
| | Bedroom2 | 10 | 2.3 | 5 | 27 |
| HSCW-9 | Livingroom | 22 | 2.6 | 0 | — |
| | Mainbedroom | 11 | 2.35 | 6 | 28 |
| | Bedroom2 | 11 | 2.35 | 6 | 28 |

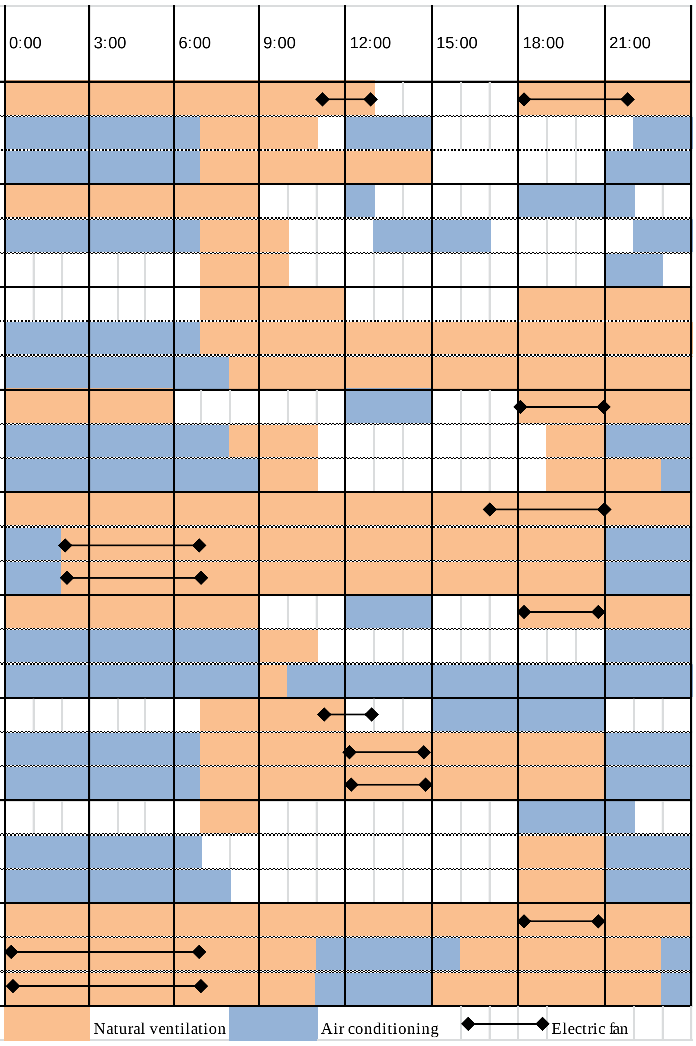



Figure 4-21 Cooling equipment and natural ventilation schedule of each residence

The service time of air conditioning and electric fans as well as natural ventilation time of different residences varied from each other. In bedroom, most residences only used air conditioning for cooling during the night (21:00~7:00) and opened the window for ventilation in the morning, while closed the window so as to avoid the heat into the room when the solar radiation intensity was strong at noon. This kind of air conditioning schedule was diametrically opposed to that reported in previous researched residences in Qingdao [(2)], which was located in a cold region. The service time of air conditioning in the Cold Zone was mostly concentrated in the noon when the solar radiation was stronger and the outdoor temperature was higher, while most of the residences chose natural ventilation for cooling by opening the window in the night. This may reflect both the climatic characteristics and the lifestyle of the residents. Compared with the Cold Zone in China, the average outdoor temperature in summer of Hangzhou which was located in Hot Summer and Cold Winter Zone was higher. The temperature difference between day and night was little, and it was stuffy and calm in the night. Therefore, most of the residents were accustomed to using air conditioning for cooling as they sleep in the night. While there was large temperature difference between day and night, it was cool at night in Qingdao, so there was almost no need to use air conditioning at night. In addition, some residents were accustomed to use the air conditioning in the bedroom when lunch break.

In contrast with bedroom, the service time of air conditioning in the living room was concentrated in the afternoon (12:00~16:00) and evening (18:00~22:00). The residents who used the air conditioning in the daytime were mostly the old and the children who were at home throughout the day as well as the office workers come back home for lunch at noon. The use of air conditioning in the evening mostly reflected the after dinner leisure period spent in the living room. However, some residences in the living room did not use air conditioning. For example, residence HSCW-1, HSCW-3, HSCW-5 and HSCW-9 hardly ever used the air conditioning in the living room, with cooling provided mainly by natural ventilation and electric fans.

In addition to cooling equipment and natural ventilation schedule was different in different residences, the setting temperature of air conditioning in different residences also differed from each another as can be seen from Figure 4-21. The setting temperature of air conditioning mainly concentrated in 26ºC~ 28ºC in most surveyed residences. However, setting temperature of air conditioning in residence HSCW-6 and bedroom 2 in residence HSCW-3 hovered between 24ºC and 25ºC, this temperature was lower than the design standard of air conditioning temperature in summer which was specified as 26ºC(3). The setting temperature of air conditioning can directly affect the indoor thermal environment quality and residential energy consumption. The over low setting temperature will inevitably lead to more energy consumption. According to the surveys (4), each 1ºC increase of the setting temperature of air conditioning in summer could reduce by about 10% energy consumption. However, the over high setting temperature will lead to the deterioration of indoor thermal environment. The thermal environment and energy consumption should be comprehensively considered to design the setting temperature of air conditioning depend on the human thermal sensation in different regions.

Moreover, the cooling capacities of air conditioning and cooling area in each room were also collected by questionnaire. Air conditioning cooling capacity per square meter can be seen from Figure 4-22. Most residents chose air conditioning power of 0.2kW/m$^2$. However, some residents used air conditioning with low power in larger room. For example, the cooling capacity of air conditioning in residence HSCW-2 was less than 0.1kW/m$^2$. The room temperature cannot reach the setting temperature for a long time, the air conditioning compressor remained running consistently, which resulted in large electricity consumption.

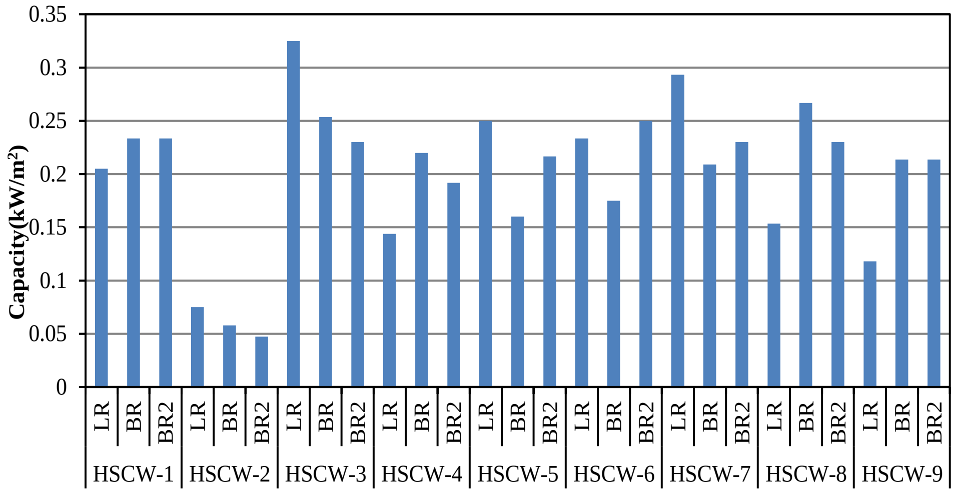
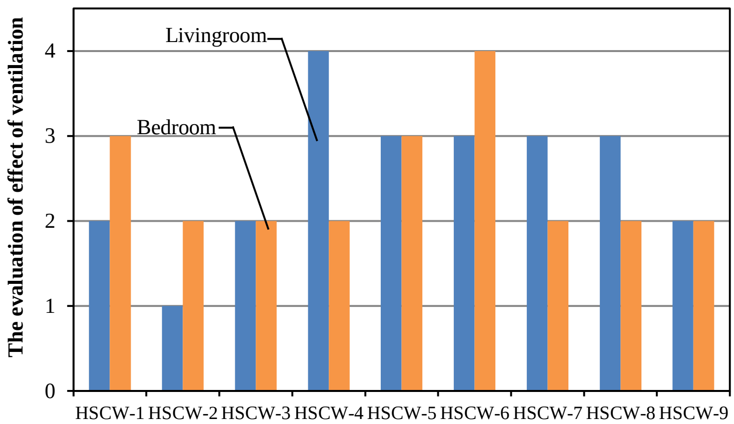


Figure 4-22 Air conditioning cooling capacity

3. The evaluation of effect of natural ventilation

The indoor thermal environment was not only related to the service condition of the air conditioning, the full use of natural ventilation in the residence buildings also can improve the indoor thermal environment and indoor air quality, shorten the service time of air conditioning in summer, and thus the energy saving purpose of air conditioning can be achieved.

Figure 4-23 shows the evaluation results of natural ventilation effect answered by the residents. The natural ventilation effects were divided into 4 levels, level 1~4 represented the poor, general, good, and great, respectively. It can be seen that the three residents of the first measured period felt the indoor natural ventilation effect of living room was general, and even the HSCW-2 residents thought that the natural ventilation effect of living room was relatively poor. This may be because that the living room of residence HSCW-2 was separated into a storage room, the connection between north and south was not good, leading to a poor natural ventilation effect. This is one of the reasons why the temperature of living room in this residence was relatively higher. In contrast, the other residents believed that the natural ventilation effects of living room were better. In addition, most of the residents thought the ventilation effect of bedroom was general, but the HSCW-6 resident believed that the natural ventilation effect of bedroom was great.



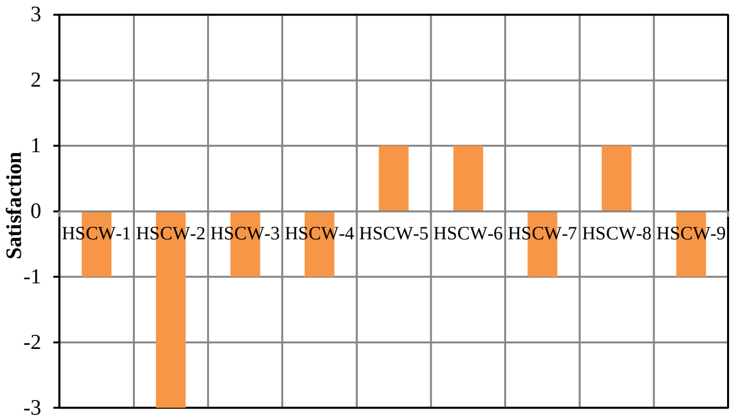

| | Ventilation effect |
|---|---|
| 1 | Poor |
| 2 | General |
| 3 | Good |
| 4 | Great |

Figure 4-23 The evaluation of effect of natural ventilation

4. Satisfaction of indoor thermal environment

1) Satisfaction

Figure 4-24 shows the satisfaction of indoor thermal environment of different residences. The satisfaction evaluation was divided into 6 levels, from-3 to 3 represented “very dissatisfied”, “dissatisfied”, “relatively dissatisfied”, “no matter”, “relatively satisfied”, “satisfied” and “very satisfied”, respectively.




| | |
|---|---|
| -3 | Very dissatisfied |
| -2 | Dissatisfied |
| -1 | Relatively dissatisfied |
| 0 | No matter |
| 1 | Relatively satisfied |
| 2 | Satisfied |
| 3 | Very satisfied |

Figure 4-24 Satisfaction of indoor thermal environment

It can be seen that only the satisfaction of indoor environment in residence HSCW-5, HSCW-6 and HSCW-8 presented +1 which meant the occupants were relatively satisfied with the indoor thermal environment. The satisfaction values of indoor thermal environment in the other residences all were negative, which meant the occupants were relatively dissatisfied with the indoor thermal environment, and even the residence HSCW-2 felt very dissatisfied. This may be due to higher indoor temperatures and relatively poor ventilation effect. Even if the indoor temperature was the main factor affecting the comfort, but the reasons for this dissatisfaction may differ from one another. For example, the indoor temperature of residence HSCW-4 was not higher than that of the other two residences measured during the same period, but the occupants of residence HSCW-4 still were dissatisfied with the indoor thermal environment.

2) Reasons for dissatisfaction

Figure 4-25 shows the reasons for dissatisfaction of indoor thermal environment in the different residences. It can be seen that the reasons for dissatisfaction in summer were mainly the residents felt sweaty and moist. This is due to the relatively humid and hot climate in summer of Hangzhou, not only the indoor temperature was relatively high but also the relative humidity was larger. At high humidity, too much skin moisture tended to increase discomfort. Therefore, the residences in this region should take some corresponding measures to dehumidification and reduce the indoor humidity, and thus the discomfort caused by the high humidity can be reduced. For some residences, the residents felt hot and face flushed with hot. In addition, some residents selected the “Parts of the body feel cold and hot”. Residents felt head hot, but felt the shoulders cooler. This may be because that the indoor blowing direction of air conditioning was accustomed to point right at the upper part of the body, the cold blowing wind of air conditioning led to the cool shoulders. Some residents selected I- others. Of which, the residents of residence HSCW-3 thought that the indoor temperature distribution was not uniform, the temperature where was close to the air outlet of air conditioning was relatively low, and the temperature where was far from the outlet was still relatively high. In addition, the indoor top and bottom temperature was also not uniform, the temperature around the feet was relatively low, but the head felt hot. The residents of residence HSCW-4 presented that due to the topmost and the intensity of solar radiation was greater in summer, the shading measures cannot play a good role, the indoor temperature was very high at noon, and the balcony outside the living room was relatively narrow, the residents felt very dry in the living room at noon.

The reasons of 「-1．Relatively dissatisfied」~「-3．Very dissatisfied」(Multiple choice)

| | |
|---|---|
| A | Feel hot |
| B | Feel cold |
| C | Feel cold-blast air |
| D | Feel sweaty |
| E | Feel flushed face with hot |
| F | Feel moist |
| G | Feel dry |
| H | Parts of the body feel cold and hot |
| I | Others |

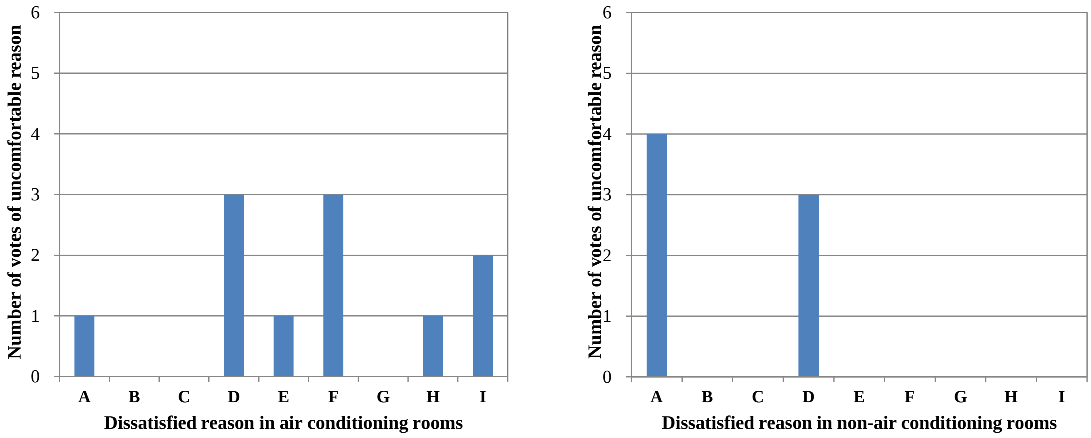



Figure 4-25 Reasons for dissatisfaction

5. Energy consumption

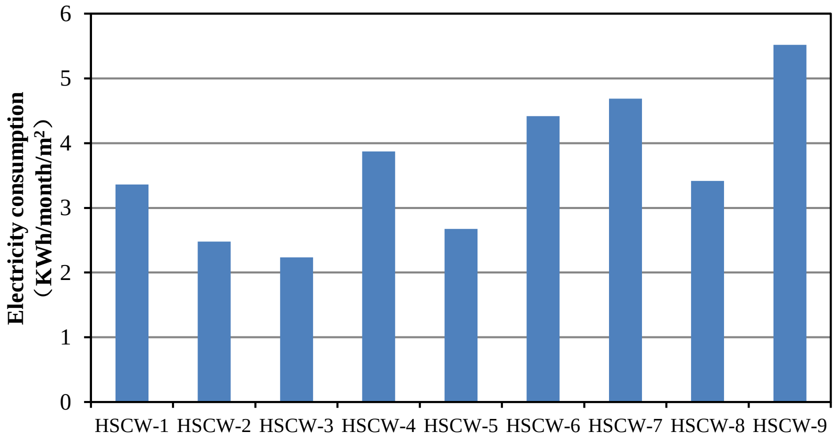



Figure 4-26 Average monthly electricity consumption in summer

Figure 4-26 shows the average monthly electricity consumption in July and August. It can be seen from that residence HSCW-9 had the largest monthly total electricity consumption, which about 5.51kWh/$m^2$. Not only the smaller construction area, but also the habit of using of air conditioning during the day when solar radiation intensity was strong led to this result. Residence HSCW-3 had the minimum monthly electricity consumption, only about 2.23kWh/$m^2$. The shorter use time (only about two days a week) of air conditioning played an important role.

### 4.3.3 Measured results in Guangzhou

#### 4.3.3.1 Air conditioning operation pattern

Because the indoor thermal environment in Hot Summer and Warm Winter Zone is not only directly related to the outdoor temperature but also affected by the service condition of indoor air conditioning or other cooling equipment. Therefore, the service condition of air conditioning including the service time, setting temperature and switching behavior should be discussed and clarified at first in this zone.

By applying statistical analysis to the questionnaire data, the schedule of cooling equipment in the nine residences including air conditioning and electric fan as well as natural ventilation by opening windows were obtained, as shown in Figure 4-27.

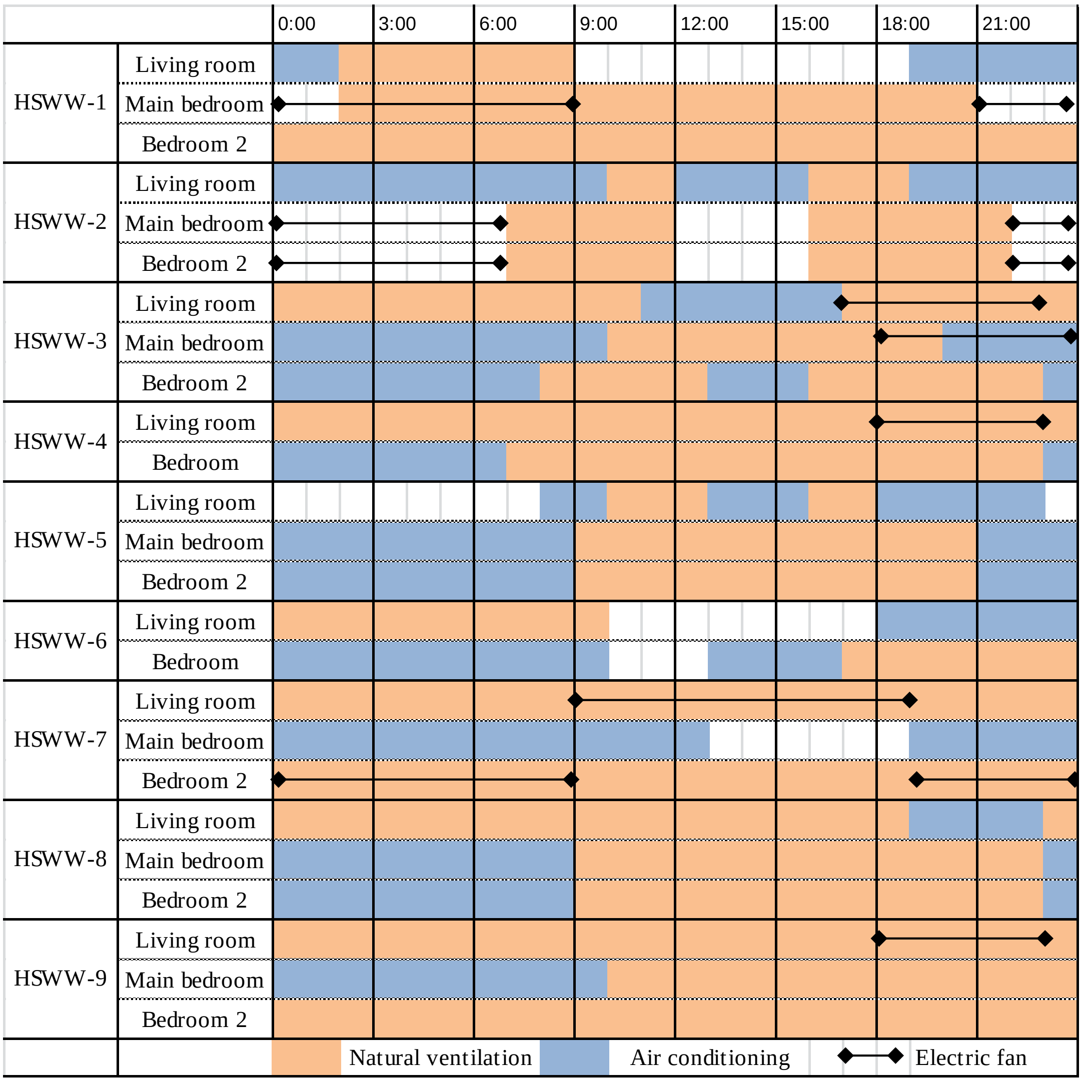



Figure4-27 Cooling equipment and natural ventilation schedule of each residence

The service time of air conditioning and electric fans as well as natural ventilation time of different residences varied from each other. Most residences only used the air conditioning for cooling during the night (23:00~9:00) and opened the window for ventilation in the daytime in bedroom. This kind of air conditioning behavior is almost the same as that of Hangzhou. This may reflect both the climatic characteristics and the lifestyle of the residents. Compared with the other three climate zones in China, the average outdoor temperature in summer of Guangzhou which was located in Hot Summer Warm Winter and Hangzhou which was located in Hot Summer Cold Winter is higher. The temperature difference between day and night was little, and it was stuffy and calm in the night. Therefore, most of the residents were accustomed to using air conditioning for cooling as they sleep at night. But there were also individual bedrooms that did not use air conditioning during the night. For example, residence HSWW-7 only used electric fan for cooling at night. And the air conditioning were also used for cooling during the lunch break in bedroom such as bedroom2 in residence HSWW-3 and bedroom in residence HSWW-6.

In contrast with bedroom, the service time of air conditioning in the living room was concentrated in the afternoon (12:00~16:00) and evening (18:00~23:00). The residents who used the air conditioning in the daytime were mostly the old and the children who were at home throughout the day. The use of air conditioning in the evening mostly reflected the leisure period after dinner spent in the living room. In addition, residence HSWW-1 and HSWW-2 only used the air conditioning in the living room including the sleeping time at night. This was attributed to the desire to save energy and the distinctive room plan of the buildings. As the living rooms of these two residences were located opposite to the two bedrooms, the air conditioning in the living room can cool the two bedrooms simultaneously by opening the door between them. Moreover, the electric fan had a secondary cooling effect. Residence HSWW-4, HSWW-7 and HSWW-9 hardly ever used the air conditioning in the living room, with cooling provided mainly by electric fans.

In addition to the qualitative description by questionnaire on the schedule of the cooling method, through the analysis on the indoor temperature curves within 5 days in a typical period, the quantitative statistics of actual indoor temperature when using air conditioning and daily accumulated use time of air conditioning were also conducted. For comparative analysis, the setting temperature obtained from questionnaire survey also collected at the same time, as shown in Figure 4-28. From the point of view of one single room, daily average accumulated use time of air conditioning in the living room of residence HSWW-2 was the longest, which was about 15.2h. Daily average accumulated use time of the living room in residence HSWW-3 was the shortest except for residences that do not use air conditioning. As for the total daily accumulated use time of air conditioning in all rooms of one residence, the residence HSWW-8 had the first place, which was about 25.4h, it was followed by residence HSWW-3, which was about 25h. The total daily accumulated use time of air conditioning in all rooms of residence HSWW-4 was the shortest, only about 2.26h during the calculated 5 days.

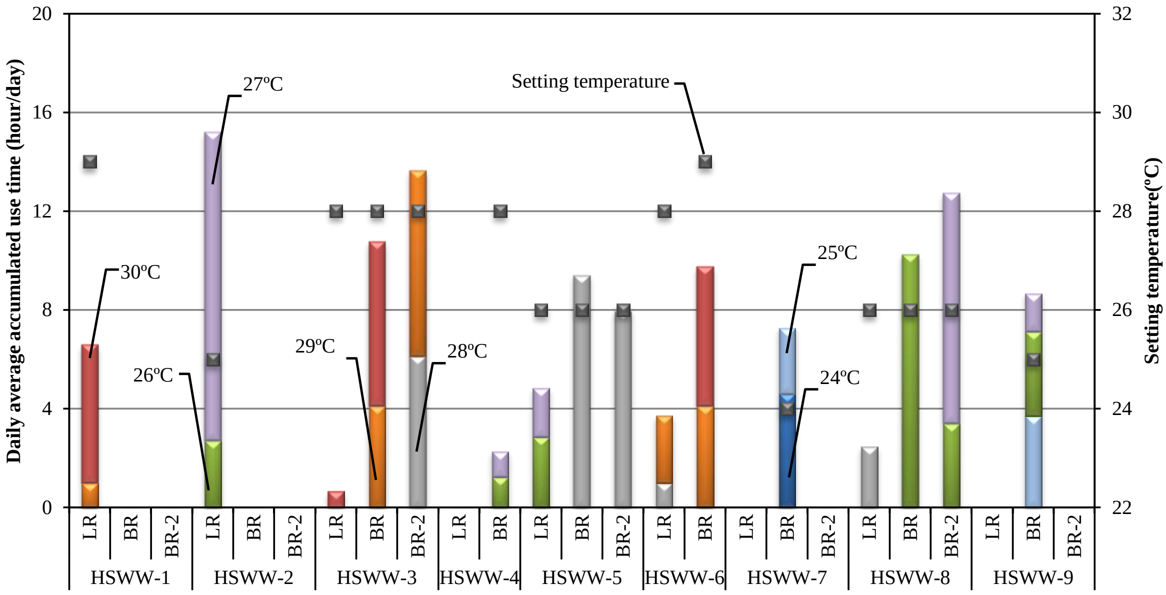



Figure 4-28 Daily average accumulated use time and setting temperature of air conditioning

Moreover, because of the different monitoring point's position and solar radiation conditions, there was a difference between the setting temperature and actual indoor temperature when using air conditioning. The setting temperature of air conditioning in most residence were 26ºC and 28ºC. However, the setting temperature of air conditioning in the living room of residence HSWW-1 and bedroom of residence HSWW-6 were relatively higher, as high as 29ºC. Maybe it is because that the two families both have babies, considering that the requirement of baby to indoor temperature was relatively lower than adults and baby will feel uncomfortable with the draft sensation of air conditioning, the setting temperature of air conditioning was relatively higher. In addition, it is worth noting that the setting temperature of air conditioning in the living room of residence HSWW-2 and main bedroom of residence HSWW-7 were 25ºC and 24ºC, respectively. This temperature was lower than the design standard of air conditioning temperature in summer which was specified as 26ºC[5].

In addition, the actual indoor temperature when using air conditioning in different residences also differed from each another as can be seen from Figure 4-28. The actual indoor temperature when using air conditioning were almost all higher than the setting temperature. Compared to other residences, because the setting temperature was higher the actual indoor temperature when using air conditioning in residence HSWW-1, HSWW-3 and HSWW-6 were relatively higher, even as high as 30ºC, it had exceeded the comfort temperature range in summer specified by

ASHRAE(6). However, as a result of the lower setting temperature of air conditioning, the actual indoor temperature when using air conditioning in residence HSWW-7 hovered between 24ºC and 25ºC. In addition to the above higher and lower setting temperature of air conditioning, the setting temperature of air conditioning of other residences were generally between 26~29ºC.

The setting temperature of air conditioning can directly affect the indoor thermal environment quality and the level of energy consumption. An excessively high setting temperature will lead to the deterioration of indoor thermal environment. However, an excessively low setting temperature will inevitably lead to more energy consumption. Previous studies(7) demonstrated that each 1ºC reduction in the setting temperature of air conditioning in summer led to an approximately 10% increase in energy consumption in Hot Summer Cold Winter zone. The thermal environment and energy consumption should be comprehensively considered to design the setting temperature of air conditioning depend on the human thermal sensation in different regions.

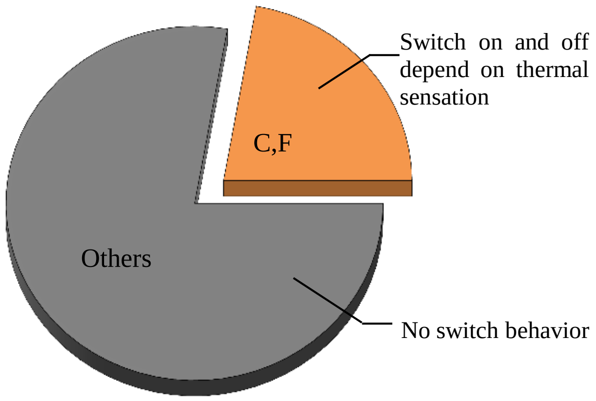



Figure 4-29 Switch behavior of air conditioning

Furthermore, the switch on-off behavior of air conditioning can also indirectly affect the energy consumption. There was almost no switch behavior of air conditioning in most of surveyed residences, as shown in Figure 4-29. However, the residence HSWW-4 and HSWW-6 both were used to switching on the air conditioning when they felt hot, and turning off when they felt cool, and restart when they felt hot. This switching behavior depended on the residents' thermal sensation may be adopted because the transition of human thermal sensation will take a certain time and there existed the “Hysteresis” phenomenon in thermal sensation.

4.3.3.2 Field measurement results

1. Indoor and outdoor temperature and relative humidity during the measured period

(1) Indoor and outdoor temperature

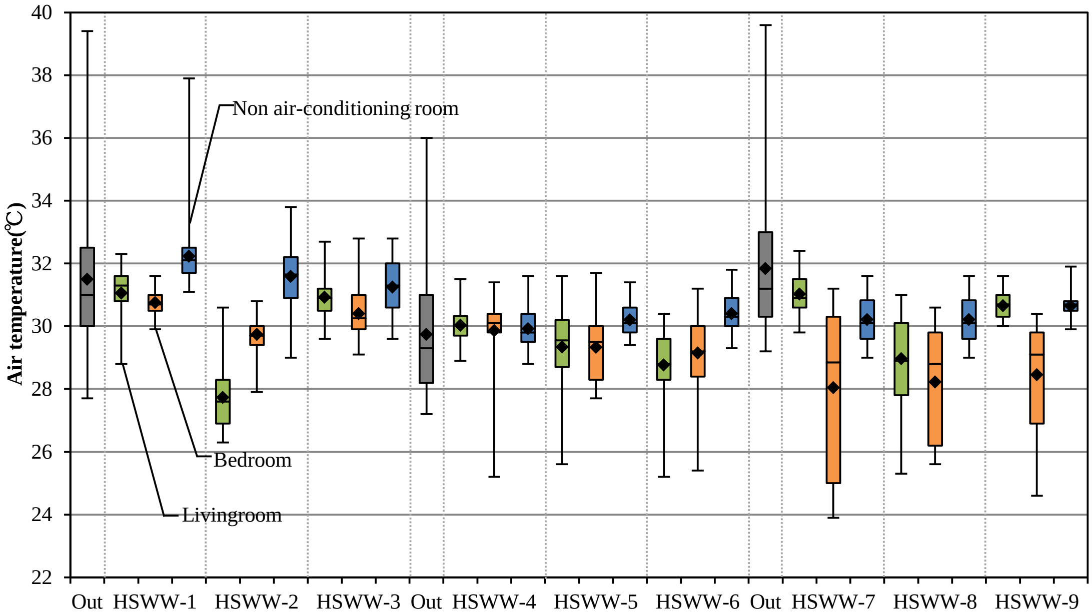



Figure 4-30 Temperature distribution during the measured period in summer in Guangzhou

Figure 4-30 shows the indoor and outdoor temperature distribution in the different residences. The indoor temperature distribution is not only directly related to the outdoor temperature but also affected by the service condition of indoor air conditioning. The variations of outdoor temperatures during the three measured periods were all dispersed, were at (27.7~39.4ºC), (27.2~36ºC) and (29.2~39.6ºC), respectively. As can be seen from the temperature distribution in the first and third measured period, the outdoor temperature was relatively higher. The average temperature was approximately 32ºC, with a maximum higher than 39ºC. Compared with the other two measured periods, because the average outdoor temperatures during the measured period of 8/4~8/17 were lower by about 2ºC, the indoor temperatures of each room of residence HSWW-4, HSWW-5 and HSWW-6 were mostly concentrated in the range of 28~30ºC. Although the air conditioning was not used in the living room of residence HSWW-4 and always cooled by natural ventilation only, the average indoor temperature still maintained at around 30ºC. The lower setting temperature and longer accumulated use time of air conditioning in the living room of residence HSWW-2 led to the lowest indoor average temperature among all measured residences, which was approximately 27.5ºC. However, although the residence HSWW-1 and HSWW-3 used the air conditioning during the measured period, the setting temperature of air conditioning was higher than that in residence HSWW-2, so the indoor temperature was almost distributed in the above 30ºC, and the average temperature of residence HSWW-1 even reached 31ºC. In addition, although the residence HSWW-2 only used the air conditioning in the living room, the two bedrooms can be cooled down at the same time through the air conditioning of living room at night. Because the setting temperature of air conditioning in living room was lower, the temperature distribution without the use of air conditioning in the bedroom was still lower than that in the other two residences.

Moreover, due to the higher outdoor temperature and generally lower setting temperature of air conditioning in the residences during the third measured period, so there was a significant difference in indoor temperature distribution between the rooms using air conditioning and the rooms without using air conditioning. In the room using air conditioning, because the setting temperature of air conditioning was generally lower, the average indoor temperature was around 28ºC. In rooms where cooling relied only on natural ventilation and auxiliary cooling by an electric fan, the indoor temperature was higher, with an average of approximately 31°C. For example, residence HSWW-7 and HSWW-9 hardly ever used the air conditioning in the living room, with cooling provided mainly by electric fans. So the indoor temperature of livingroom in these two residences were higher than that of bedroom, and even higher that of non-air conditioning room. In addition, it can be seen from the indoor temperature distribution, the temperature distribution of rooms using air conditioning was more widespread, while more concentrated for rooms without the use of air conditioning, which indirectly indicated that the temperature difference between daytime and night-time of outdoor temperature in Guangzhou city was small.

Furthemore, the average temperature of non-heating room of most residences were over 30ºC. The temperatures of non-heating rooms of residence HSWW-1 was the highest, the average temperature was around 32ºC. This may be because the monitoring point of non-air conditioning room was set in kichen which was located in the west. The heat generated by the cooking as well as the window with a western exposure resulted in the higher temperature of non-heating room in residence HSWW-1. Because the outdoor temperature was not high, the temperature of non-heating rooms of residences during the second measured period were lower than other two measured period. It was almost same as the other rooms in residece HSWW-4, and only about 1ºC higher than livingrooms and bedrooms in residence HSWW-5 and HSWW-6.

(2) Indoor and outdoor relative humidity

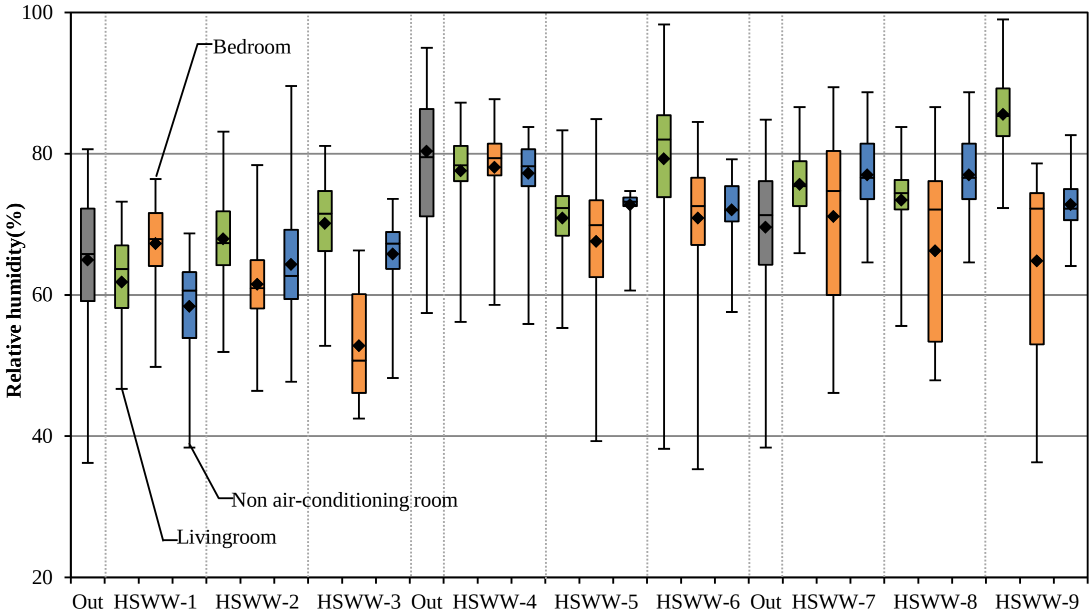
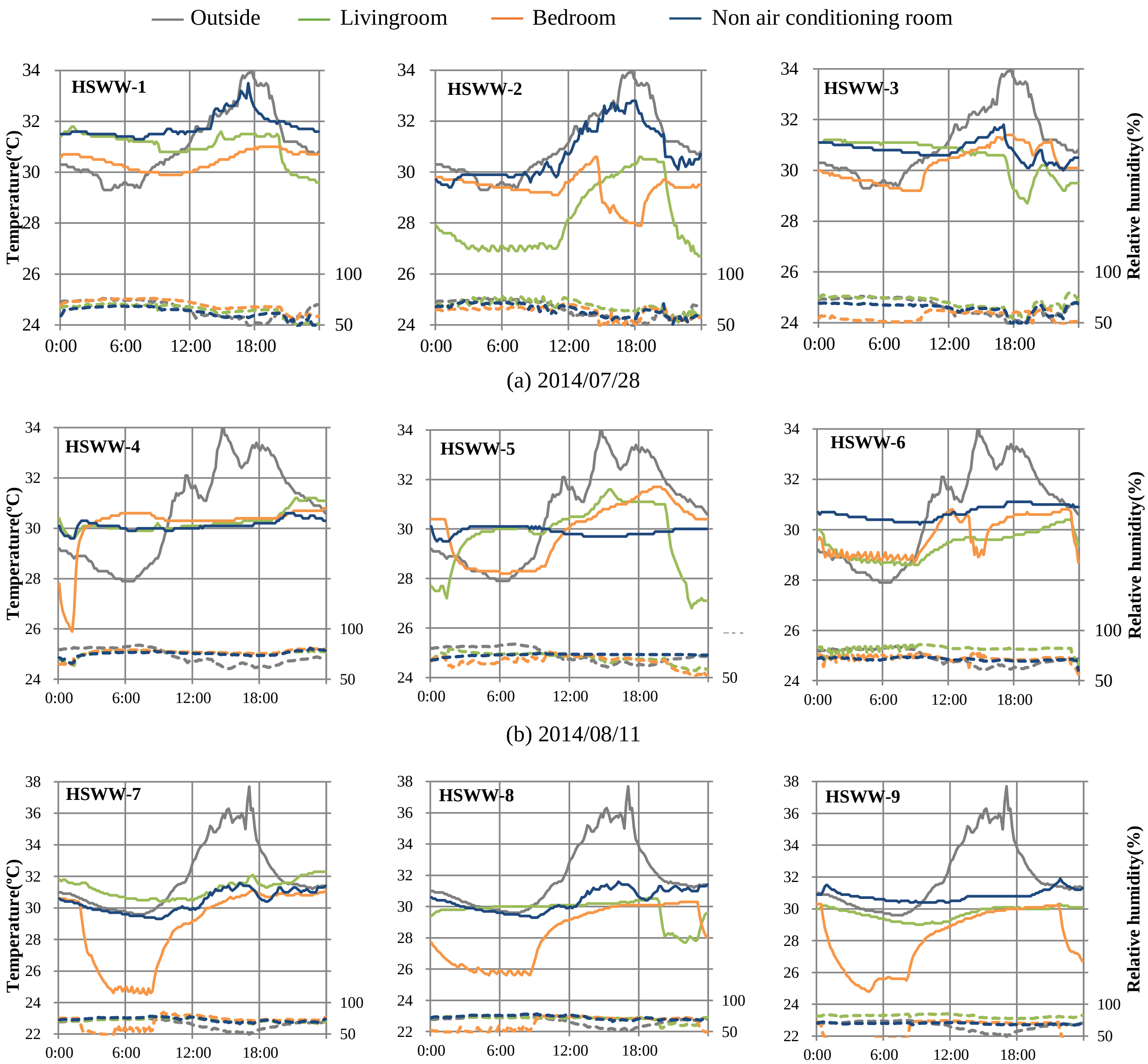



Figure 4-31 Relative humidity distribution during the measured period

Figure 4-31 shows the indoor and outdoor relative humidity distribution during the summer measured period in Guangzhou. The outdoor relative humidity in the second measured period was relatively higher than other two measured period. Overall considering the lower outdoor temperature and higher relative humidity, it can be inferred that overcast and rainy appeared in the second measured period. The average values of three period were about 64.9%, 80.3% and 69.5%, respectively.

The distribution of relative humidity of most residences in most of the time concentrated in about 60~80%. According to Chinese specification <Design code for heating ventilation and air conditioning of civil building>, the comfortable indoor relative humidity range was 40%~65%. Therefore, the relative humidity in summer was slightly higher than the comfortable humidity range. Even to the extent that, the average relative humidity in the living room of some residences were higher than 80%. This may be because these several residents were accustomed to having dinner in the living room, and the measuring points were just located in the vicinity, leading to the larger relative humidity. In addition, the relative humidity of bedroom was higher than that in livingroom in most surveyed resideces. This is because the majority of residences used the air conditioning in the bedroom for a longer time. The use of air conditioning can not only reduce the temperature but also play a role in reducing relative humidity.

2. Variation curve of indoor and outdoor temperature and humidity in a typical day




(a) 2014/07/28

(b) 2014/08/11

(c) 2014/08/23

Figure 4-32 Variation curve of indoor and outdoor temperature and humidity in a typical day

Figure 4-32 shows the variation curve of indoor and outdoor temperature and humidity in a typical day. It can be clearly understood the service time of air conditioning from the curve. Fig. (a) shows the variation curves of indoor and outdoor temperature as well as humidity in a typical day during the first measured period. It can be seen that the outdoor temperature reached the maximum at around 18:00pm, and the temperature fluctuation range within 1 day was between 29.3~34ºC. The temperature difference between day and night was not as big as other measured period. Compared to the other residences, residence HSWW-1 only used air conditionging for a while (20:00~24:00) in the livingroom during the night. And there was no traces of using air conditioning in bedroom. However, the temperature of bedroom was lower than that in living room in most of time. This is because the bedroom is located in the north, the solar radiation heat gain was less than livingroom. Due to the unique using method of air conditioning that the two bedrooms were cooled by the air conditioning in the living room simultaneously, the temperature of livingroom in residence HSWW-2 maintained at about 27ºC during the night(20:00~10:30). Although the door between the main bedroom and livingroom was opened during the night, the main bedroom was farther away from the living room than bedroom2, the temperature of main bedroom only reduced by less than 1ºC than non-air conditioning room. The temperature of main bedroom had a decrease between about 15:00~18:00 benefited from the using of air conditioning in mainbedroom. Because the setting temperature was relatively higher, even though air conditioning was opened during the night in bedroom of residence HSWW-3, the temperature only maintained at about 29ºC. The service time of air conditioning in the living room was only the dinner time. The indoor temperature of non-air conditioning room in residence HSWW-1and HSWW-2 changed significantly along with the outdoor temperature, while changed slightly little in residence HSWW-3. This is because the measuring point of non-air conditioning room was placed in the entrance where communicated with the living room. The measured point was not affected by the heat of solar radiation, and affected by the service condition of air conditioning in livingroom.

Fig. (b) shows the variation curves of indoor and outdoor temperature as well as humidity during the second measured period. It can be seen that although the outdoor temperature had the maximum of 34ºC. There were two large floating reduction because of the overcast. Although three residences all used air conditioning in bedroom, the service lengths were different. Residence HSWW-4 had the shortest using time of air conditioning which was only a while at night. The using time of air conditioning in residence HSWW-6 was the longest including the whole night and break after lunch. In addition to the service lengths were different, the temperature when use air conditioning were also different. Though existing for a relatively short time, the temperature of bedroom in residence HSWW-4 was the lowest which was 26ºC. The temperature when use air conditioning hovered at about 28ºC and 29ºC respectively in the bedroom of residence HSWW5 and HSWW-6. In addition, the air conditioning was not used in livingroom of residence HSWW-4, while were used in other two residences. The residence HSWW-5 used air conditioning for cooling as entertainment after dinner in the living room, the setting temperature was relative lower than that in bedroom. However, the air conditioning in the livingroom in residence HSWW-6 was used during the whole night. May guests staying in living room led to this results. The temperature of non-air conditioning room changed little in all three residences, maintain at about 30ºC~ 31ºC.

Fig. (c) shows the variation curves of indoor and outdoor temperature as well as humidity in a typical day during the third measured period. It can be seen that the maximum outdoor temperature of the third measured period was increased by about 4ºC. The temperature fluctuation range within 1 day was between 29.6~37.7ºC. Therefore, due to the higher outdoor temperature and generally lower setting temperature of air conditioning in the residences during the third measured period, so there was a significant difference in indoor temperature distribution between the rooms using air conditioning and the rooms without using air conditioning. Three residences all used air conditioning for cooling in bedroom during the night. The temperature when used air conditioning maintained at about 25ºC in the bedroom of residence HSWW-7 and HSWW-9, while was 26ºC in residence HSWW-8. Only the residence HSWW-8 used air conditioning after dinner in the livingroom. And there were no traces of using air conditioning in livingroom in other two residences. The temperature of rooms which did not use air conditioning were higher in residence HSWW-7. This may be because the residence HSWW-7 was located in the lower layer, the ventilation condition was poor.

3. ASHRAE comfort zone

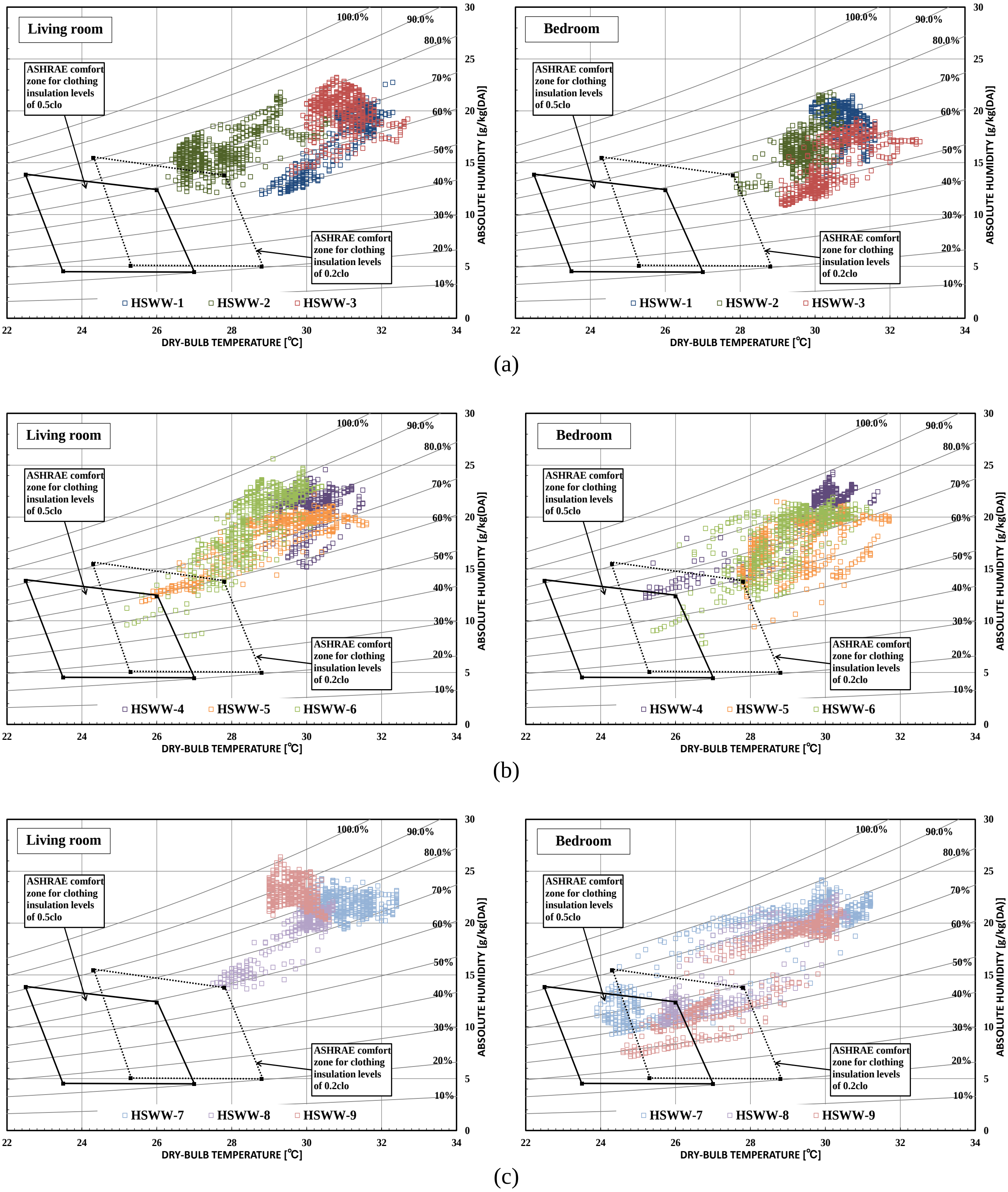



Figure 4-33 Indoor temperature and relative humidity distribution and ASHRAE comfort zone in summer

Figure 4-33 shows the indoor temperature and relative humidity distribution as well as the location of ASHRAE comfort zone in summer in Guangzhou. The use of air conditioning results in different indoor thermal environment, and the habits of using air conditioning in living room and bedroom of different residences were also different. Therefore, the indoor thermal comfort condition of living room and bedroom was both evaluated by the ASHRAE comfort zone.

It can be seen that there was obvious difference between the indoor temperature of living room of residence HSWW-2 and that of other two residences. Because of the using of air conditioning and lower setting temperature, the temperature of living room of residence HSWW-2 was concentrated in 26~28ºC for most of time, while over 30ºC in residences HSWW-1 and HSWW-3. However, the temperature was still higher than the upper limit of ASHRAE comfort zone, there was no data falling into the ASHRAE comfort zone for clothing insulation levels of 0.5clo. Similarly, the ASHRAE comfort zones for less clothing levels can be approximated by increasing the temperature borders of this zone by 0.6K for each 0.1clo increase of clothing insulation, the comfort zone moved to the right along with the reduction of clothing insulation. After moving, only a portion of the indoor temperature and humidity data of residence HSCW-2 fell into the ASHRAE comfort zone for clothing insulation levels of 0.2clo. It seems there was not much difference among the indoor temperature and relative humidity distribution of bedroom in three residences during the first measured period. Due to the higher temperature and relative humidity, there was no any data falling into the ASHRAE comfort zone for clothing insulation levels of 0.5clo as well as 0.2clo.

Although the three residences used air conditioning during the third measured period, and the setting temperature were 26ºC and 28ºC, the indoor actural temperature distributions of livingroom and bedroom in all three residences were still over 28% for most of the time. Residential indoor relative humidity were mainly distributed over 60ºC. There was also little data falling into the ASHRAE comfort zone for clothing insulation levels of 0.2clo. After moving with the reduction of clothing insulation, a few data of livingroom in residence HSWW-5 and HSWW-6 as well as the bedroom in residence HSWW-4 and HSWW-5 fell into the comfort zone.

Because residence HSWW-7 and HSWW-9 did not use air conditioning in living room during the measured period, the temperature were both higher 29ºC. And the relative humidity were higher than 70%. So the temperature and humidity data distributions of the livingroom of residence HSWW-7 and HSWW-9 are far away from the ASHRAE comfort zone. Although the air conditioning in the living room was used for entertainment after dinner in residence HSWW-8, the indoor temperature of living room when using the air conditioning was still higher than the comfort temperature specified by the ASHRAE. Therefore, the temperature and humidity data in the living room of the residence HSWW-8 still did not fall into the comfort zone.

Because the setting tempereture of air conditioning in the bedroom was relatively lower, leading to the lower indoor temperatures of the bedrooms of the three residences during the third measured period, the temperature distribution was between 24~28ºC at most of the time. Moreover, the relative humidity of bedroom was somewhat reduced than that of living room. Therefore, the temperature and humidity data of bedroom of these three residences fell into the ASHRAE comfort zone for clothing insulation levels of 0.5clo. After moving along with the reduction of clothing insulation, the data falling into the comfort zone became more.

4. Predicted Mean Vote (PMV)

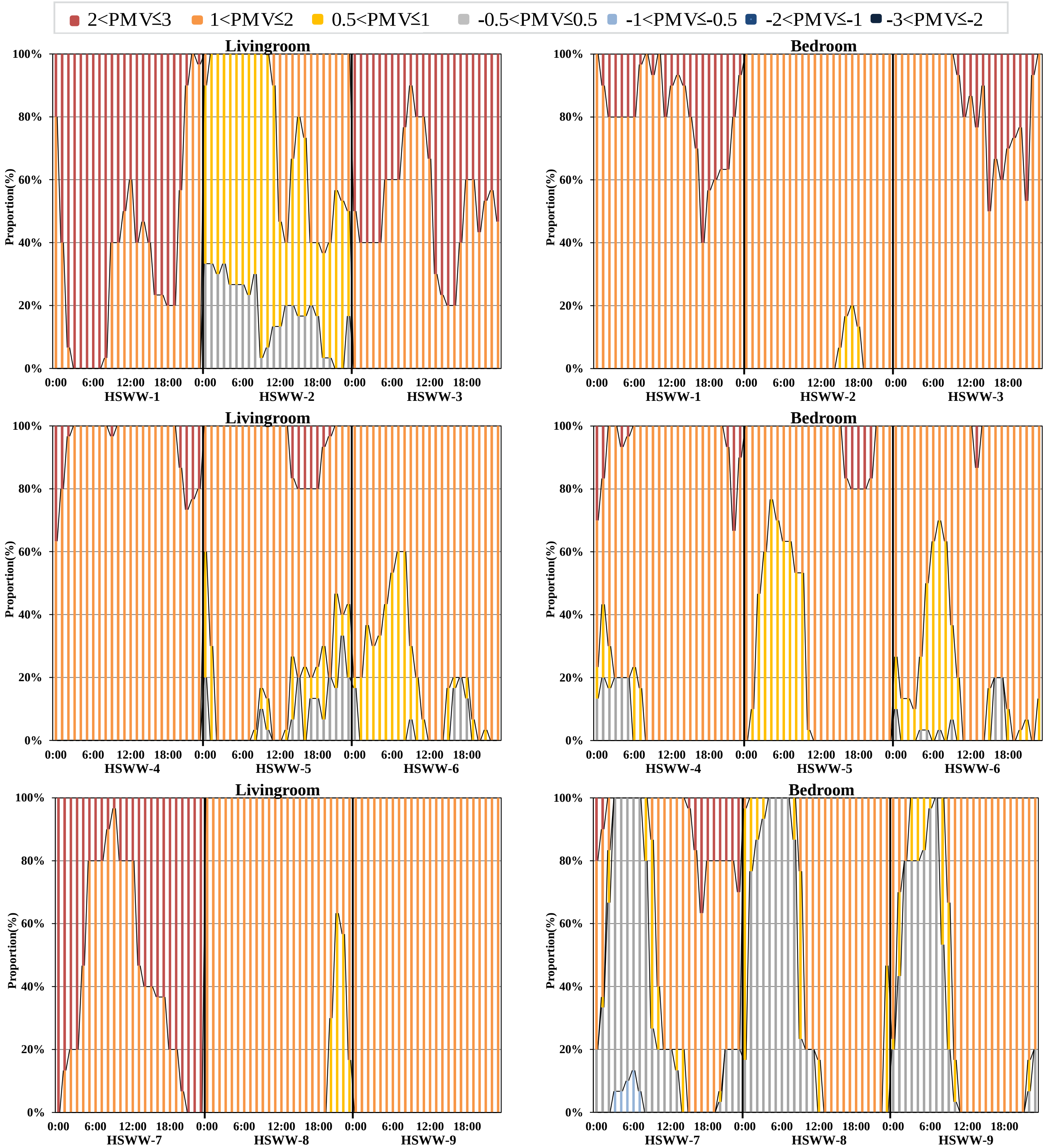


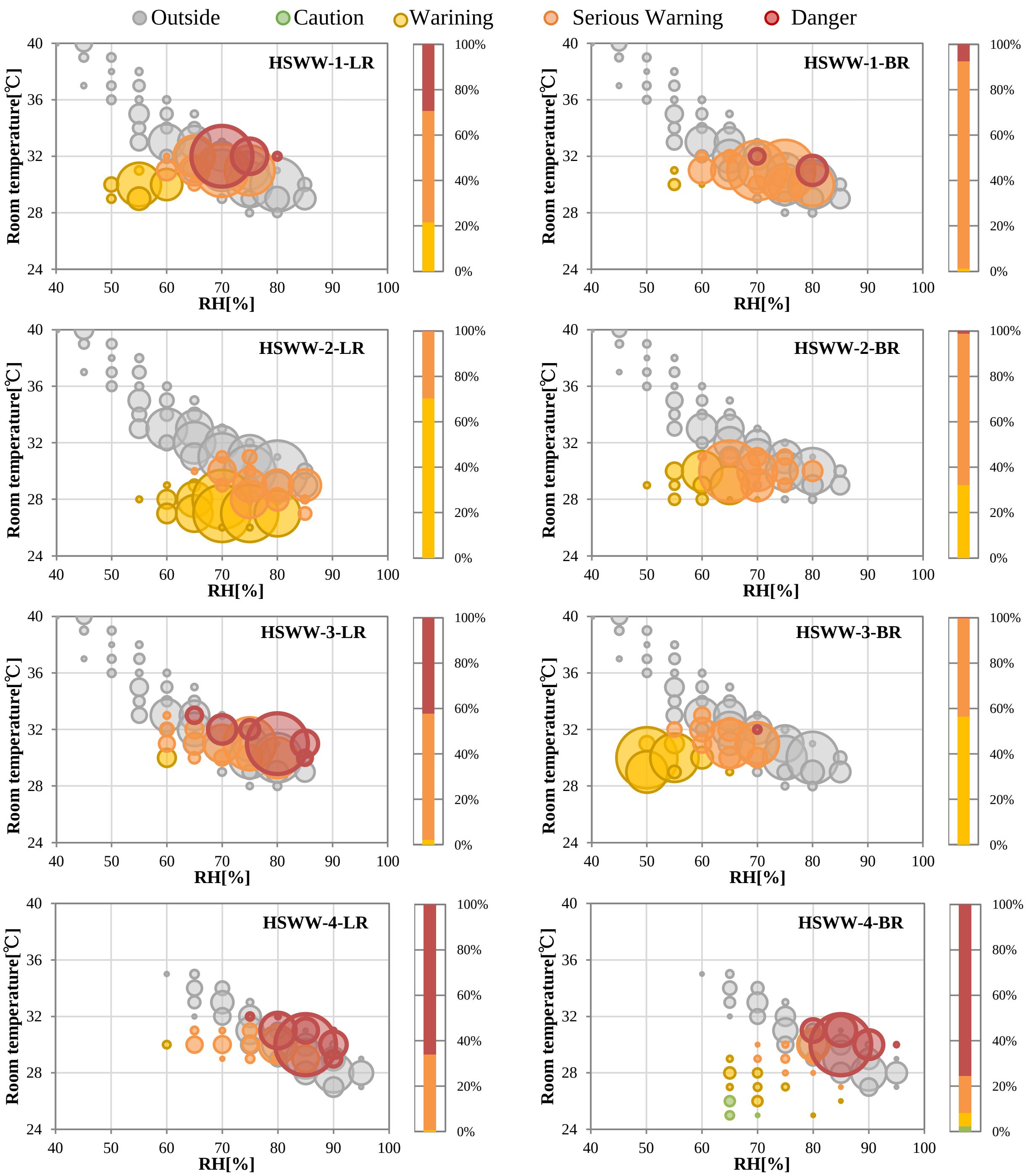

Figure 4-34 Proportion of PMV in summer of Hangzhou

（Annotation: PMV's calculation condition: M=1.2met, v=0.25m/s）

Figure 4-34 shows the proportions of PMV values of the living room and bedroom of three residences in summer of Guangzhou during different measured periods. Compared with the PMV values and its proportions of indoor thermal environment of these three residences during the first measured period, it can be seen that the indoor thermal environment of living room in residence HSWW-2 was significantly better than those in residence HSWW-1 and HSWW-3. The PMV value of living room in residence HSWW-2 at night (23:00~9:00) was between 0.5~1 for most of the time, and even was located in the range of -0.5~0.5 which means the residents felt comfortable for around 30% of the time. However, the proportion of comfort in the living room was reduced in the morning (9:00~11:00) and entertainment time after dinner in the evening (19:00~23:00). The reason for the decline in the proportion of comfort at noon was the use frequency of air conditioning was relatively lower in this period of time, leading to an increase of indoor temperature. The residents were all located in the living room after dinner, the more personnel heat radiation may be the main reason for the decline in the proportion of comfort in the evening. In contrast, the proportion that the PMV values for indoor thermal environment of living rooms in residence HSWW-1 and HSWW-3 were located in 2~3 which means residents felt hot both accounted for more than 50%. In particular, the proportion that the PMV value of living room in residence HSWW-1 in the morning (3:00~8:00) was located in 2~3 reached up to 100%. The PMV values for indoor thermal environment of living rooms in these three residences during the first measured period were all located in 1~2 which means the residents felt slightly hot for most of the time. Compared to the living room, the indoor thermal environments of bedrooms in residence HSWW-1 and HSWW-3 were improved slightly, the PMV value was increased at around 18:00 in the afternoon.

Compared to the first measured period, due to the slightly decline of outdoor temperature and the use of indoor air conditioning, the PMV values for indoor thermal environment in these three residences during the second measured period were located in 1~2 which means the residents felt slightly hot for most of the time, but located in 2~3 for a fraction of the time. Meanwhile, there was not big difference in the PMV values of living room and bedroom in these three residences. However, there was great differences in the PMV values of living room and bedroom in these three residences during the third measured period. The PMV value for indoor thermal environment of living room in residence HSWW-7 at night was located in 2~3 for most of the time, the PMV value during the day was decreased. However, the proportions of comfort in the bedrooms of these three residences between 0:00~12:00 were almost close to 100%, and the PMV value was increased to 1~2 in the afternoon, the comfort was reduced.

5. Heatstroke possibility evaluation by WBGT



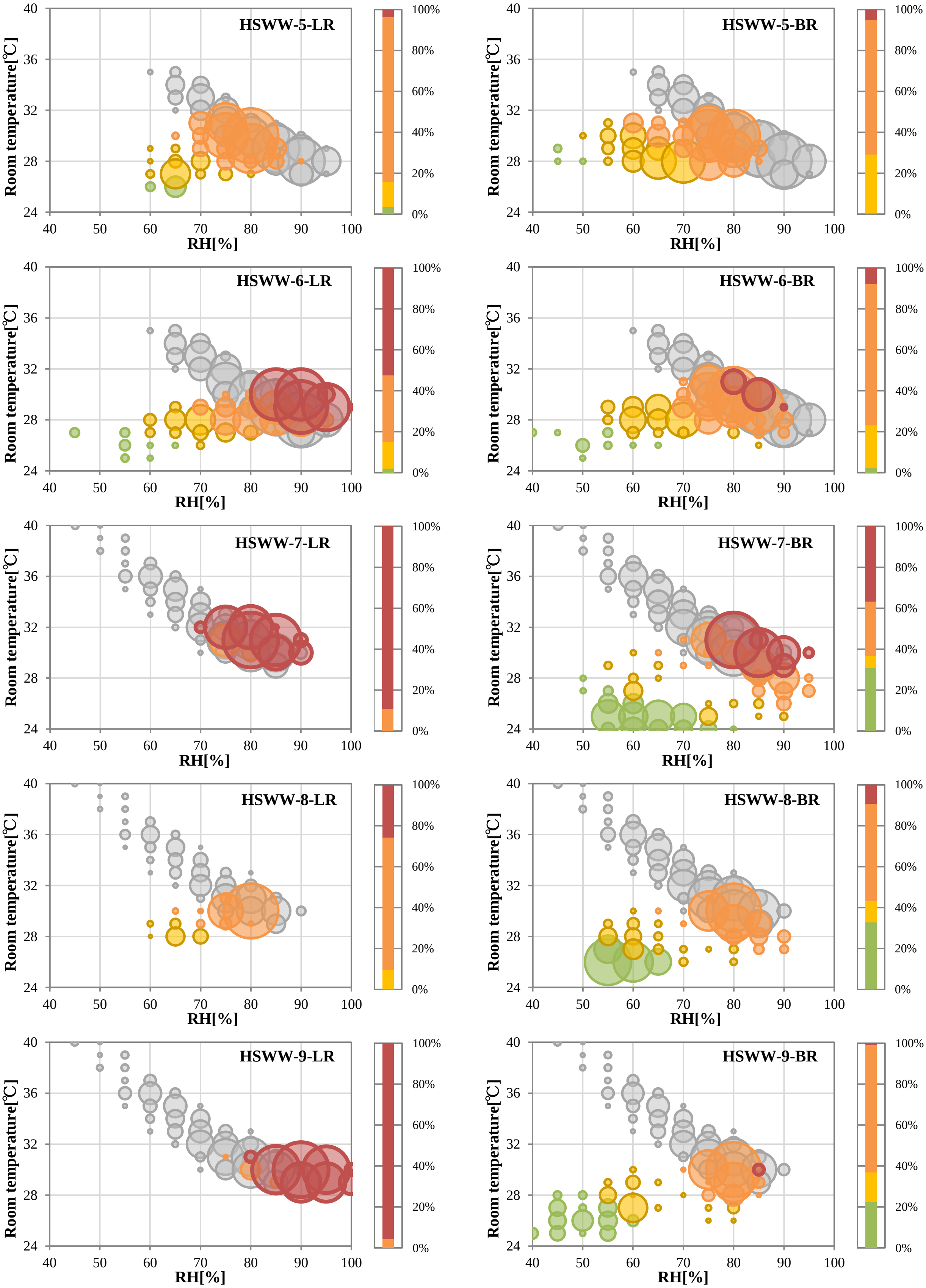



Figure 4-35 Temperature and humidity distribution and heatstroke

Figure 4-35 shows the temperature and relative humidity distributions of living room and heat stroke risk as well as its proportion in Guangzhou during different measured periods. the risk of heat stroke in livingroom and bedroom were both evaluated by WBGT. It can be seen that the heatstroke possibility between the rooms which used air conditioning and without using air conditioning room was completely different. More significantly, the setting temperature and service time of air conditioning had a obvious influence on the heat stroke risk of indoor thermal environment. Because the service time of air conditioning in the living room of residence HSWW-2 was longest and the setting temperature was relatively lower, the indoor thermal environment was not located in the danger zone of heat stroke, only located in the serious warning and warning zones of heat stroke for about 30% and 70% of the time, respectively. On the contrary, due to the shorter service time and higher setting temperature of air conditioning, the indoor thermal environments of the living rooms in the residence HSWW-1 and residence HSWW-3 were located in the danger zone of heat stroke for about 30% and 40% of the time respectively, which indicated a probability of heat stroke in livingroom in residence HSWW-1 and HSWW-3. Compared to the heat stroke of livingroom, only 7% of the time of the indoor thermal environment in residence HSWW-1 was located in the danger zone of heat stroke. Although the bedroom of residence HSWW-2 and HSWW-3 were not located in the region of heat stroke, the proportion of serious warning covered 67% and 43%, respectively. If the residents did not pay attention to take measures to reduce the temperature and relative humidity, there was still the possibility of heat stroke.

Compared to the residence HSWW-1 and HSWW-3, benefiting from the reduction of outdoor temperature distribution and the use of indoor air conditioning in the living room of the three residences during the second measured period, although the temperature was reduced slightly, the overcast weather as well as indoor humidity source such as having dinner in the living room resulted in a high relative humidity, which would increase the risk of heat stroke. For example, the average temperature of living room in residence HSWW-6 was only 28.5ºC, but the relative humidity reached up to more than 90% for a part of the time, causing that the indoor environment was located in the danger zone of heat stroke for above 50% of the time. However, compared with the living room, the relative humidity of bedroom reduced to below 90%, the proportion of danger of heat stroke only accounted for 8%. Moreover, because of the comprehensive effect of higher temperature and relative humidity, the residence HSWW-4 took the risk of heat stoke for 66% of the time. Because only temporary use of air conditioning in the bedroom, the proportion of danger of heat stroke even reached up to 76%. Therefore, residence HSWW-4 should take appropriate measures to prevent heatstroke.

What is more notable about these impressions is that the indoor thermal environments of residence HSWW-7 and HSWW-9 were almost all the time located in the danger zone of heat stroke. This is because that both of these two residences did not use the air conditioning in the living room where the cooling only relied on the natural ventilation and auxiliary cooling by an electric fan, leading to the higher indoor temperature with an average temperature of approximately 31°C. In addition, the higher relative humidity in the living room also increased the probability of heat stroke. As a result, the residence HSWW-7 and HSWW-9 both should take the corresponding measures to reduce the risk of indoor heat stroke such as reducing the temperature by the air conditioning and reducing the relative humidity by the desiccant. However, due to the use of air conditioning, indoor temperature and relative humidity in bedroom in residence HSWW-7 had decreased, heat stroke possibility was obviously divided into two extremes. Heat stroke possibility reduced to "Caution", while still locaed in the danger zone of heat stroke when did not use air conditioning. Because the setting temperature of air conditioning in bedroom was low, and indoor relative humidity was only distributed in 40%~60% when using air conditioning, the residence HSWW-9 was almost no data located in the danger zone.

4.3.3.3 Questionnaire survey results

1. Clothing insulation

(1) Clothing insulation value

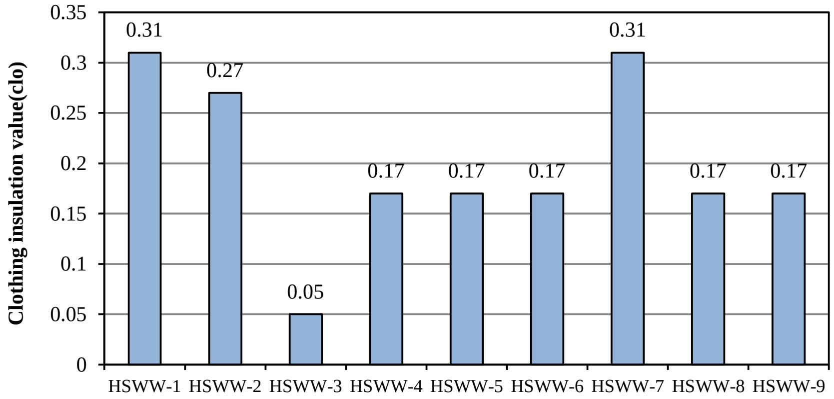



Figure 4-36 Clothing insulation value in summer in Guangzhou

Figure 4-36 shows clothing insulation values for typical indoor clothing of the surveyed residences during summer measurement in Guangzhou. The clothing insulation value of most of surveyed residences in Guangzhou was concentrated in about 0.17clo same as that in Hangzhou. In addition, the clothing insulation value of residence HSWW-1, HSWW-2 and HSWW-7 were slightly higher, about 0.3clo. The average value of clothing insulation in summer was 0.2clo. It can be seen that clothing insulation levels were also relatively lower than the ASHRAE recommended value in summer which was 0.5clo.

(2) Relationship between clothing insulation value and living room temperature

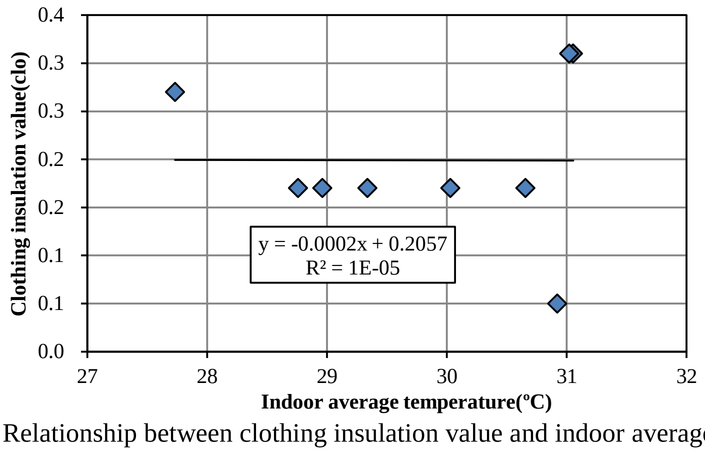



Figure 4-37 Relationship between clothing insulation value and indoor average temperature

Figure 4-37 shows the relationship between the clothing insulation and indoor average temperature in summer in Guangzhou. It can be seen that the clothing insulation shows no linear relationship with indoor temperature. In addition, the average temperature of living room in residence HSWW-1 and HSWW-7 were both over 31°C, while the clothing insulation of these two residences were the highest. This may be due to the different heat endurance.

2. Thermal comfort condition

(1) Thermal sensation vote (TSV)

1) TSV value

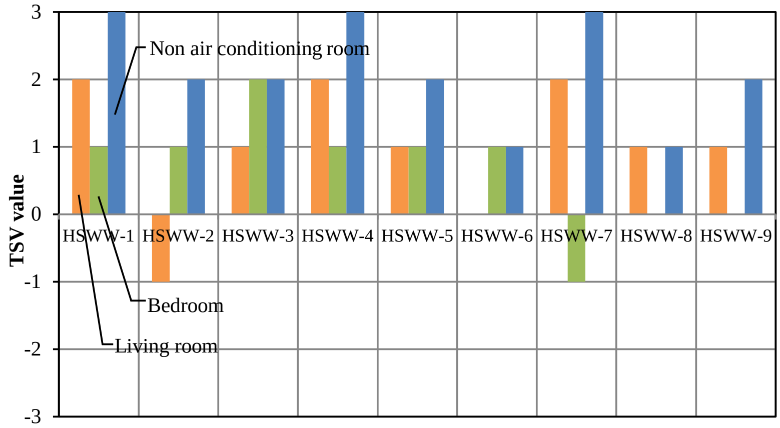



Figure 4-38 TSV value

Figure 4-38 shows the TSV value in different residences in summer in Guangzhou. It can be seen that the thermal sensations vote of most of living rooms and bedrooms were 1 or 2. This means that these residents feel the indoor environment was in a warm or slightly hot condition. Even the thermal sensation values of some non-air conditioning rooms were evaluated as 3, which corresponds to the thermal sensation of hot. Compared with the living room, the comfort of bedroom in most surveyed residences seems to move in the cooler direction by one level. Only the indoor thermal environment of living room in residence HSWW-6, bedrooms in residences HSWW-8 and HSWW-9 showed a neutral state benefitting from the using of air conditioning. In addition, the thermal sensation values of living room in residence HSWW-2 and bedroom in residence HSWW-7 were evaluated as -1 which means that these residents felt the indoor environment was in a cool condition. This is mainly because the setting temperatures of air conditioning in these two residences were lower.

2) TSV and indoor average temperature

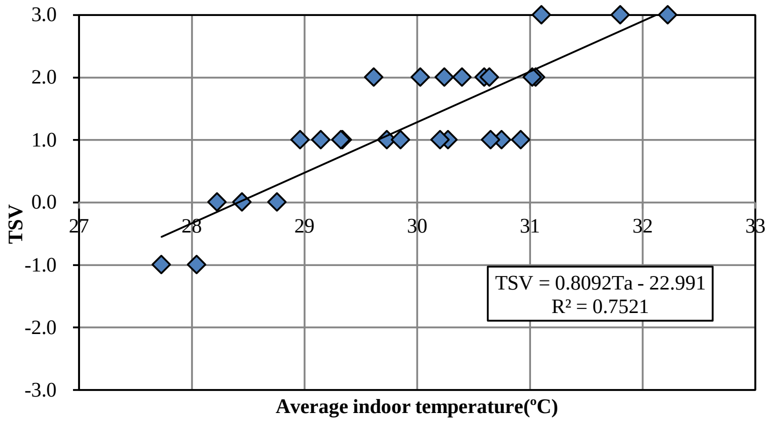



Figure 4-39 The relationship between TSV and indoor average temperature

Figure 4-39 shows the relationship between TSV and indoor average temperature in summer in Guangzhou. It can be seen that there was a relatively significant linear relationship between the subjective average thermal sensation of occupants and average indoor temperature in summer in Guangzhou. The fitting linear equation of the measured thermal sensation (TSV) and average indoor temperature (Ta) is obtained as follows:

$$TSV = 0.81Ta - 22.99 \ (R^2 = 0.75)$$

Similarly, according to the linear regression equation between the average thermal sensation and average indoor temperature, it can be obtained 28.4ºC as the thermal neutral temperature when TSV was 0 and 29.6 ºC as acceptable temperature of human body when TSV was 1 in summer in this region. Meanwhile, compared with other research results, it can be found that the thermal neutral temperature in summer of this area was higher than that of other areas. For example, the thermal neutral temperature of residents in Hot Summer and Cold Winter Zone in summer was 27.3ºC [8], while it was 25.3ºC [9] in the cold region. This illustrates that the thermal sensations of people to same temperature were different depend on different regions in summer, and the requirements or expectations to thermal comfort were also different.

3) The relationship between TSV and PMV

Figure 4-40 shows the comparison of TSV and PMV. The result shows that the subjective TSV value was far wider than calculated PMV value in summer in Guangzhou same as surveyed results in winter other cities. The indoor temperature was 24.67ºC when PMV=0, far lower than the surveyed thermal neutral temperature that was 28.4ºC. It was also proved that human comfortable temperature range in the actual thermal environment was wider than the theoretical prediction.

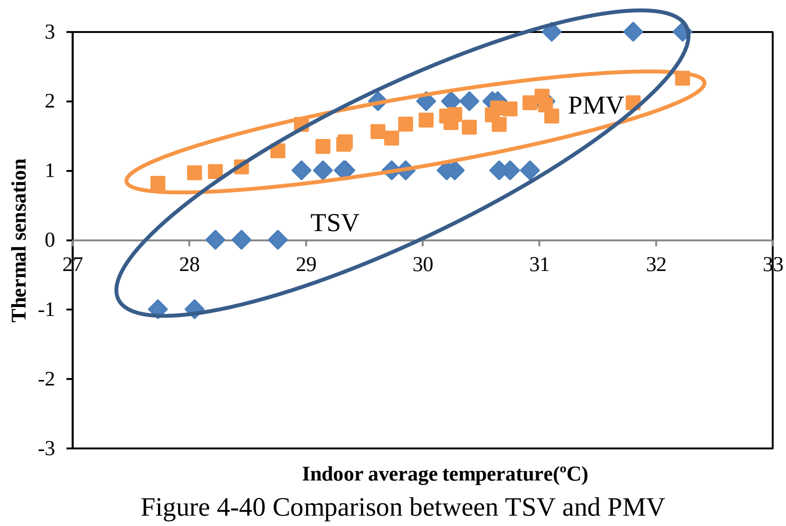



Figure 4-40 Comparison between TSV and PMV

(2) Thermal comfort vote (TCV)

1) TCV value

Figure 4-41 shows the results of thermal comfort vote about the environment in summer in Guangzhou. It can be seen that except for residence HSWW-2 and HSWW-5, the TCV values of living rooms concentrated in -1 and -2 which meant the residents were not satisfied with the indoor thermal environment. While the comfort condition of bedroom in most surveyed residences seemed better than that of living room. The TCV value of bedrooms in most residences presented +1, which meant the occupants in these two residences felt the indoor thermal environment of bedrooms slightly comfortable. In addition, the evaluation of thermal comfort in non-heating room was worse than that in heating rooms, mainly was concentrated in the -1~-2.

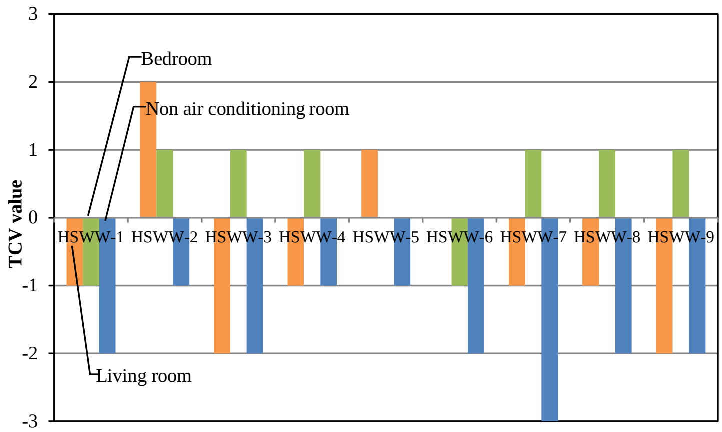



Figure 4-41 TCV value

2) Uncomfortable reason

Figure 4-42 shows the uncomfortable reason in the rooms which used air conditioning and non-air conditioning rooms. It can be seen that the uncomfortable reasons in the rooms which used air conditioning were mainly the residents felt hot overall. Because the relative humidity was the larger in part of residences, residents felt sweaty and moist were also one of the main reasons for feeling uncomfortable. In addition, some residents selected the “Indoor temperature rises rapidly after stopping the cooling equipment”. May be residents felt hot and opened air conditioning or electric fan for auxiliary cooling. After stopping the cooling equipment, the indoor temperature rose rapidly, so they felt uncomfortable. And another 4.76% of residents selected the “part of the body feels hot”, they felt head sweating with hot.

For the reasons why most of the residents felt uncomfortable in non-heating room, the reason A which meant the room was hot overall accounted for 50%. It was followed by the reason H and F which meant the residents feel sweaty and felt sweaty in part time in non-air conditioning room, respectively. Due to relatively high temperature and humidity, so some residents felt stuffy in non-air conditioning rooms.

The reasons of 「-1．Slightly uncomfortable」~「-3．Very uncomfortable」(Multiple choice)

| | |
|---|---|
| A | Room is hot overall |
| B | A part of the body feels hot |
| C | The effect of air-conditioning is poor, it works after a long time with open |
| D | Indoor temperature rises rapidly after stopping the cooling equipment |
| E | Feel stuffy |
| F | Feel sweaty |
| G | Feel moist |
| H | Feel sweaty in part time |
| I | Others |

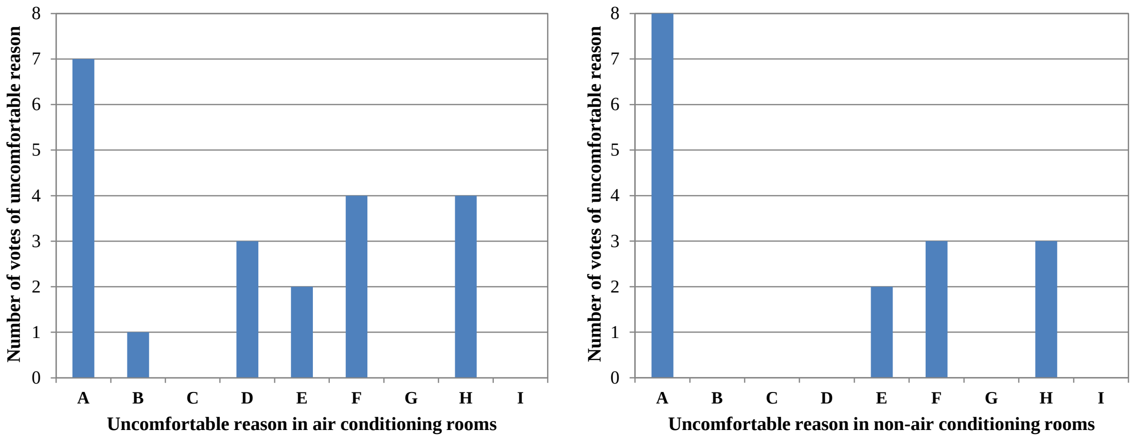



Figure 4-42 Uncomfortable reason

3. Energy consumption

(1) Electricity charging system

Table 4-5 Charging system in Guangzhou (yuan)

| | | Summer standard | | | Non summer standard | | |
|---|---|---|---|---|---|---|---|
| | | ~260kWh | 261~600kWh | 601~kWh | ~200kWh | 201~400kWh | 401~kWh |
| Flat hours | 8:00~14:00; 17:00~19:00; 22:00~24:00; | 0.58 | 0.63 | 0.88 | 0.58 | 0.63 | 0.88 |
| Peak hours | 14:00~17:00; 19:00~22:00; | 0.95 | 1.0 | 1.25 | 0.95 | 1.0 | 1.25 |
| Trough hours | 0:00~8:00 | 0.29 | 0.34 | 0.59 | 0.29 | 0.34 | 0.59 |

Table 4-5 shows the charging electricity system in Guangzhou. As can be seen, the electricity bill was divided into two methods of valuation with three-tiered pricing. In hot and humid regions, the electricity consumption of air conditioning in summer accounted for the major part, the electricity shortage even occurred during the peak hours of air conditioning. Aiming at the electricity shortage and the rapid increase of electricity bill, in order to reasonably control the monthly electricity consumption, not only the tiered pricing had been implemented by Guangzhou power supply department but the peak and valley TOU (time-of-use) electricity price of pilot residential electricity consumption also carried out from 2012. The power price of peak period in electricity consumption (14:00~17:00; 19:00~22:00 ;) was over three times than that of off-peak period (0:00~8:00). Therefore, using the air-conditioning at different time had a greater impact on the total electricity consumption. Most residences only used air conditioning in bedroom for cooling in the night and opened the window for ventilation in the daytime. The use of air conditioning during the peak period in electricity consumption had a negative impact on electricity savings.

(1) Electricity consumption

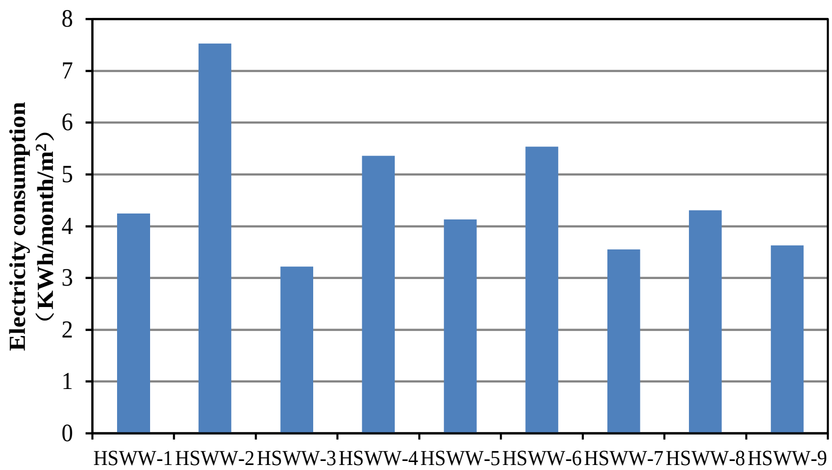



Figure 4-43 Average monthly electricity consumption in winter

Figure 4-43 shows the monthly total electricity consumption of July and August per square meter of different residences. It can be seen that the monthly total electricity consumption of residence HSWW-2 was largest. This may be because of the distinctive operation pattern and lower setting temperature of air conditioning in residence HSWW-2. The residence HSWW-2 was used to cooling down two bedrooms at the same time through the air conditioning of living room, so the capacity of air conditioning must be larger and air conditioning load was larger due to the greater cooling area, the room temperature cannot reach the setting temperature for a long time, the air conditioning compressor remained running consistently, which resulted in a large electricity consumption. It was followed by residence HSWW-4 and HSWW-6 in terms of monthly electricity consumption mainly because of the large number of appliances and smaller floor area. Residence HSWW-3 had the minimum monthly electricity consumption, except for benefitting from larger construction area, the resident had better awareness of energy saving ,the setting temperature of air conditioning was higher, and the air conditioning will be turned off after a period time, and then opened until the dwellers felt hot.

## 4.4 Conclusion

This chapter mainly researched the actual condition of thermal environments in summer in multi-unit residences in three hotter climate zones of China through field measurement and questionnaire analysis. On such basis, rational improvement proposals and measures to improve the comfort of indoor thermal environments and energy conservation in Chinese multi-unit residences are discussed. The main conclusions are as follows:

(1) For the Cold Zone:

1) The indoor average temperatures maintained at about 27ºC, and slightly reduced when entering September. And the distribution of relative humidity of most residences concentrated in about 65~75%.

2) The temperatures of most surveyed residences in a typical day changed gently. Cooling equipment was seldom used because the summer in Qingdao is not intensely hot during the day and cool at night.

3) The indoor thermal environment of most residences did not fall into the comfort zone of ASHRAE mainly because of the higher relative humidity.

4) The indoor thermal environments of all surveyed residences were all not located in the danger zone of heat stroke, but located in the warning and serious warning zone of heat stroke for almost all the time.

5) PMV evaluation results also showed that the indoor thermal environment of most residences were in neutral or slightly hot state.

Therefore, for the Cold Zone, the proper room layout and direction of residence that are better for summer natural ventilation should be constructed in this zone where it is not intensely hot in summer. Corresponding measures should be adopted for reducing the indoor humidity obviously.

(2) For the Hot Summer and Cold Winter Zone:

1) The indoor average temperatures maintained at about 30ºC, and reduced about 2~3ºC because of the consecutive overcast and rainy weather during the measured period. And the average relative humidity of most surveyed residences was about 80% in summer, even reached up to above 90% in rainy day.

2) Due to the higher temperature and relative humidity as well as less using of air conditioning, there was no data falling into the ASHRAE comfort zone in most surveyed residences.

3) Compared with that of Qingdao, the risk of heat stroke in summer of Hangzhou was relatively high, the risk assessment of heat stroke of indoor thermal environment in some residences was dangerous.

4) PMV value of the indoor thermal environment in most residences concentrated in 1~2 which corresponds to the thermal sensation of warm and slightly hot, while decreased in the early morning.

5) The clothing insulation value of most of surveyed residences in Hangzhou concentrated in about 0.17clo.

6) The frequency of using air conditioning per week was not so much in most surveyed residences. The air conditioning system in the living room used mainly in the afternoon and evening and that in bedroom only used during the night. And The setting temperature of air conditioning mainly concentrated in 26ºC~ 28ºC and the cooling capacity of air-conditioning system distributed in 0.2kW/$m^2$ in most surveyed residences.

8) Most of the surveyed residents thought the indoor ventilation effect was general.

9) The satisfaction of indoor environment in most residences presented -1 which means the occupants were relatively unsatisfied with the indoor thermal environment, and the unsatisfied reason was mainly residents feel sweaty and flushed face with hot.

10) The monthly electricity consumption of most surveyed residences were over 3 kWh/$m^2$, slightly higher than that in winter. Using of air conditioning during the day when solar radiation intensity is strong would lead to more energy consumption.

Therefore, for the Hot Summer and Cold Winter Zone, the ventilation condition is firstly needed to improve. The frequency of air conditioning should be increased, so as to reduce indoor temperature and relative humidity effectively. Using of air conditioning during the daytime when solar radiation intensity is strong should be avoided as far as possible. What's important in this climate zone is to take measures to reduce indoor humidity.

(3) For the Hot Summer and Warm Winter Zone:

1) The service time of air conditioning in bedroom of most surveyed residences was at night (23:00~9:00), while usually used in the afternoon and evening in living room. The setting temperature of air conditioning in most surveyed residences were 26ºC and 28ºC, while the lower (24ºC) and higher (29ºC) ones also existed. There was almost no switching behavior of air conditioning in most of surveyed residences.

2) The indoor average temperatures in the rooms which used air conditioning in long term and lower setting temperature maintained at about 28ºC, while reached up to 31ºC in the residences without using the air conditioning. And the distribution of relative humidity of most residences concentrated in about 70%~80%.

3) Due to the higher temperature and relative humidity, there was no data falling into the ASHRAE comfort zone in most surveyed residences.

4) The setting temperature and service time of air conditioning had a obvious influence on the heat stroke risk of indoor thermal environment. The residences with longer service time and lower setting temperature of air conditioning was not located in the danger zone of heat stroke, while there was higher the possibility of heatstroke in other residences, and the higher relative humidity also increased the probability of heat stroke.

5) PMV evaluation results showed that the indoor thermal environment of most residences were in hot state, while in the neutral state in the residence which used air conditioning in long term and lower setting temperature.

6) The same as that in Hangzhou, the clothing insulation value of most of surveyed residences in Guangzhou concentrated in about 0.17clo.

7) The thermal sensations vote of most living rooms and bedrooms were 1 or 2 which corresponds to the thermal sensation of warm and slightly hot. And it can be obtained 28.4ºC as the thermal neutral temperature of human body in summer of this zone.

8) The monthly electricity consumption of most surveyed residence were about 4 kWh/m$^2$. The multiple rooms simultaneously cooled by one air conditioning unit would lead to an increase of the cooling energy consumption. The switching behavior depend on the residents' thermal sensation seemed to have a positive effect on energy consumption.

Therefore, for the Hot Summer and Warm Winter Zone, the thermal environment and energy consumption should be comprehensively considered to design the setting temperature of air conditioning depend on the human thermal sensation. The appropriate setting temperature of air conditioning is the temperature which could achieve the actual indoor temperature maintain at approximately 28~29ºC. The doors and the windows should be shut tight when using the air conditioning. An air conditioning should be avoided to conduct the cooling for more than one room at the same time. Switching behavior of air conditioning depends on the residents' thermal sensation also could be adopted.

## References

(1)China Academy of Building Research, Standard of climate regionalization for architecture(GB50178-93), Ministry of Construction of the PRC,1993

(2)Meinan Wang, Nobuyuki Sunaga, The effects of building performance and air-conditioning setting temperature on energy consumption and thermal comfort in multi-unit residences in China, Journal of Environmental Engineering, AIJ, Vol.82, No.734, pp.471-480, 2017.4.

(3)Design standard for energy efficiency of residential buildings in Hot Summer and Warm Winter Zone (JGJ75-2012). Beijing: China Architecture& Building Press.

(4)Zhu, G., Zhang, X. Effects of operation mode of air conditioning on energy consumption of heating and air conditioning in residential buildings. Journal of Chongqing Jianzhu University, 128(5), pp. 119-121, 2006.

(5)Design standard for energy efficiency of residential buildings in Hot Summer and Warm Winter Zone (JGJ75-2012), China Architecture& Building Press, 2012.

(6)ASHRAE Handbook-Fundamentals 2005, M. Atlanta: American Society of Heating Refrigeration and Air Conditioning Engineers, Inc.

(7)Guangjun Zhu, Xiaoliang Zhang. Effects of operation mode of air conditioning on energy consumption of heating and air conditioning in residential buildings [J], Journal of Chongqing Jianzhu University, pp119~121,Vol.128, No.5,2006.

(8)J.G. Li, L. Yang, J.P. Liu, A thermal comfort field survey in residential buildings in hot summer and cold winter area, Sichuan Building Science 4(2008) 200-205.

(9)Y.Z. Xia, R.Y. Zhao, Y. Jiang, Study on thermal comfort of residential environment in Beijing, Journal of HV&AC 2(1999).

# CHAPTER 5 SIMULATION STUDY ON THE ENERGY SAVING POTENTIAL OF CURRENT CONDITIONS AND INFLUENTIAL PARAMETER IN DIFFERENT CLIMATE ZONES

## 5.1 Introduction

The previous two chapters described the residential indoor thermal environment and energy consumption condition as well as heating and cooling mothods in winter and summer of four climate zones in China. Through the analysis of indoor physical parameters and subjective questionnaire, it can be found that the existing problems of indoor thermal environment were different depend on different climate zones. However, the indoor thermal environment of multi-unit residences can be mutual affected by the various influencing factors. The envelope structure performance of residential buildings and the service condition of indoor heating or cooling equipment both can affect indoor thermal environment and energy consumption of residence directly or indirectly. This chapter compiled four different parameters and performed simulations based on new national energy saving standard. The energy saving potential of current conditions was analyzed. Meanwhile, the influential parameter on energy demand and indoor thermal comfort was clarified in all five climate zones.

## 5.2 Methodology and Settings

In order to identify the influential parameters for different climate zones and achieve the optimum building energy performance, the district heating and air conditioning energy consumption of the unit construction area were calculated. At the same time, indoor thermal comfort was also compared and analyzed for a performance evaluation of the thermal environment. A significant overlap between different influential parameters for the total energy consumption and comfortable indoor thermal environment could reveal possibilities for improvement, which could lead to reduced energy consumption and a higher comfort level.

### 5.2.1 Selection of simulation software

Modelling studies were performed and undertaken in sequence by Energy-Plus (v8.1) software. Energy Plus is a brand-new software, which was developed by Lawrence Berkeley National Laboratory and several U.S. universities as well as other units working together with the support of the U.S. Department of energy. It not only absorbed the advantages of building energy consumption analysis software DOE-2 and BLAST but also possessed many new functions, is regarded as a new generation of building energy consumption analysis software to replace the DOE-2. It has been widely used to simulate heating, ventilation and air conditioning etc. based on response factor and heat balance method and so on(1).

### 5.2.2 Selection of simulation cities

For comparison of the results of measurement and simulation, five representative cities were selected based on previously filed measurement. The climate data comes from the freely available Energy-Plus weather database-International Weather for Energy Calculations (IWEC). Meteorological data files are in the form of EPW. Because of the lack of weather data for Qingdao in IWEC, here it was replaced with the nearby city of Longkou. The representative cities and location information are as shown in Table 5-1.

Table 5-1 Representative cities and location information

| **Location NO.** | CHN_509530 | CHN_547530 | CHN_584570 | CHN_592870 | CHN_567780 |
|---|---|---|---|---|---|
| **Location** | Harbin | Qingdao | Hangzhou | Guangzhou | Kunming |
| **Province** | Heilongjiang | Shandong | Zhejiang | Guangdong | Yunnan |
| **Latitude** | 45.75° | 37.62° | 30.23° | 23.17° | 25.02° |
| **Longitude** | 126.77° | 120.32° | 120.17° | 113.33° | 102.68° |
| **Elevation** | 142.3m | 4.8m | 41.7m | 41m | 1892.4m |

Figure5-1 shows the climate characteristic of the five cities. It is worth noting that the climates of the different cities have great disparities. The annual temperature difference of Harbin which is located in the Severe Cold Zone is the maximum. In contrast, the annual temperature of Kunming which is located in Temperate Zone is relatively mild, the monthly average temperature is mainly distributed between 10~20ºC. In order to ensure the basic indoor environment, the thermal performance design of residential buildings in different cities should be quite different.

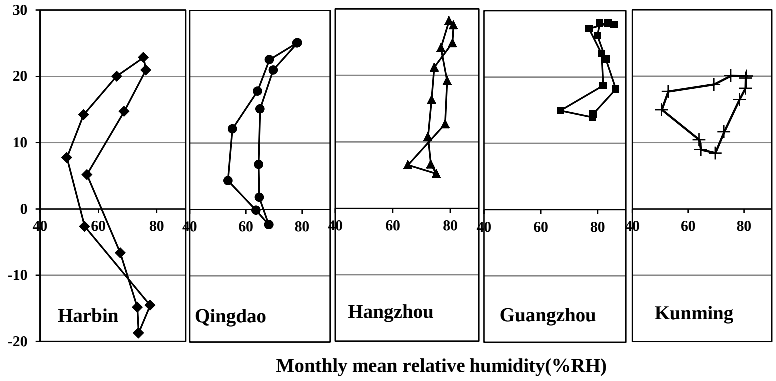



Figure 5-1 Climate characteristics of five representative cities

5.2.3 Simulation model and conditions

The demonstration building for the simulations was set up based on the National Building Standard Design Atlas (13J815)[(2)]. This was a dual-aspect (north and south) building comprised of five floors. Figure 5-2 shows the typical floor of the target residential building. The simulation model appearances are as shown in Figure 5-3.

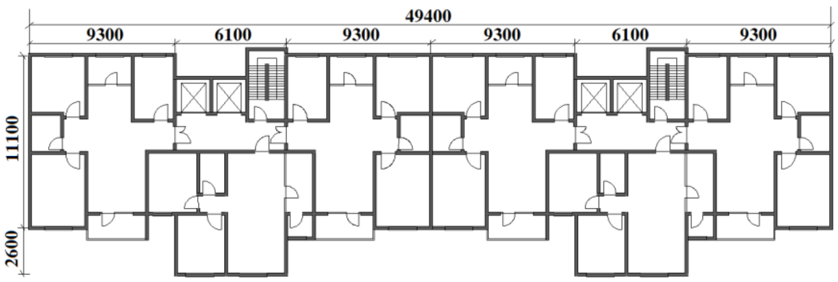
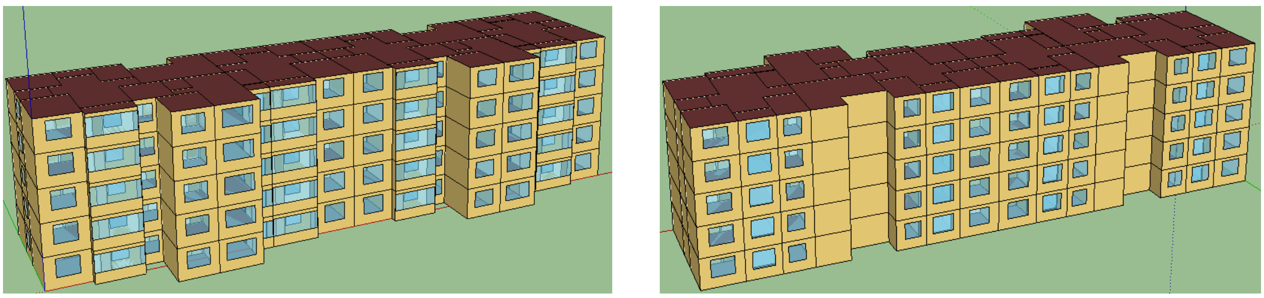



Figure 5-2 Typical floor of the target residential building (Unit: mm)



(a) The south face

(b) The north face

Figure 5-3 The simulation model appearance

Because the thermal environment of middle layers is stable, the selected target was the intermediate dwelling unit of layer 3. The representative dwelling consists of a living room with a balcony, a kitchen with a dining room, two bedrooms, a bathroom, a study, a hallway and an enclosed balcony as shown in Figure 5-4. The floor area of the house is 115.3m$^2$, its net height is 2.7m, and the average window to wall ratio is 35%. The fill color of the room represents the air conditioning and heating area. Representative apartment details are given in Table 5-2. The dwelling is assumed to be occupied by a family of three (one couple plus a preschool-aged child) according to the investigation results. The corresponding internal gains and daily schedules were assigned according to the occupation condition of the residents during the field investigation as shown in Table 5-3. All households use the same daily schedules.

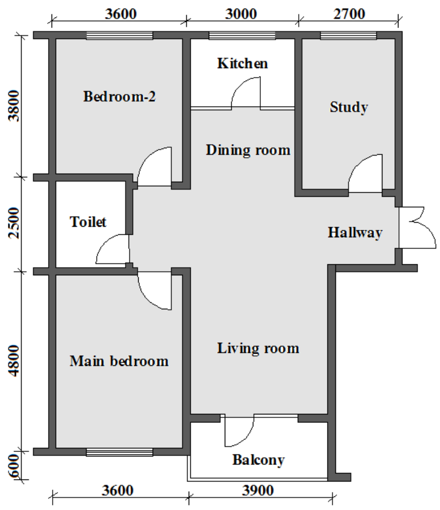


Figure 5-4 Representative plan (Unit: mm)

Table 5-2 Representative apartment details

| Room | Room area(m$^2$) | Window area(m$^2$) |
|---|---|---|
| LR+DR+H | 34.14 | — |
| Main bedroom | 15.64 | 2.52 |
| Bedroom-2 | 13.02 | 2.52 |
| Study | 10 | 1.96 |
| Kitchen | 4.32 | 2.52 |
| Toilet | 5.12 | —/1.68 |
| Balcony | 2.68 | 5.85 |
| Floor area | | 115.3m$^2$ |
| Net height | | 2.7m |
| Usable floor area | | 84.92m$^2$ |
| Air conditioning area | | 72.8m$^2$ |

Table 5-3 Energy-Plus input summary

| Room | Lighting gain | | Occupancy gain | | Equipment gain | |
|---|---|---|---|---|---|---|
| | (W/m$^2$) | Time | Number | Time | (W/m$^2$) | Time |
| Main bedroom | 8 | 21:00-23:00 | 2<br>1 | 21:00-7:30<br>7:30-8:00 | 7 | 21:00-23:00 |
| Livingroom | 8 | 18:00-21:00 | 3<br>2 | 8:00-8:30;12:30-13:30;18:30-20:00<br>18:00-18:30;20:00-21:00 | 7 | 18:00-21:00 |
| Bedroom-2 | 8 | 21:00-21:30 | 1 | 21:00-8:00 | - | - |
| Study | 8 | 20:00-21:00 | 1 | 17:00-18:00;20:00-21:00 | - | - |
| Kitchen | 8 | 17:30-18:30 | 1 | 7:30-8:00;12:00-12:30;17:30-18:30 | 10 | 12:00-12:30;17:30-18:30 |

Table 5-4 shows the basic material and construction of existing building. The basic construction of simulation model was selected based on the common structure of the investigated residences. The external wall is composed of reinforced concrete, cement mortar and EPS, The thickness of EPS is changed to achieve different insulation performance. And the interior wall has no thermal insulation layer. Roof and floor used the same construction that there waterproofing materials in the outermost layer. The diagram of exterior wall and roof (floor) are shown in Figure 5-5 and Figure 5-6(10).

Table 5-4 Construction of existing building

| Part | Materials | Thickness(mm) |
|---|---|---|
| Roof (From outside to inside) | Waterproof roll | 10 |
| | Cement mortar | 30 |
| | Expanded polystyrene (EPS) | δ |
| | Cement slag | 100 |
| | Reinforced concrete | 120 |
| | Cement mortar | 25 |
| External wall (From outside to inside) | Cement mortar | 20 |
| | Expanded polystyrene (EPS) | δ |
| | Reinforced concrete | 200 |
| | Cement mortar | 20 |
| Floor (From outside to inside) | Waterproof roll | 10 |
| | Cement mortar | 30 |
| | Expanded polystyrene (EPS) | δ |
| | Cement slag | 100 |
| | Reinforced concrete | 120 |
| | Cement mortar | 25 |
| External window | Glass | X |
| | Plastic steel | 55 |
| | External shading(ES) | - |

δ represents the thickness of insulation material;
X represents different thickness and different kinds of glass.

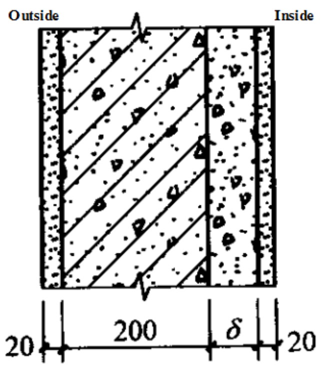


Figure 5-5 Diagram of exterior wall

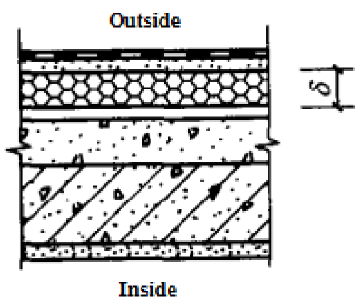


Figure 5-6 Diagram of roof (floor)

Different cities used different types and different thickness of glass. And there is external shading in some cities. The external shading is only used in summer, its method is to add blind in the outside of the window. Figure 5-7 shows the diagram of blind, and performance of blind is shown in Figure 5-8.

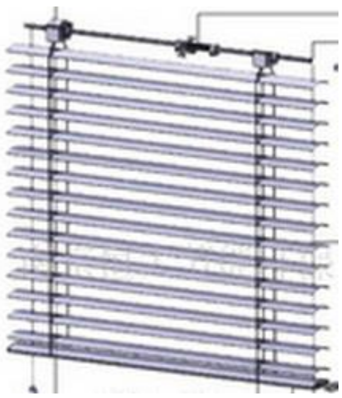


Figure 5-7 Diagram of exterior wall

| Field | Units | Obj1 |
|---|---|---|
| Name | | blind |
| Slat Orientation | | Horizontal |
| Slat Width | m | 0.025 |
| Slat Separation | m | 0.01875 |
| Slat Thickness | m | 0.001 |
| Slat Angle | deg | 45 |
| Slat Conductivity | W/m-K | 0.1 |
| Slat Beam Solar Transmittance | | 0 |
| Front Side Slat Beam Solar Reflectance | | 0.7 |
| Back Side Slat Beam Solar Reflectance | | 0.7 |
| Slat Diffuse Solar Transmittance | | 0 |
| Front Side Slat Diffuse Solar Reflectance | | 0.7 |
| Back Side Slat Diffuse Solar Reflectance | | 0.7 |
| Slat Beam Visible Transmittance | | 0 |
| Front Side Slat Beam Visible Reflectance | | 0.5 |
| Back Side Slat Beam Visible Reflectance | | 0.5 |
| Slat Diffuse Visible Transmittance | | 0 |
| Front Side Slat Diffuse Visible Reflectance | | 0.5 |
| Back Side Slat Diffuse Visible Reflectance | | 0.5 |
| Slat Infrared Hemispherical Transmittance | | 0 |
| Front Side Slat Infrared Hemispherical Emissivity | | 0.9 |
| Back Side Slat Infrared Hemispherical Emissivity | | 0.9 |
| Blind to Glass Distance | m | 0.05 |
| Blind Top Opening Multiplier | | 0.5 |
| Blind Bottom Opening Multiplier | | 0.5 |
| Blind Left Side Opening Multiplier | | 0 |
| Blind Right Side Opening Multiplier | | 0 |
| Minimum Slat Angle | deg | 0 |
| Maximum Slat Angle | deg | 180 |

Figure 5-8 Performance of blind

### 5.2.4 Cases for simulation

According to the current research, improvement of residential building envelope structure is mainly focused on the thermal insulation of wall and window, and the air tightness of the building. Therefore, the selected design parameters in this paper is the external wall thermal resistance, type of glass including shading condition, air tightness (ACH: air change rate per hour) and heating or cooling setting temperatures.

The actual condition (case0) of each city is introduced in Table 5-5. The actual conditions were determined in accordance with Chinese codes and current building situations. The actual envelope structure and insulation conditions of residential buildings for each city were mainly derived from local researchers. And the setting temperature (the actual indoor temperature) of each city was set according to the field measurement results. In addition, because there is no annual statistical data, air tightness was selected according to the design standard for the energy efficiency of residential buildings [3][4][5]. The indoor natural ventilation will be conducted when the indoor temperature is between heating setting temperature and cooling setting temperature, and the air change rate is set as 20h$^{-1}$.

Table 5-5 Envelope properties and design parameters of the actual conditions for different zones

| Zone | Representative city | External wall (W/m$^2$K) | External window (W/m$^2$K) | Roof/Floor/Ceiling (W/m$^2$K) | ACH[3][4][5] (h$^{-1}$) | Setting temperature[3][4][5] (°C) |
|---|---|---|---|---|---|---|
| SC | Harbin | 0.54 | 3.0 | 0.21/0.41/0.76 | 0.5 | 23.5 |
| C | Qingdao | 1.2 | 4.7 | 0.41/0.61/0.76 | 0.5 | 21/26.6 |
| HSCW | Hangzhou | 1.72 | 4.7 | 0.76/1.47/0.76 | 1.0 | 13.7/27.8 |
| HSWW | Guangzhou | 3.0 | 4.7 | 0.76/1.47/0.76 | 1.0 | 29.6 |
| T | Kunming | 3.0 | 4.7 | 0.76/1.47/0.76 | 1.0 | 18/26 |

In addition to the actual condition, eight other cases were simulated for each climate zone as shown in Table 5-6:

Case1 represents current actual residential building envelopes with the national standard of setting temperature which the heating setting temperature is set as 18 ºC, and cooling setting temperature is set as 26ºC.

And case 2 represents the current national standard which is the design standard for the energy efficiency of residential buildings (3) (4) (5). However, because there is no energy efficiency design standard for the Temperate Zone, the current standard in Kunming was set the same as adjacent Guangzhou.

Cases 3 to 6 represent a single variable analysis of four design parameters, respectively. In order to compare the influence of each parameter, wall and window insulation conditions and air tightness vales decreased by about 50% on the basis of the national standards. Because there is no window material that heat transfer coefficient is almost exactly $0.9W/m^2K$, the heat transfer coefficient of window improvement in Harbin was adjusted to $1.0W/m^2K$. In order to ensure the indoor air quality, the air tightness improvement in Harbin and Qingdao was adjusted to $0.3h^{-1}$ (fresh air of $30m^3/h$ per person). According to the residential volume of residences and the number of residents, the necessary air change rate per hour of target residence can be calculated, as shown below:

Residential construction area: $115m^2$ Height: 2.7m

Residential volume: $115m^2 \times 2.7m = 310.5m^3$

Fresh air demand of residents: $30m^3/h \times 3 = 90\ m^3/h$

The necessary air change rate per hour that met the demand of fresh air volume:

$$\frac{90\ m^3/h}{310.5m^3} = 0.29h^{-1}$$

Heating or cooling temperatures were changed by 2ºC according to the upper and lower limits of building indoor acceptable temperature for human body (6).

Cases 7 and 8 represent the building structure comprehensive improvement case and building structure plus heating or cooling setting temperature comprehensive improvement case, respectively.

Table 5-6 Simulation calculation cases for each city in different climate zones

| Cities | Cases | External wall Improvement ($W/m^2K$) | External window Improvement ($W/m^2K$) | Infiltration Improvement ($h^{-1}$) | Setting temperature Improvement (℃) |
|---|---|---|---|---|---|
| Harbin | Case0 (Current case) | 0.54 | 3.0 | 0.5 | 23.5 |
| | Case1 (Current case/standard ST) | 0.54 | 3.0 | 0.5 | 18 |
| | Case2 (National Standard) | 0.4 | 1.8 | 0.5 | 18 |
| | Case3 (Wall Improvement) | 0.2 | 1.8 | 0.5 | 18 |
| | Case4 (window Improvement) | 0.4 | 1.0 | 0.5 | 18 |
| | Case5 (Infiltration Improvement) | 0.4 | 1.8 | 0.3 | 18 |
| | Case6 (ST Improvement) | 0.4 | 1.8 | 0.5 | 16 |
| | Case7 (Improvement-1) | 0.2 | 1.0 | 0.3 | 18 |
| | Case8 (Improvement-2) | 0.2 | 1.0 | 0.3 | 16 |
| Qingdao | Case0 (Current case) | 1.2 | 4.7 | 0.5 | 21/26.6 |
| | Case1 (Current case/standard ST) | 1.2 | 4.7 | 0.5 | 18/26 |
| | Case2 (National Standard) | 0.6 | 2.5 | 0.5 | 18/26 |
| | Case3 (Wall Improvement) | 0.3 | 2.5 | 0.5 | 18/26 |
| | Case4 (window Improvement) | 0.6 | 1.25 | 0.5 | 18/26 |
| | Case5 (Infiltration Improvement) | 0.6 | 2.5 | 0.3 | 18/26 |
| | Case6 (ST Improvement) | 0.6 | 2.5 | 0.5 | 16/28 |
| | Case7 (Improvement-1) | 0.3 | 1.25 | 0.3 | 18/26 |
| | Case8 (Improvement-2) | 0.3 | 1.25 | 0.3 | 16/28 |
| Hangzhou | Case0 (Current case) | 1.72 | 4.7 | 1.0 | 13.7/27.8 |
| | Case1 (Current case/standard ST) | 1.72 | 4.7 | 1.0 | 18/26 |
| | Case2 (National Standard) | 1.0 | 3.2 | 1.0 | 18/26 |
| | Case3 (Wall Improvement) | 0.54 | 3.2 | 1.0 | 18/26 |
| | Case4 (window Improvement) | 1.0 | 1.6+ES | 1.0 | 18/26 |
| | Case5 (Infiltration Improvement) | 1.0 | 3.2 | 0.5 | 18/26 |
| | Case6 (ST Improvement) | 1.0 | 3.2 | 1.0 | 16/28 |
| | Case7 (Improvement-1) | 0.54 | 1.6+ES | 0.5 | 18/26 |
| | Case8 (Improvement-2) | 0.54 | 1.6+ES | 0.5 | 16/28 |
| Guangzhou | Case0 (Current case) | 3.0 | 4.7 | 1.0 | 29.6 |
| | Case1 (Current case/standard ST) | 3.0 | 4.7 | 1.0 | 26 |
| | Case2 (National Standard) | 2.0 | 3.2 | 1.0 | 26 |
| | Case3 (Wall Improvement) | 1.0 | 3.2 | 1.0 | 26 |
| | Case4 (window Improvement) | 2.0 | 1.6+ES | 1.0 | 26 |
| | Case5 (Infiltration Improvement) | 2.0 | 3.2 | 0.5 | 26 |
| | Case6 (ST Improvement) | 2.0 | 3.2 | 1.0 | 28 |
| | Case7 (Improvement-1) | 1.0 | 1.6+ES | 0.5 | 26 |
| | Case8 (Improvement-2) | 1.0 | 1.6+ES | 0.5 | 28 |
| Kunming | Case1 (Current case/standard ST) | 3.0 | 4.7 | 1.0 | 18 |
| | Case2 (National Standard) | 2.0 | 3.2 | 1.0 | 18 |
| | Case3 (Wall Improvement) | 1.0 | 3.2 | 1.0 | 18 |
| | Case4 (window Improvement) | 2.0 | 1.6 | 1.0 | 18 |
| | Case5 (Infiltration Improvement) | 2.0 | 3.2 | 0.5 | 18 |
| | Case6 (ST Improvement) | 2.0 | 3.2 | 1.0 | 16 |
| | Case7 (Improvement-1) | 1.0 | 1.6 | 0.5 | 18 |
| | Case8 (Improvement-2) | 1.0 | 1.6 | 0.5 | 16 |

ES: external shading from 10 a.m. to5 p.m. in summer. In order to not affect the ventilation and sunshine in other seasons as well as being easier to open and close, an active exterior blind was used here.

## 5.3 Simulation Results Analysis

5.3.1 Comparison of simulation, literature survey and field investigation results

1. Comparison of annual energy demand between simulation and literature survey

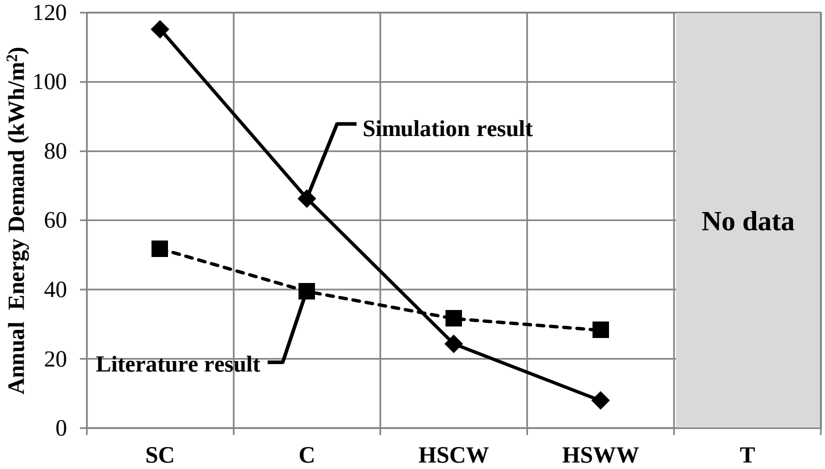



Figure 5-9 Comparison of annual energy demand

Figure 5-9 shows the comparison of annual energy demand between the current case (case0) of simulation result and literature survey. It can be seen that the annual energy demand of current case of simulation was far higher than that of literature survey in SC and C zones. This is mainly because the heating setting temperature of current case in simulation study was set according to field investigation result in winter, which was 23.5ºC and 21ºC in Harbin and Qingdao, respectively. These temperatures were higher than that of literature survey. And the heating energy demand accounts for the main part of annual energy demand in these two climate zones. Therefore, the annual energy demand of simulation was higher than that of literature survey in SC and C zone.

In addition, although the cooling setting temperature in simulation was slightly lower than that of literature survey, the annual energy demand of current case of simulation was lower than that of literature survey in HSCW and HSWW zones. This may be because the objects of literature survey were the articles published within the past 15 years, in which the insulation performance of residential envelope structure was relatively poor. On the other hand, the lower efficiency of the past cooling equipment led to an increase in energy consumption. However, the temperature control type- central air conditioning cooling system was used in the simulation study; the system would stop running when the temperature dropped to the setting temperature at night. Therefore, the energy consumption was lower than those of single air conditioning and other cooling equipment.

2. Comparison of annual energy demand between simulation and field investigation

Figure 5-10 shows the comparison of monthly heating energy demand between simulation and field investigation. The monthly heating energy demand in winter in simulation was derived from the average data from November to February. It can be seen that the monthly heating energy demand of simulation was far higher than that of field investigation result in Harbin and Qingdao. Although the average indoor temperature was the same, but the heating system was different. The temperature control type- central air conditioning or heating system was adopted in the simulation study, the boiler district heating system was adopted in these two cities in the field measurement. Because the outdoor temperatures of these two winters were both relatively lower, the efficiency of district boiler central heating was relatively higher. Therefore, although the existing district boiler central heating system was not equipped with household heat-regulating system which led to the indoor overheat; its economy was still higher than that of air-conditioning heating. In addition, it can be seen that the monthly heating energy demand of simulation was almost the same as that of field investigation result in Hangzhou.

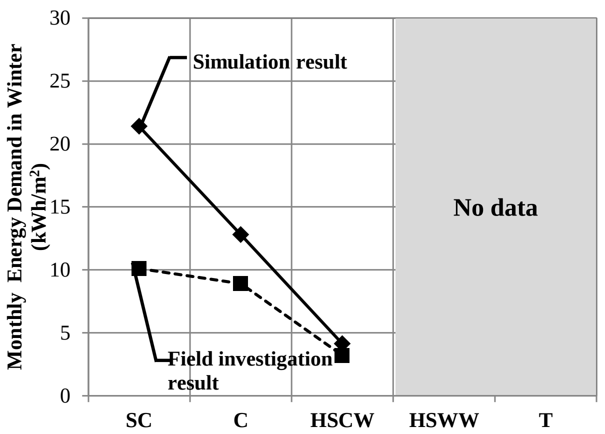



Figure 5-10 Comparison of monthly energy demand in winter

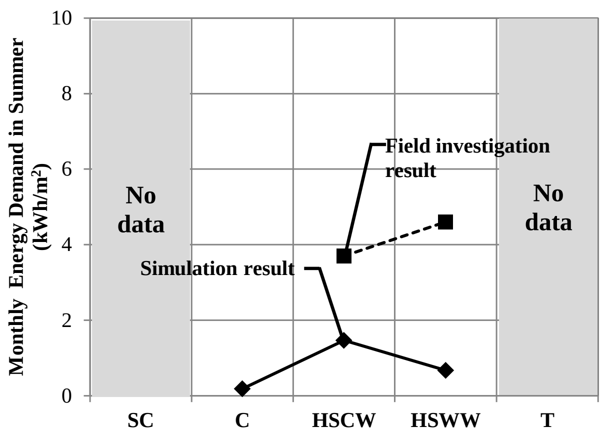



Figure 5-11 Comparison of monthly energy demand in summer

Figure 5-11 Comparison of monthly cooling energy demand in summer between simulation and field investigation. The monthly cooling energy demand in summer in simulation was derived from the average data from June to September. It can be seen that the monthly energy demand of field investigation was higher than that of simulation result. This is because the energy consumption data of summer in Hangzhou and Guangzhou not only included the energy consumption of air conditioning and other cooling equipment but also household appliances. On the other hand, as the mentioned in the previous research, the using pattern of air conditioning in summer has a direct impact on energy consumption(9). For example, the residence HSWW-2 was accustomed to using the air conditioning of living room to cool down the two bedrooms, which led to the increase of cooling energy consumption.

### 5.3.2 Comparison of current case, current case/standard ST and national standard case

1. Comparison of current case (case0) and current case/standard ST (case1)

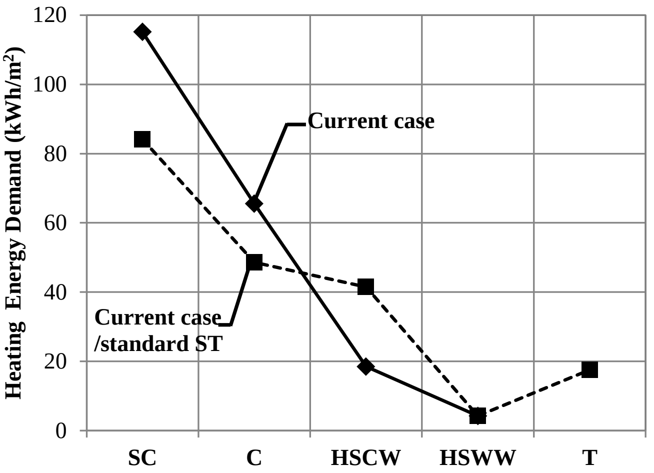



Figure 5-12 Comparison of heating energy demand

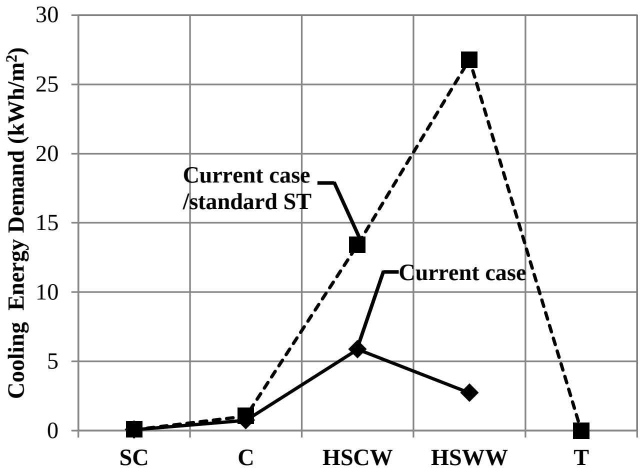



Figure 5-13 Comparison of cooling energy demand

Figure 5-12 shows the comparison of heating energy demand between the current case (case0) and current case/standard ST (case1). It can be seen that reducing the heating temperature from actual temperature to national standard temperature, the heating energy consumption was decreased by 31kWh/$m^2$ and 17kWh/$m^2$ in Severe Cold Zone and Cold Zone. This also demonstrated there was the situation of wasting energy source in the existing district heating system. However, because the indoor temperature was far lower than the standard temperature in non-district heating zones, the heating energy consumption of current case was lower by 23kWh/$m^2$ than current case with standard setting temperature (case1).

Figure 5-13 shows the comparison of cooling energy demand between the current case (case0) and current case/standard ST (case1). It can be seen that because the indoor actual temperatures in summer of Hangzhou and Guangzhou were higher than national standard temperature (26 ºC),causing that the cooling energy demand of current case was lower by 7.5kWh/$m^2$ and 24kWh/$m^2$ respectively than current case with the standard setting temperature (case1).

2. Comparison of current case/standard ST (case1) and national standard case(case2)

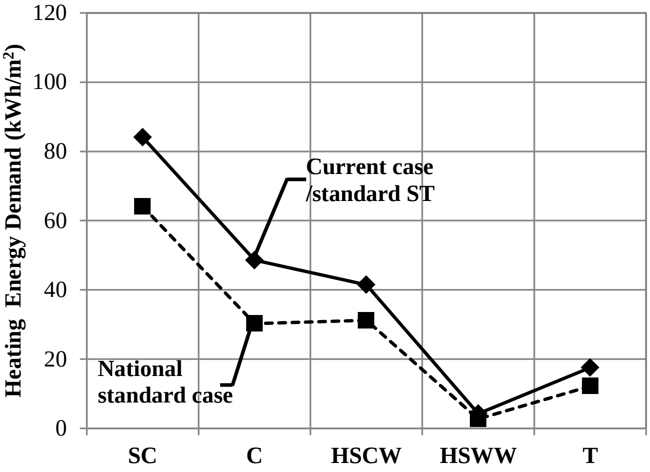



Figure 5-14 Comparison of heating energy demand

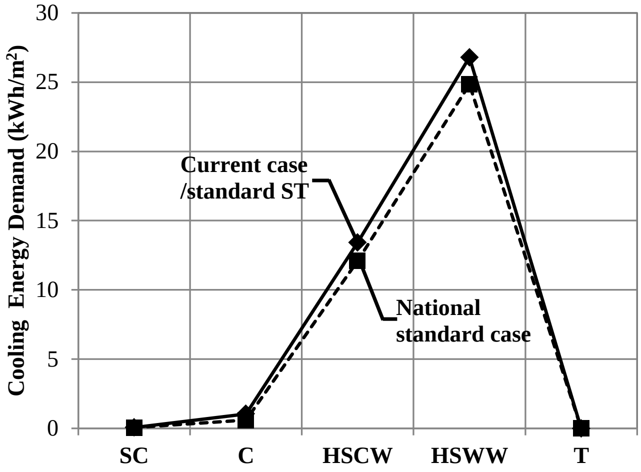



Figure 5-15 Comparison of cooling energy demand

Figure 5-14 and Figure 5-15 show the comparison of energy demand between the current case with standard ST (case1) and national standard case (case2).The difference of case1 and case2 represented the energy saving potential of improving the thermal insulation performance of existing residential envelope structure to reach the national standard. It can be seen that Improving the thermal insulation performance of envelope structure reduced the heating energy demand by 24% and 37%, respectively in SC and C zones. It also demonstrates the thermal insulation performance of envelope structure had a significant effect on the heating energy demand in the colder zones. However, the effect of improving the insulation performance of envelope structure on cooling energy consumption was not significant. This is mainly because the temperature difference of indoor and outdoor when cooling in summer was far less than that of heating in winter.

### 5.3.3 Comparison of energy demand for different cases

1. Results for the Severe Cold Zone

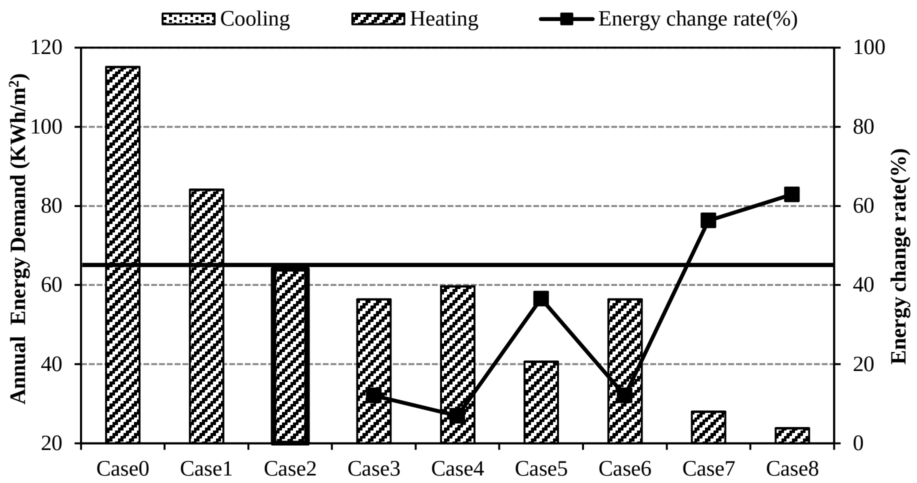



Figure 5-16 Effects of different cases on annual energy demand in Harbin

This climate zone only requires district heating in winter. Figure 5-16 shows the effects of different cases on annual energy demand in Harbin. It demonstrates that the heating load occupied the entire annual energy demand in this climate zone. The energy reduction rate represents the energy reduction for different improvement schemes in comparison with the national standard case (case 2). It also shows the energy-saving potentials of the improvement cases.

Filed measurement results showed that due to the better effect of district heating, the actual indoor temperature of heating rooms were over 23ºC in most surveyed residences. The current case delivered an energy consumption of 115 $kWh/m^2$ with the average indoor temperature that is 23.5ºC. When the indoor temperature (setting temperature) reduced to standard heating temperature which is 18ºC, heating demand could be reduced by 27% with the same current envelope structure condition. Therefore reducing the indoor heating temperature had a significant effect on energy conservation. At the same time, the national standard case had another 24% energy reduction that benefitting from the standard envelope structure in comparison with the actual case.

Different improvement cases all have varying degrees of contribution to energy saving. Increasing the thickness of thermal insulation material as an external wall improvement and lowering the heating setting temperature could make the same contribution in terms of reducing the energy demand; the annual load decreased by 12%. External window improvement had the least impact on energy saving for this climate zone which it can only contribute to a reduction of 7%. Because the average temperature during the coldest month in Harbin is close to -20ºC, it can be seen that the air tightness improvement becomes the main contributor in Severe Cold Zone which delivered an energy reduction in space heating of 36% under the present setting conditions. From energy conservation viewpoint, under the condition of ensuring the quantity of fresh air for residents, there is thought to be an urgent requirement for air tightness improvements in Severe Cold Zone. In addition, overheating resulting from better air tightness cannot occur in this climate zone. Moreover, it is worthwhile pointing out that lowering the heating setting temperature can only contribute to a further 6% reduction against the building structure comprehensive improvement case. Thus, heating temperature improvement after structure improvement is not particularly effective in Severe Cold Zone. On the contrary, properly increasing the heating temperature after building structure improvement will not lead to greater energy demand.

2. Results for the Cold Zone

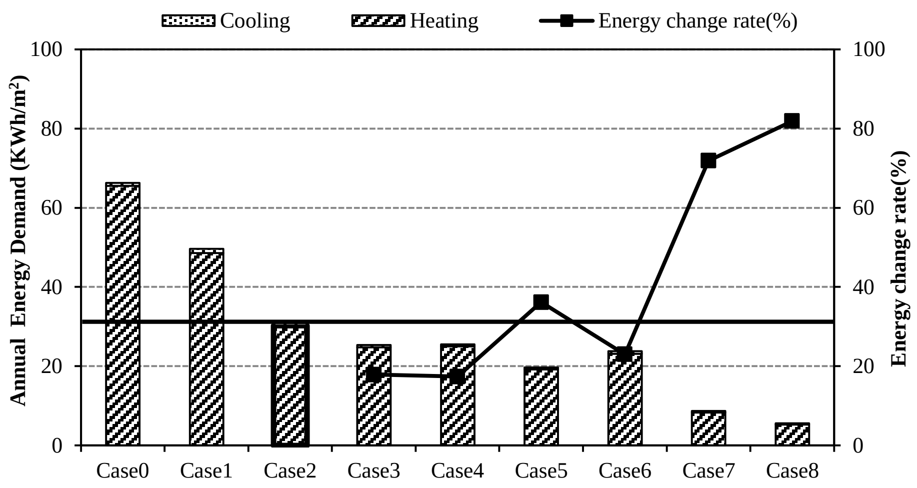



Figure 5-17 Effects of different cases on annual energy demand in Qingdao

Figure 5-17 shows the effects of different cases on annual energy demand in Qingdao. This climate zone needs heating in winter and usually cooling in summer in some areas. Conclusions can be drawn that heating energy consumption accounted for most of the annual energy demand same as the Severe Cold Zone. However, it is much lower than that of the Severe Cold Zone.

The actual condition delivers an energy consumption of 66kWh/m$^2$ with the actual indoor temperature that is 21ºC, approximately half reduced than that in Harbin. The current case with the standard setting temperature delivers an annual energy consumption reduction of 16.4kWh/m$^2$, which decreased by about 25%. Improving the insulation of the building envelope structure to the national standard can contribute to a further 37% reduction on heating energy demand. Compared to the setting temperature, the improvement of existing residential building envelope structure to the national standard is more important.

In this climate zone, different improvement cases also have varying degrees of contribution to energy saving. The external wall and external window improvements make almost the same contribution to the annual energy consumption. Both of them deliver a reduction in the annual energy consumption of 17%. Most notably, this is similar to the Severe Cold Zone, because the average temperature during the coldest month in Qingdao is still below 0 ºC, improving the infiltration rate can make the largest contribution in terms of reducing the energy demand, a reduction of about 45%. The annual energy consumption varies from 30.8 to 6.2kWh/m$^2$ between the standard case (case 2) and the building structure comprehensive improvement case (case 7), which represents a reduction of almost 80% upon implementation of case 7. It is a qualitative over for energy saving research. The goal of low energy consumption has been achieved. Same as the Severe Cold Zone, lowering the heating setting temperature after building structure improvements can only contribute to a further 7% reduction. This reduction is lower than that of only changing heating temperature, which is 23%. This also means that compared with residences with better envelope structure, blindly increasing the heating temperature in the residence which with poor envelope structures will result in more energy consumption.

3. Results for the Hot Summer and Cold Winter Zone

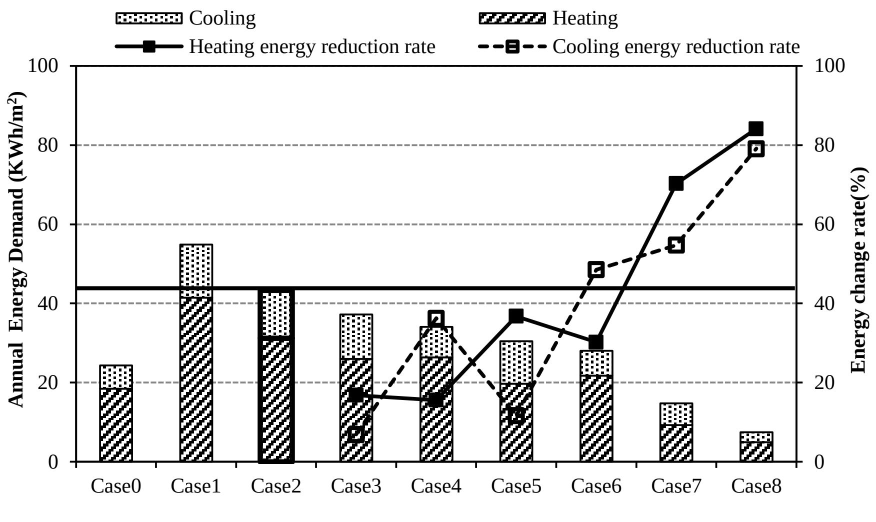



Figure 5-18 Effects of different cases on annual energy demand in Hangzhou

Both requirements of heating in winter and cooling in summer should be taken into account in this climate zone. It can be observed from Figure 5-18 that the annual energy demand in this zone consists of both heating and cooling loads, of which the cooling load accounted for about 30%. Therefore, different energy saving strategies need to be adopted correspondingly between winter and summer.

Because there is almost no district heating system in most cities in this climate zone and less using of air conditioning for heating, filed measurement results showed that the actual indoor temperature in winter were distributed in 10~15ºC in most surveyed residences in Hangzhou, and the average indoor temperature was only 13.7ºC, far lower than the national standard design heating temperature which is 18ºC. At the same time, the actual indoor temperature in summer was about 27.8ºC, slightly higher than the national standard design cooling temperature which is 26ºC. Therefore, in the case of the actual indoor temperature, the current case only delivered an energy consumption of 24.3 kWh/$m^2$, it was less than half of the energy demand of case1 which has the standard setting temperature. On the basis of case1, the national standard case reduced an annual energy consumption of 21% after the envelope performance of residence improved from the current situation to the national standard.

In terms of reducing heating demand, the improvement strategies are similar to those used in the Cold Zone. External wall and external window improvement have almost the same effect on the heating energy consumption, and infiltration improvement is the most effective contributor for the heating energy consumption. However, for the cooling energy demand, because of the influence of strong solar radiation and the long duration of sunshine, the impact of external window improvement using double glazed windows with low-e glass and added external shading during the summer is much larger than those of external wall and air tightness improvement. More importantly, because the average temperature during the hottest month in Hangzhou is 28.2ºC, raising the cooling temperature from 26ºC to 28ºC makes the largest contribution to the cooling energy demand, which is about 49%. This energy reduction is quite valuable for research on energy saving in residential buildings. Moreover, it is worthwhile pointing out that raising the cooling temperature after building structure improvements can contribute to a further 24% reduction in cooling energy demand.

4. Results for the Hot Summer and Warm Winter Zone

Improvements are further developed for the Hot Summer and Warm Winter Zone, where buildings must fully meet the cooling requirements in summer and generally do not consider heating in winter. Figure 5-19 demonstrates that cooling energy occupied almost the entire annual energy demand in this climate zone.

Filed measurement results showed that the indoor average temperatures in the few rooms which used air conditioning in long term and lower setting temperature maintained at about 28ºC which have always been not in the majority, but rather in the minority. While the indoor average temperatures reached up to 29.6ºC, higher than the standard cooling design temperature which is 26ºC. Therefore, the current case only delivered about 7 kWh/$m^2$ of annual energy demand, far less than the case1 which has the current envelope structure and the standard cooling temperature. Case1 and the national standard case demand an annual energy consumption of 54kWh/m$^2$ and 43kWh/m$^2$ respectively. It also means the national standard case reduced an annual energy consumption of about 20% after the envelope performance of residence improved from the current situation to the national standard.

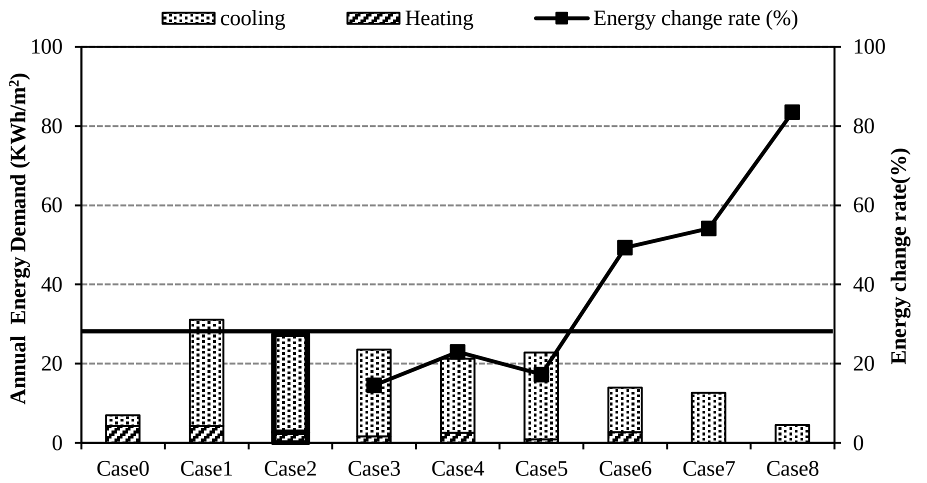



Figure 5-19 Effects of different cases on annual energy demand in Guangzhou

In terms of reducing cooling demand, the strategies are similar to those used in the Hot Summer and Cold Winter Zone. All of these improvements are able to reduce energy load from 31 to 4.5kWh/m$^2$ under the present setting conditions. Compared with building structure improvements, raising the cooling temperature has the most significant effect on energy saving, which can reach about 49% reduction of the annual energy demand. The comprehensive influence of building structure improvements delivered an energy reduction of 54%. Moreover, one key finding was that case 8 delivered a further energy reduction of 30%, which is a significant energy saving potential achieved by raising the cooling temperature. Thus, no matter what the envelope structure properties are, the passive cooling strategy should be addressed primarily in this climate zone. Inefficient air conditioning usage pattern was emphasized again as the main barrier to implementing energy savings.

5. Results for the Temperate Zone

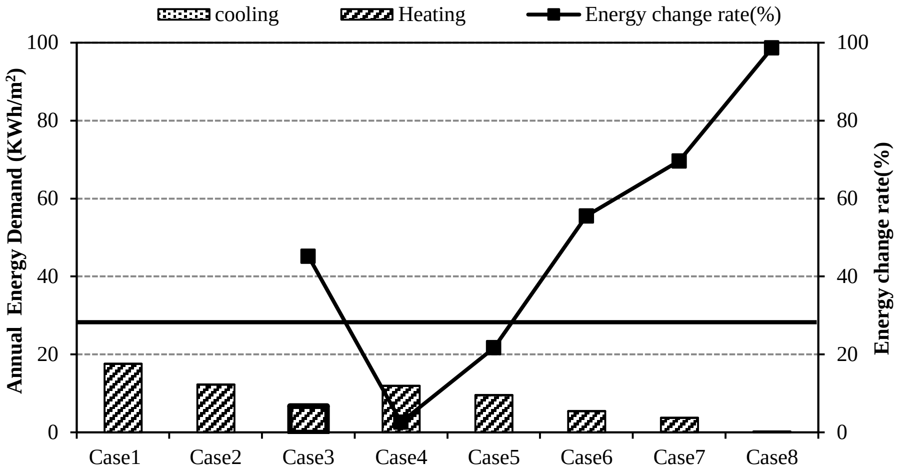



Figure 5-20 Effects of different cases on annual energy demand in Kunming

Possessing the temperate climate zone that needs to consider heating in winter in some areas; and generally do not consider cooling in summer. Because the field measurement had not been carried out in this climate zone, there is no actual data of indoor temperature. So the current case which has the current envelope structure and actual indoor temperature cannot be simulated.

Because of its unique geographical conditions, the air temperature of this climate zone varies little from day to night and from summer to winter. Therefore, the annual heating energy consumption is low, and there is almost no air conditioning energy consumption. Figure 5-20 demonstrates that the annual energy demand is minimal compared with other climate zones. The annual energy consumption delivered only 12.1kWh/m$^2$ for the standard case. Improving external wall performance can make a large contribution in terms of reducing the energy demand, the annual load decreases by 45%. However, the improvement of external windows has almost no effect on the annual energy consumption. Moreover, a 22% reduction in energy demand benefited from the infiltration improvement. A combination of all building structure improvement measures, case 7 has only the remaining 3.7kWh/m$^2$ of energy demand. Unlike other heating zones, lowering the heating setting temperature has the most significant impact on heating energy demand. Even more surprising is that energy consumption was almost zero by changing heating setting temperature after building structure improvement. This improvement maybe has the highest feasibility in this climate zone.

### 5.3.4 Comparison of indoor thermal environment for different cases

Predicted Percentage of Dissatisfied (PPD) is widely used and accepted for the design and field assessment of comfort conditions. Fanger related the PPD to the PMV as follows(7):

$$PPD=100-95\exp[-(0.03353PMV^4+0.2179PMV^2)]$$

This relationship is shown in Figure 5-21.

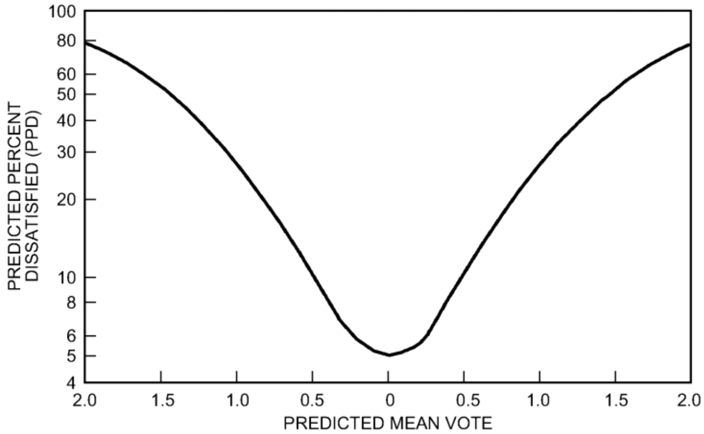



Figure 5-21 PPD as function of PMV

PPD is used in this paper to evaluate the indoor thermal environment. PPD was calculated by the software which comes from Tanabe Lab(8).

PPD of 10 % corresponds to the boundary values of comfort which means that the Predicted Mean Vote (PMV) is from –0.5 to +0.5. A PPD of 26 % corresponds to the boundary values of slight discomfort. This means that the PMV is from –1 (slightly cool) to +1 (slightly warm). PPD of 51 % corresponds to the boundary values of discomfort, which means that the PMV is from -2 (cold) to +2 (hot).

And the evaluation of the indoor thermal environment is divided into three stages: winter, the transitional season and summer. Winter is from Dec to Feb; the transitional season refers to from Mar to May and from Sep to Nov; summer refers to from June to Aug.

PPD calculation conditions are as follows: T, MRT, RH come from simulation results; Metabolic rate was set as 1.0met; Clothing insulation was set as 1.2clo in winter, 0.8clo in the transitional season and 0.55clo in summer; Velocity of air was set as 0.1m/s.

1. Results for the Severe Cold Zone

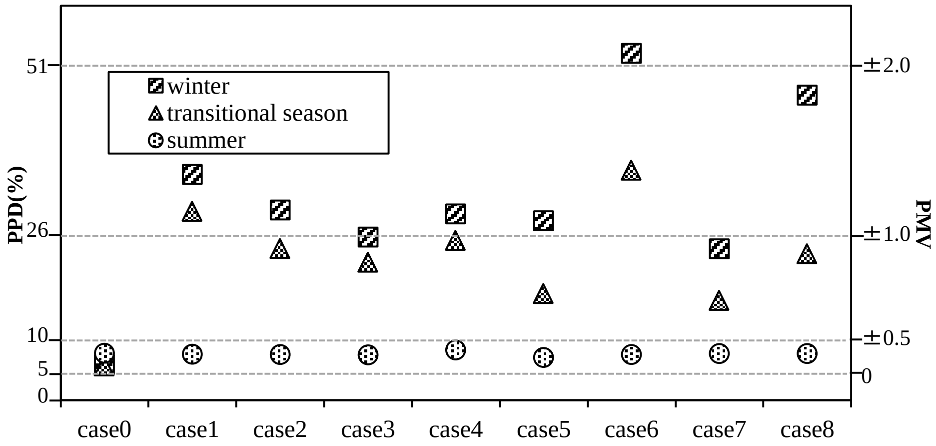



Figure 5-22 Effect on PPD of different cases in Harbin

Figure 5-22 shows the effect on PPD of different improvement cases in Harbin. It can be seen that the indoor thermal environment in summer are comfortable for different cases. However, due to the relatively lower outdoor temperature in winter as well as the lack of heating in the transitional season, the PPD in winter and transitional season are both higher than 10% except for the current case which has the higher indoor temperature due to the better effect of district heating. When the district heating setting temperature is reduced to 18ºC and the envelope structure is still in the current insulation level, the PPD of indoor thermal environment in winter and transitional season significantly increased. And the PPD of the national standard case can be reduced by about 6% after the envelope performance of residence improved from the current situation to the national standard.

Compared with the standard case, the improvement cases have varying degrees of reduction. Wall improvement makes the biggest contribution to improving indoor comfort in winter. The PPD of indoor thermal environment in winter after improving the wall insulation can be reduced to below 26%. While the effect of reducing the infiltration rate is the most significant in the transitional season. Compared with the national standard case (case2), PPD of improving air tightness of residence in transitional season can be reduced from 23% to 16%. Increasing the thermal insulation performance of external window not only has the least impact on energy saving, but also the least impact on the improvement of indoor environment for this climate zone. By synthesizing various building structure improvement methods, the PPD for case7 was controlled within 20% in winter, and about 12% in the transitional season. In addition, only lower heating temperature leads to the deterioration of the indoor thermal environment. PPD of case 6 runs at more than 51% in winter, and about 35% in the transitional season. Although it decreases to 45% benefiting from building structure improvement in case8, it is still in the zone of slight discomfort. At the same time, this improvement also has not so much positive influence on energy consumption, so it can be regarded as invalid improvement plan.

2. Results for the Cold Zone

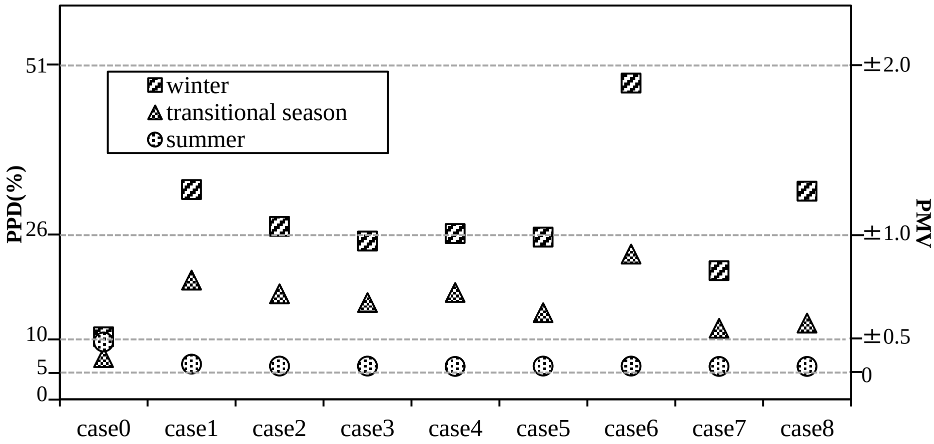



Figure 5-23 Effect on PPD of different cases in Qingdao

Figure 5-23 shows the effect on PPD of different improvement cases in Qingdao. The same with the Severe Cold Zone, the indoor thermal environment in summer is more comfortable. PPD stays at around 5% and does not change because of the different improvement plan. Compared with the current case in Harbin, because actual indoor temperature was reduced to 21ºC, the PPD of indoor thermal environment of the current case in Qingdao has a slight increase in winter, but still locates in the comfort zone. The PPD of indoor thermal environment in winter significantly increased after the district heating setting temperature was set as 18ºC, while the amount of increase is smaller and still in slight comfort zone in transitional season. And the PPD of indoor thermal environment can be reduced by further 5% after the envelope performance of residence improved from the current situation to the national standard.

Compared with the national standard case (case2), there is almost the same 8% reduction in the PPD benefiting from the improvement of external wall and infiltration in winter. No matter which season it is, the improvement of the exterior window seems to have less influence on the indoor thermal environment. Comprehensive results of structure improvements show that PPD in summer and transitional season are both controlled within 10%, and about 17% in winter. This is a good sign for residents. Compared with changing only the heating temperature, PPD related to lowering heating temperature after building structure improvements in winter can be reduced from 48% to 29%, but it is still in the uncomfortable zone. Based on a comprehensive consideration of energy consumption and indoor comfort, we can draw the conclusion that the necessity of lowering the heating temperature is less in a residence with a better performing envelope structure.

3. Results for the Hot Summer and Cold Winter Zone

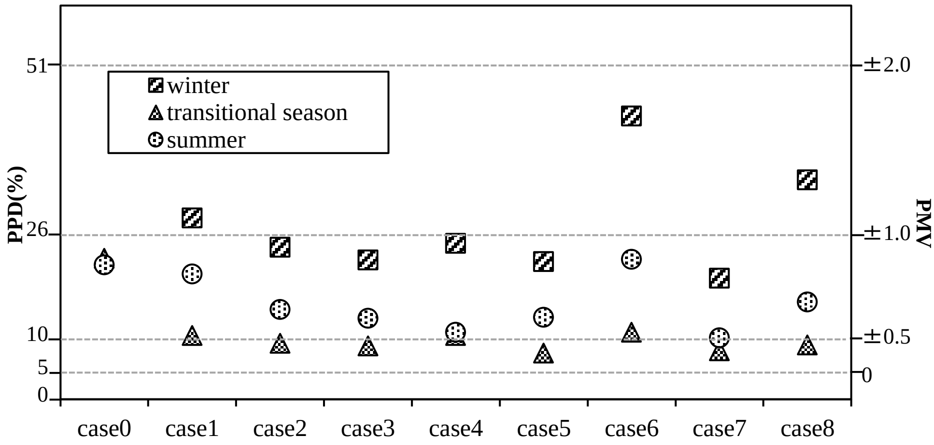



Figure 5-24 Effect on PPD of different cases in Hangzhou

Figure 5-24 shows the effect on PPD of different improvement cases in Hangzhou. In this climate zone, the PPD of the indoor thermal environment in winter is still higher than that in other seasons, and the transition season has become the most comfortable period.

Because the actual indoor temperature in winter was only distributed about 13.7ºC in Hangzhou, far lower than the national standard design heating temperature. Although the current case with the lower indoor temperature delivered less annual energy demand, but the PPD of indoor thermal environment of current case reached up to 73.8% in winter. It means the indoor thermal environment was very poor, and located in the uncomfortable zone. The PPD of indoor thermal environment in winter sharply decreased to 27.6% after the heating setting temperature was set as 18ºC, and controlled within 26% by the envelope performance of residence improved from the current situation to the national standard.

Comparison of different envelope improvement program, the conclusion can be drawn that external window improvement in this climate zone can not only reduce the energy consumption in summer, but also have a significant impact on improving the indoor thermal environment. However, the effect of external window seems to be less significant in winter. The result demonstrates that careful consideration of glazing types can be an effective solution in this zone, where energy needs to be efficiently balanced according to the changing seasons. However, a sudden increase of the PPD in winter emerged as a result of the lowered heating temperature. Therefore, this improvement is less desirable. However, because the difference between the outdoor temperature and the cooling temperature in summer is small, the thermal adaptability of residents is relatively high. The PPD for raising the cooling temperature in summer has no sharp rise. Based on a comprehensive consideration of energy consumption and indoor comfort, appropriately raising the cooling temperature could be implemented in this climate zone. The occupants may be an important factor in the energy saving in summer and adopt a new passive cooling strategy by raising the cooling temperature.

4. Results for the Hot Summer and Warm Winter Zone

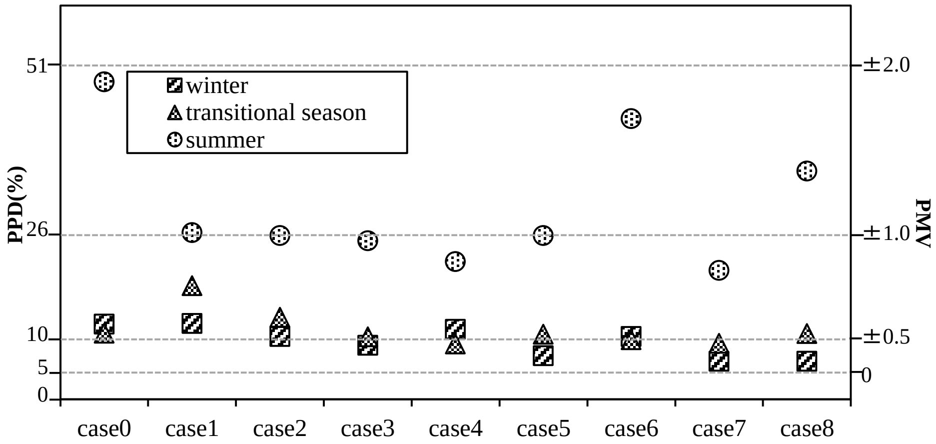



Figure 5-25 Effect on PPD of different cases in Guangzhou

Figure 5-25 shows the effect on PPD of different improvement cases in Guangzhou. It can be seen that PPD of indoor thermal environment in summer becomes the highest of all the seasons in this climate zone. Winter becomes the most comfortable period. Due to the relatively higher outdoor temperature in summer as well as the less use of cooling equipment during the daytime, the actual average indoor temperature reached up to 29.6ºC. Although the current case only delivered about 7 kWh/$m^2$ of annual energy demand, the PPD of indoor thermal environment of current case reached up to 48.3% in summer. And the PPD in summer was controlled within 26% by reducing the cooling temperature to the national standard. However, the reduction of PPD was little by improving the envelope performance from the current situation to the national standard.

In terms of improving the comfort, Different improvement cases all have varying degrees of contribution. External window improvement can contribute the biggest reduction to PPD in summer, but lead to a slight increase of PPD in winter. This is the result of using low-e glass, which led to a reduction in solar radiation received in winter. In addition, there is barely any change of PPD under the condition of improving the external wall and air tightness. Similarly, raising the cooling temperature causes a little rise in the PPD of indoor thermal environment. However, compared with only changing the cooling temperature, the PPD of raising the cooling temperature after building structure improvements in summer can be reduced to about 26%. At the same time, taking into account its contribution to energy saving, this improvement may be accepted by residents with energy saving awareness.

5. Results for the Temperate Zone

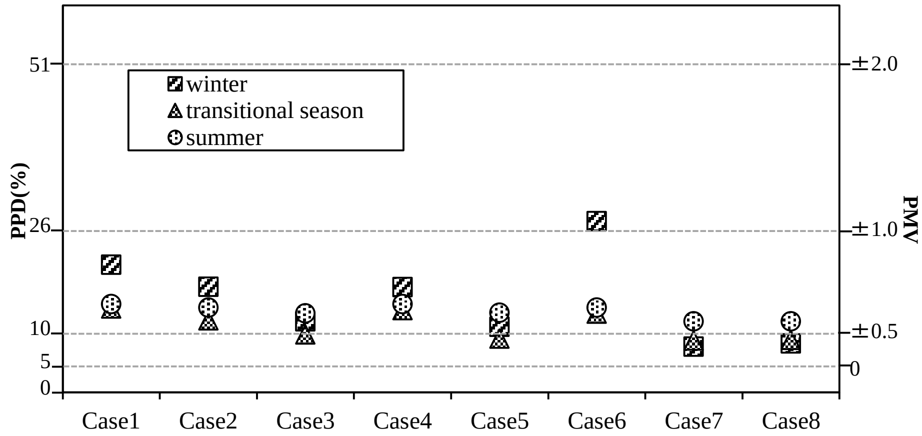



Figure 5-26 Effect on PPD of different cases in Kunming

Because of the better climate conditions, not only there is less annual energy demand, but also the indoor thermal environment is more comfortable in this climate zone. Figure 5-26 demonstrates that improving the external wall and infiltration leads to a PPD that remains at around 10% in all seasons. The improvement of external windows has no influence on the indoor thermal environment. Only lowering heating temperature will lead to a slight increase of PPD in winter. Even to the extent that lowering the heating temperature after building structure improvements does not deteriorate the indoor thermal environment. This means that with a good building envelope structure, energy saving can be achieved with no deterioration of the indoor environment.

## 5.4 Conclusion

This chapter compiled four different parameters and performed simulations based on new energy saving standard. The energy saving potential of current conditions was analyzed. Meanwhile, the influential parameter on energy demand and indoor thermal comfort was clarified in all five climate zones. The main conclusions are as follows:

(1) The energy consumption of current status based on the actual results of field investigation was larger than that of new energy saving standard, and the energy saving potentials of current district heating system in SC Zone and C Zone was large, about 27% and 25%, respectively.

(2) Changing the thermal insulation performance of envelope structure from current status to new energy saving standard had a significant energy saving effect on the heating energy demand in SC Zone and C Zone, about 24% and 37%, respectively.

(3) There are similar improvement strategies for the Severe Cold and Cold Zones based on the present setting conditions. Air tightness of building has the most significant effect on energy saving, whereas better wall insulation is the main contributor to the indoor thermal environment in winter. From energy conservation viewpoint, there is an urgent requirement for air tightness improvements in the Severe Cold Zone and the Cold Zone under the condition of ensuring the quantity of fresh air for residents. According to the comprehensive effects of energy saving and indoor comfort improvement, lowering the heating temperature, from 18 ºC to 16 ºC, can be regarded as an ineffective improvement program in these climate zones.

(4) For the Hot Summer and Cold Winter Zone, in terms of reducing the heating demand, the improvement strategies are similar to those used in the Cold Zone. Under the conditions of present setting, external window improvement can not only maximally reduce the cooling energy load in summer, but also have a significant impact on improving the indoor thermal environment in summer. Furthermore, compared to the effect of heating temperature improvement in winter, the cooling temperature improvement in summer, from 26 ºC to 28 ºC, is relatively effective for energy saving without causing a sharp deterioration of indoor thermal environment.

(5) For the Hot Summer and Warm Winter Zone, raising the cooling temperature has the most significant effect on energy saving under the conditions of present setting. And the influence of external window improvement becomes secondary. Although there is a certain degree of deterioration of the indoor thermal environment, a significant energy saving potential is achieved by raising the cooling temperature. This improvement may be accepted by residents with energy saving awareness.

(6) Because of its unique geographical conditions, it not only has less annual energy demand, but also its indoor thermal environment is more comfortable in the Temperate Zone under the conditions of present setting. Compared with other improvement schemes, improving external

wall performance can make a greater contribution to reducing energy demand. Even to the certain extent that there is almost zero energy load after lowering the heating setting temperature under the condition of a better building envelope structure. At the same time, this improvement does not deteriorate the indoor thermal environment.

## References

(1) Development and application of building energy simulation software based on Energy-Plus, Master Thesis, Hunan University, 2009.

(2) Design code atlas for residential buildings (13J815), China building standard design and Research Institute, 2013.

(3) Design standard for energy efficiency of residential buildings in Severe Cold and Cold Zones (JGJ26-2010), China Architecture& Building Press, 2010.

(4) Design standard for energy efficiency of residential buildings in Hot Summer and Cold Winter Zone (JGJ134-2010), China Architecture& Building Press, 2010.

(5) Design standard for energy efficiency of residential buildings in Hot Summer and Warm Winter Zone (JGJ75-2012), China Architecture& Building Press, 2012.

(6) Evaluation standard for indoor thermal environment in civil buildings (GB/T50785-2012), China Architecture& Building Press, 2012.

(7) Fanger, P.O. Thermal comfort. Robert E. Krieger, Malabar, FL. 1982.

(8) Tanabe Lab, PMV and PPD calculation software, available at: http://www.tanabe.arch.waseda.ac.jp.

(9) Meinan Wang, Nobuyuki Sunaga, Effect of Air Conditioning Operation Patterns on Indoor Thermal Environment and Energy Consumption of Multi-Residential Buildings in Hot and Humid Region Paper_0508, The 33° International Passive Low Energy Architecture (PLEA) Conference, UK, 2017.

(10) Yaoqing LU, Practical design handbook for heating and air conditioning, China Architecture & Building Press, 2008.

# CHAPTER 6 COMPARISON ANALYSIS OF INVESTIGATION AND SIMULATION RESULTS IN DIFFERENT CLIMATE ZONES

## 6.1 Introduction

The first three chapters mainly described the residential indoor thermal environment and energy consumption condition as well as the influential parameters for improving indoor thermal environment and energy consumption in different climate zones of China. There were great disparities in different climate zones. For a better understanding of the differences between different climate zones and their respective causes, this chapter compared and analyzed the measured results in different climate zones from the aspects of indoor thermal environment and energy consumption.

## 6.2 Comparison of results in different climate zones

Table 6-1 shows the comparison of investigation and simulation results as well as the corresponding improvement proposals for each climate zone.

Table 6-1 Comparison of results* in different climate zones

| **Climate zone** | | | **SC** | **C** | **HSCW** | **HSWW** | **T** |
|---|---|---|---|---|---|---|---|
| **Investigation city** | | | **Harbin** | **Qingdao** | **Hangzhou** | **Guangzhou** | **Kunming** |
| **Investigation in winter** | **Measured period** | | 2016.12~2017.2 | 2014.12~2015.2 | 2014.12~2015.2 | | |
| | **Outdoor temperature** | | -12.0ºC | 3.8ºC | 8.0ºC | | |
| | **Heating** | **Method** | District heating system | | AC/Electric heater | | |
| | | **Service time/day(h)** | 24 | | 5.5/2.5 | | |
| | | **Frequency/week(day)** | 7 | | 2.5 | | |
| | **Indoor temperature (ºC)** | | 23.5 | 20.9 | 13.7 | | |
| | **Indoor relative humidity (%)** | | 27.9 | 38.2 | 58.2 | | |
| | **Vertical temperature difference (ºC)** | | 2.4 | 3.2 | 1.3 | | |
| | **Clothing insulation(clo)** | | 0.5 | 0.9 | 1.5 | | |
| | **Thermal neutral temperature(ºC)** | | 22.1 | 20.6 | 18.1 | | |
| | **Energy consumption($kWh/m^2$)** | | 10.1 | 8.9 | 3.2 | | |
| **Investigation in summer** | **Measured period** | | | 2014.8~9 | 2014.7~9 | 2016.7~9 | |
| | **Outdoor temperature** | | | 25.3 | 28.5 | 31.0 | |
| | **Cooling** | **Method** | | AC/Electric fan | AC/Electric fan | AC/Electric fan | |
| | | **Service time/day(h)** | | Seldom | 6.7/2 | 8.6/1.3 | |
| | **Indoor temperature(ºC)** | | | 26.6 | 27.8 | 29.6 | |
| | **Indoor relative humidity(%)** | | | 68.6 | 74.8 | 70.1 | |
| | **Clothing insulation(clo)** | | | 0.3(1)** | 0.2 | 0.2 | |
| | **Thermal neutral temperature(ºC)** | | | 25.3(2) | 27.3(3) | 28.4 | |
| | **Energy consumption($kWh/m^2$)** | | | - | 3.7 | 4.6 | |
| **Simulation*** ** | **Energy demand** | **External wall** | 12% | 18% | 14% | 15% | 45% |
| | | **External window** | 7% | 17% | 21% | 23% | 3% |
| | | **Air tightness** | 37% | 36% | 30% | 17% | 22% |
| | | **Setting temperature** | 12% | 23% | 35% | 49% | 56% |
| | **Comfort** | **External wall** | 14% | 8% | 10% | 7% | 35% |
| | | **External window** | 2% | 4% | 9% | 13% | 13% |
| | | **Air tightness** | 6% | 6% | 9% | -16% | 37% |
| | | **Setting temperature** | -82% | -83% | -71% | -59% | -6% |

*The results are the average values of living rooms and bedrooms in different residence in the same city.

**The results are derived from previous research.

*** The results of energy demand and comfort in simulation represent the reduction rate of energy demand and PPD relative to standard case, respectively.

### 6.2.1 Comparison of investigation results in winter

1. Comparison of heating methods and service time

(1) Heating methods


Figure 6-1 District heating coverage area in China

Figure 6-1 shows the district heating coverage area in China. It can be seen that in China's five different climatic zones, only Severe Cold Zone and Cold zone have the higher coverage of district heating system. This is mainly because the outdoor temperatures of other zones are relative higher, at the same time, the heating period of southern zones is short. The cost of construction and maintenance of district heating is relatively high, and the cost cannot be recycled in shorter use. Therefore, the district heating rate is low in southern china. The split self-heating including the split air conditioning and electric heater becomes the main heating methods in southern cities.

(2) Service time of heating

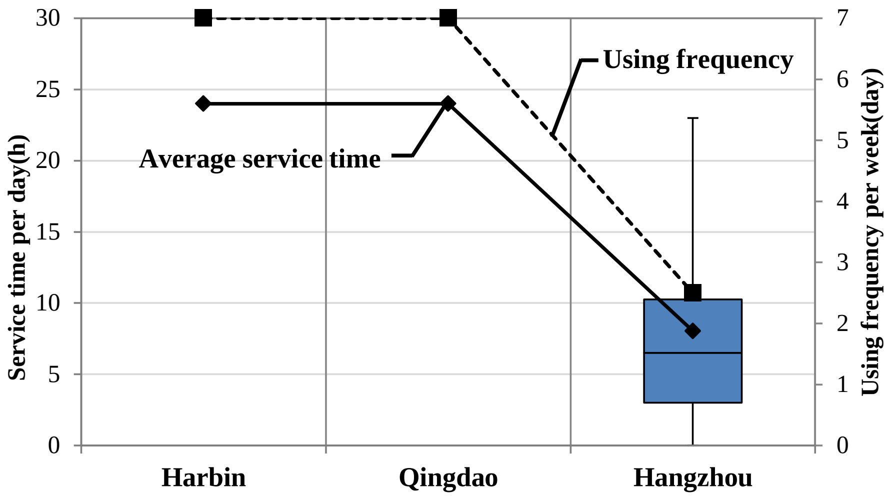



Figure 6-2 Comparison of service time

Figure 6-2 shows the comparison of service time in the three investigated cities. It can be seen that the district heating system in Harbin and Qingdao worked 24h uninterruptedly. Compared with these two cities, the service time of heating equipment in Hangzhou was relatively lower. The average daily service time of heating equipment was only about 8h, and the average daily service time of air conditioning was only about 5.5h. What's more the using frequency per week was also far lower than those in the district heating cities. This is mainly because the occupancy time of the residents in living room was shorter; the service time of heating equipment was mainly concentrated in the night when sleeping in bedroom.

2. Comparison of indoor thermal environment

(1) Indoor temperature

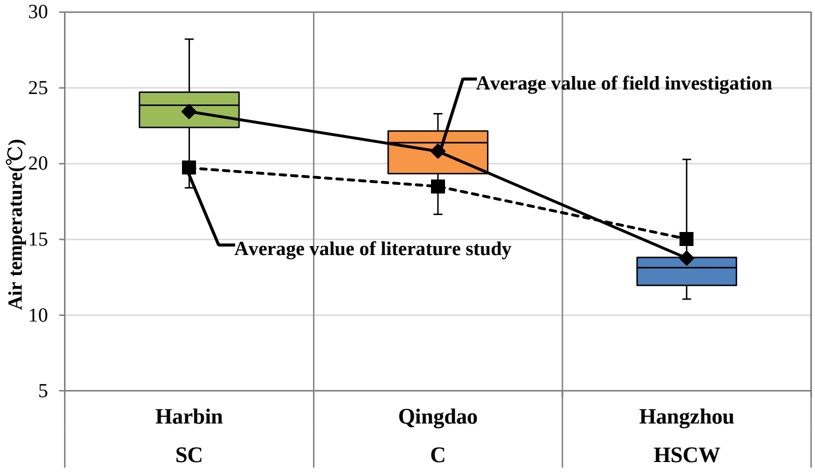


Figure 6-3 Comparison of indoor temperature in winter

Figure 6-3 shows the average indoor temperatures of field investigation and literature survey in different climate zones in winter. The results of literature survey and field investigation were derived from chapter 2 and chapter 3, respectively. The indoor temperature of heating rooms in Harbin was the highest. The average indoor temperature was 23.5ºC in Harbin. Although Harbin and Qingdao cities both had the district heating system and used the national unified standard temperature of district heating (The indoor temperature remained at 18~22ºC when heating), there were also differences in the actual indoor temperature. This is mainly because that the residential thermal insulation performance of envelope structure in Harbin in Severe Cold Zone was better than that in Qingdao in Cold Zone. However, in Hangzhou without the district heating system, because the service time of heating equipment was shorter compared to district heating and the use frequency was relatively lower, resulting in a lower indoor temperature.

In addition, the average indoor temperature of field investigation was higher than that of literature survey in Harbin and Qingdao. This is mainly because the average indoor temperature in the literature survey was the data over the past 15 years, the envelope structures of residences were continuously improved with the development of the age, and the district heating system was also perfected, so the indoor temperature of heating rooms in the field investigation was higher than that in the literature survey. However, the average indoor temperature of field investigation was slightly lower than that of literature survey in Hangzhou. This may be because the residents in this field investigation were all the university teachers, due to the special nature of work, the time they stayed in room during the daytime was short, leading to the shorter service time of air conditioning and heating equipment. However, the occupations of residents in the literature survey were no single and the service time of heating equipment was long, so the indoor temperature was relatively higher.

(2) Indoor relative humidity

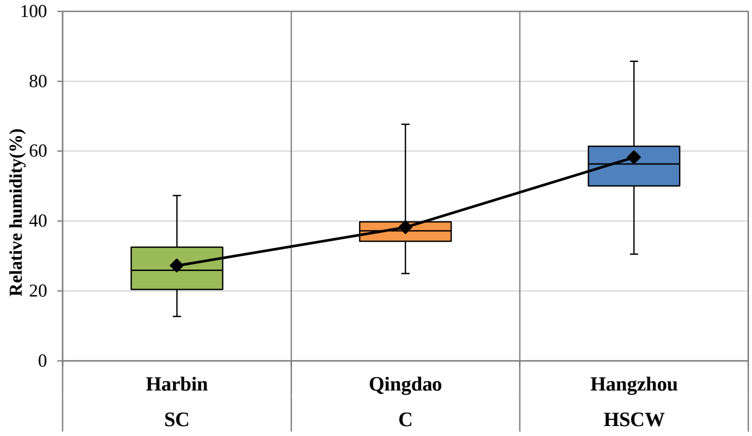


Figure 6-4 Comparison of indoor relative humidity in winter

Figure 6-4 shows the comparison of indoor relative humidity in different cities in winter. It can be seen that the relative humidity of residences in Harbin was the lowest, and far lower than the comfortable zone which specified by ASHRAE standard. This is because that the air tightness of residential envelope structure in Harbin where is located in the Severe Cold Zone was relatively better, and the indoor district heating system was running all-weather without intermission, the higher indoor temperature resulted in the evaporation of water vapor and thus the indoor relative humidity was reduced. The indoor relative humidity of heating rooms of residences in Qingdao increased slightly, but still remained below the comfort range (40%~60%). In addition, the indoor relative humidity of residences in Hangzhou was more appropriate. On the one hand, because the air tightness of residential envelope structure in Hangzhou where is located in the Hot Summer and Cold Winter Zone was not as good as those in northern cities and the outdoor relative humidity in winter was relatively larger in Hangzhou. On the other hand, compared to the all-weather district heating system, the service time of heating equipment used in this zone was relatively shorter which cannot cause the evaporation of indoor water vapor. Therefore, the indoor relative humidity in this zone was more comfortable.

(3) Vertical temperature difference

The vertical temperature differences in the cities which had district heating system were larger than that in the cities which used the air conditioning or other electric heater for heating. This is mainly because most of the district heating system adopted the wall type heat radiator, the thermal updraughts led to the relatively lower temperature around the floor in most surveyed residences. This kind of obvious temperature difference would not appear for the residences which used the air conditioning and other heating equipment for short time.

3. Comparison of clothing insulation

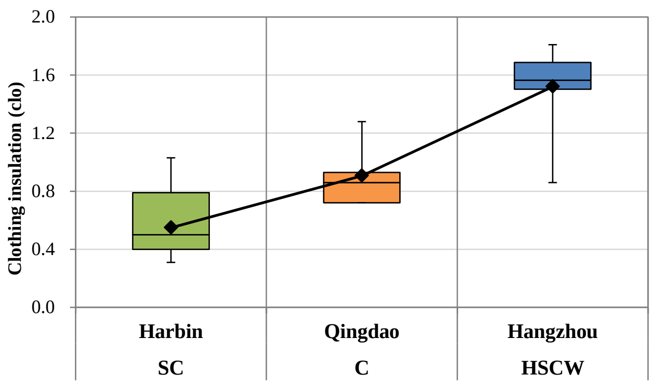



Figure 6-5 Comparison of indoor clothing insulation in winter

Figure 6-5 shows the comparison of indoor clothing insulation in winter. It can be seen that the clothing insulation was lower in the colder zone in winter. This is mainly due to the insulation and moisture diffusion hinder effects of clothing during the thermal balance process of human body. The residents would adjust the clothing thermal resistances depend on indoor thermal environmental conditions so as to reach a comfortable state. Therefore, the clothing insulation level of residents was the lowest in Harbin because of the highest indoor temperature, while the clothing insulation level of residents was the highest in Hangzhou because of the lowest indoor temperature.

4. Comparison of thermal neutral temperature

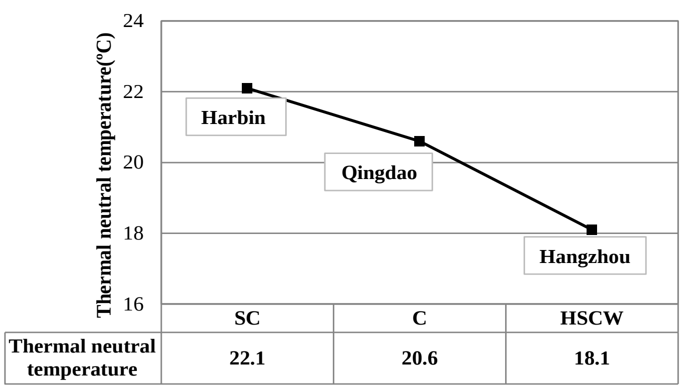



Figure 6-6 Comparison of thermal neutral temperature in winter

Figure 6-6 shows the comparison of thermal neutral temperature in different climate zones in winter. The neutral temperature refers to the most moderate temperature of thermal sensation for the residents. It can be seen that the thermal neutral temperature was higher in the colder zone in winter. The thermal neutral temperature for residents in Harbin where is located in the Severe Sold Zone was the highest, was 22.1ºC; while the thermal neutral temperature for residents in Hangzhou where is located in the Hot Summer and Cold Winter Zone was the lowest, which was 18.1ºC. Table 6-2 shows the comparison of thermal neutral temperature with other cities. It can be seen that the result of thermal neutral temperature in this study was slightly higher than that of previous research. Mainly due to the better envelope structure performance, higher indoor air temperature and surface temperature of field measured residences, the clothing insulation was lower than that of previous research. Therefore, the residents need a higher indoor temperature to satisfy their thermal comfort.

Table 6-2 Comparison of thermal neutral temperature with other cities

| Climate zone | Location | Indoor average temperature(ºC) | Clothing insulation(clo) | Thermal neutral temperature(ºC) |
|---|---|---|---|---|
| SC | Harbin(4) | 20.8 | 1.4 | 21.5 |
| | Hulunbuir(5) | 25.4 | 0.5 | 21.9 |
| C | Jiaozuo(6) | 20.4 | 1.2 | 19.2 |
| | Dalian(7) | 21.6 | 1.1 | 19.9 |
| HSCW | Hangzhou(8) | 15.1 | - | 15.9 |
| | Hangzhou(9) | 15.4 | 1.5 | 15.6 |
| | Hunan(10) | 17.9 | 1.2 | 19.8 |
| | Hefei(8) | 18.5 | - | 19.1 |

In addition, it also can be seen from Table 6-2 that the thermal neutral temperatures of cities which are located in the Severe Sold Zone were higher than those of the other cities. This is mainly because the indoor temperature in the Severe Sold Zone was higher, and thermal sensation of human body had a certain thermal adaptability. This kind of thermal adaptation can be expressed as: if people suffer from thermal discomfort due to the changes of the external environment, then people will respond to restore their thermal comfort in some way (11).Humphreys, Brager et al. had done a lot of research on thermal adaptability. Humphreys pointed out the thermal adaptability included the behavioral adaptability, psychological adaptability and physiological adaptability. The behavioral adjustment adaptability of human body was initiatively to create a thermal environment that you feel comfortable through a series of behavior adjustment measures, such as the behaviors of putting on or taking off clothes (changing the clothing insulation), turning on or shutting down the air conditioning (12). Brager also conducted a questionnaire survey to demonstrate that the behavioral adjustment had a higher influence on thermal comfort of human body among these three types of adjustments, especially the adjustment of clothes thermal insulation. The results showed that the field measurement investigation for 23 respondents in 7 residential buildings was conducted for 864 hours. There were behavioral adjustment activities for 273 times in total, of which the adjustment of clothing amount accounted for 62 times(13). Based on the data of field investigation and previous research, the relationship between the thermal neutral temperature and indoor clothing insulation can be obtained as shown in Figure 6-7. There was a strong linear relationship between the thermal neutral temperature and indoor clothing insulation. This also proved that the adjustment of clothing insulation had a direct influence on the thermal neutral temperature.

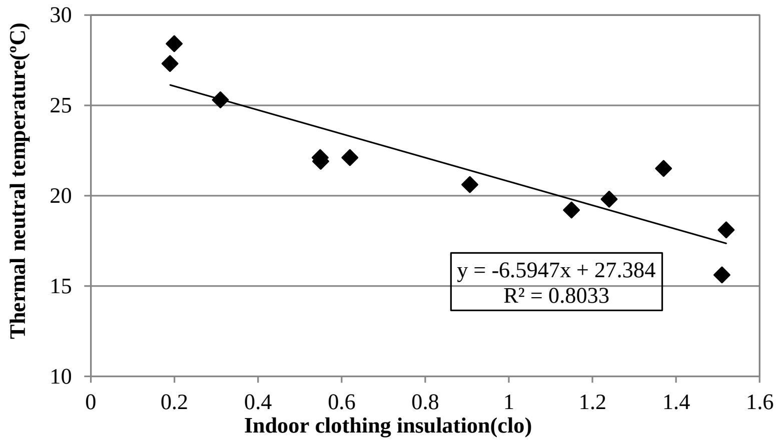



Figure 6-7 Relationship between thermal neutral temperature and indoor clothing insulation

Psychological adaptability refers to the reduction of thermal sensation sensitivity of human body caused by the exposure to thermal stress environment for a long time. The physiological adjustment mainly embodied as the body temperature regulation, sweating function, water and salt metabolism and the adaptive changes of cardiovascular system. Humphreys had ever studied the thermal neutral temperatures of 36 investigators from different countries all over the world and found that there was a high correlation between the thermal neutral temperature and indoor air temperature (12).

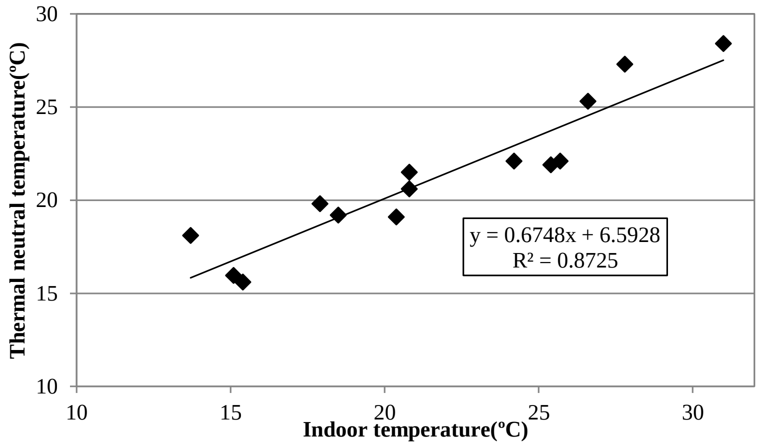



Figure 6-8 Relationship between thermal neutral temperature and indoor temperature

Based on the combination data of field investigation and previous research, the relationship between the thermal neutral temperature and indoor temperature can be obtained as shown in Figure 6-7. It can be seen that there was a strong linear relationship between the thermal neutral temperature and the indoor air temperature. This also demonstrated that because of thermal adaptability of human body, the higher the indoor temperature, the thermal neutrality temperature was higher.

In conclusion, due to the thermal adaptability, the higher indoor temperature and lower indoor clothing insulation in Harbin resulted in a higher thermal neutral temperature. Similarly, the lower indoor temperature and higher indoor clothing insulation led to a lower thermal neutral temperature than those of the other zones.

5. Comparison of monthly energy consumption

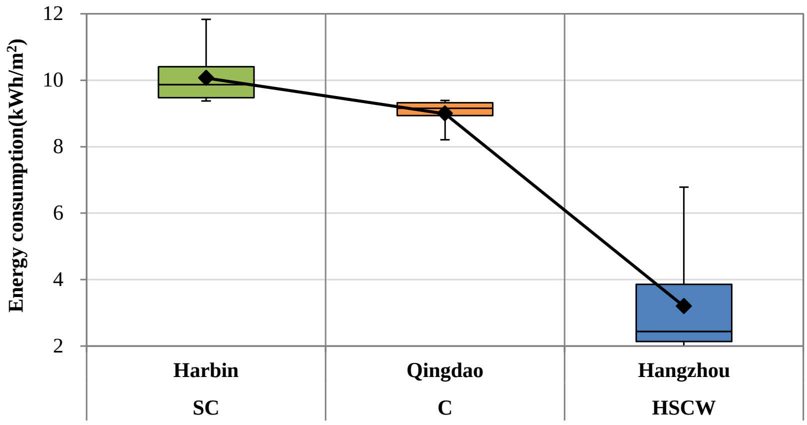



Figure 6-9 Comparison of monthly energy consumption in winter

Figure 6-9 shows the comparison of monthly energy consumption in different cities in winter. The monthly energy consumption in Harbin and Qingdao was larger, and the least in Hangzhou. This is because the energy consumption of district heating accounted for the major part of total energy consumption. At present, the charge of district heating was based on floor area, ran 24h uninterruptedly without household regulating system. There really existed problems about energy wasting. However, the service time of heating equipment in Hangzhou was shorter, thus the energy consumtion for heating was less than Harbin and Qingdao. In addition, because the difference in indoor and outdoor temperature in Harbin was far larger than that that in Qingdao, the heat amount which was required to reach the same temperature was greater, leading to the slightly higher heating price in Harbin than that in Qingdao. In addition, the colder climate of Harbin resulted in the slightly higher heating proportions of different rooms of residences in Harbin than that in Qingdao. Therefore, the monthly energy consumption in Harbin was slightly higher than that in Qingdao.

### 6.2.2 Comparison of investigation results in summer

1. Comparison of service time of cooling equipment

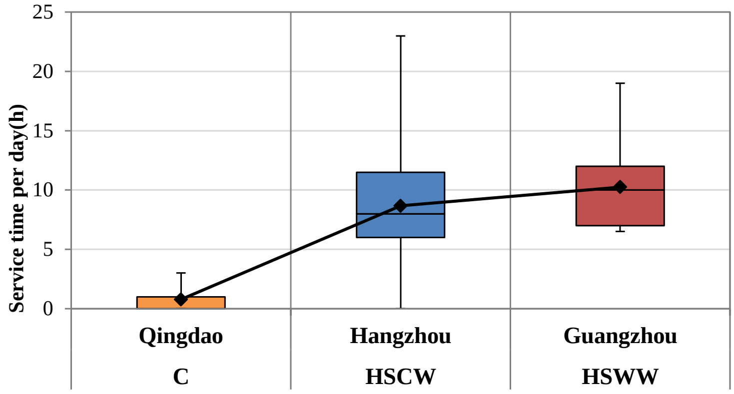



Figure 6-10 Comparison of service time of cooling equipment in summer

Figure 6-10 shows the comparison of service time of cooling equipment in summer. The service time of cooling equipment was the least in Qingdao. This is mainly because the summer in Qingdao was not intensely hot during the day and cool at night. Cooling equipment was seldom used. However, the service time of cooling equipment was the longest in Guangzhou. The service time of air conditioning and electric fan was 8.6h and 1.3h, respectively. This is mainly because Guangzhou was located in the Hot Summer and Warm Winter Zone which the outdoor temperature in summer was the highest. In addition, the difference between daytime and night-time temperatures was relatively small. Therefore, most of the residents were accustomed to using air conditioning for cooling when they slept in the night.

2. Comparison of indoor thermal environment

(1) Indoor temperature

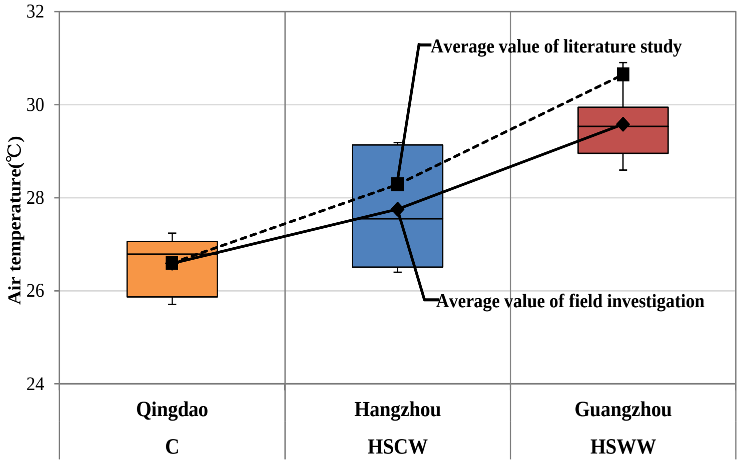



Figure 6-11 Comparison of indoor temperature in summer

Figure 6-11 shows the comparison of indoor temperatures in different cities in summer as well as the comparisons between the field investigation and literature survey. The results of literature survey and field investigation were derived from chapter 2 and chapter 4, respectively. Although cooling equipment was seldom used, the indoor temperature in Qingdao was the lowest. This mainly profited from the lower outdoor temperature. Due to the consecutive overcast and rainy weather, the indoor temperature was not same as high as those in previous years in Hangzhou. Although the service time of indoor air conditioning of residences in Guangzhou was relatively longer, the indoor temperature was relatively higher due to the far higher outdoor temperature than those of the other two cities. As a result, it can be observed that the residential indoor temperature in summer was mainly determined by climatic conditions, while the residential indoor thermal environment in winter was mainly determined by service conditions of heating equipment.

In addition, the indoor temperature of field investigation was slightly lower than that of literature survey. There were two main reasons for this, on the one hand, the envelope structure performance of field investigated residences was better than that of literature studied residences which were constructed earlier. On the other hand, the penetration rate and using frequency of air conditioning were higher than those in the past.

(2) Indoor relative humidity

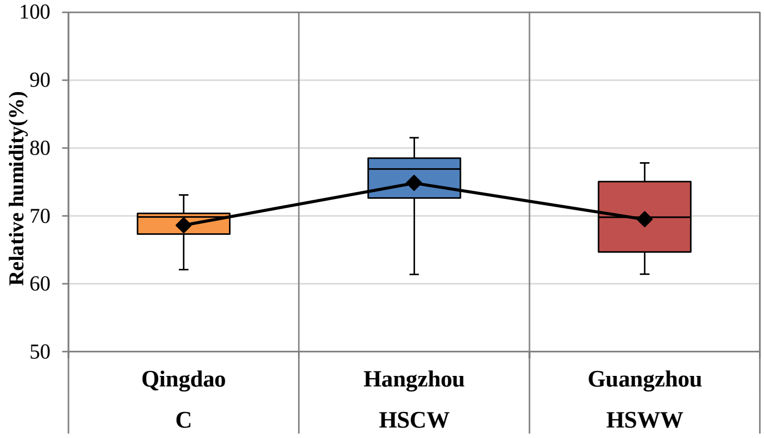



Figure 6-12 Comparison of indoor relative humidity in summer

Figure 6-12 shows the comparison of indoor relative humidity in different cities in summer. There were little differences between the residential indoor relative humidity in summer of these three cities, and all higher than the comfort range of relative humidity. The reasons were because that these three cities all belonged to the coastal cities with greater rainfall in summer, resulting in the larger indoor relative humidity.

3. Comparison of clothing insulation

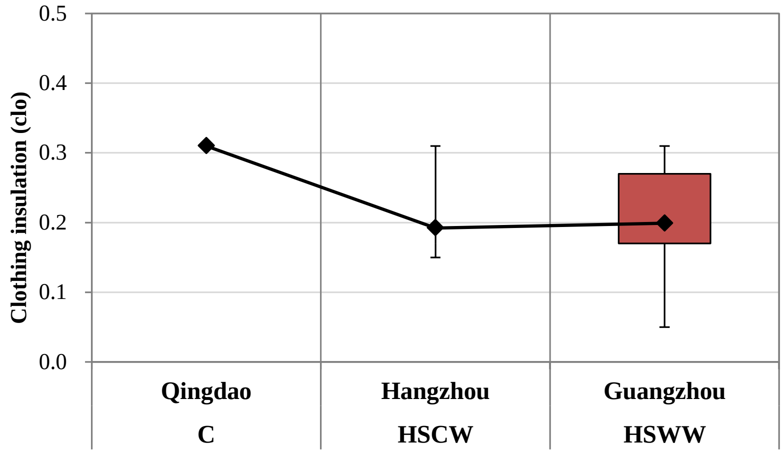
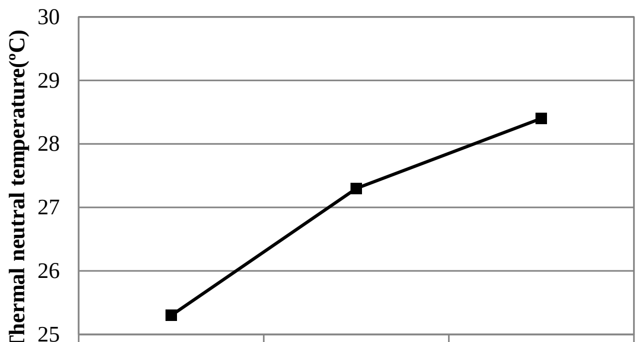



Figure 6-13 Comparison of clothing insulation in summer

Figure 6-13 shows the comparison of clothing insulation in different cities in summer. The indoor clothing insulation of residents in different cities was approximately similar. The residents would adjust the clothing thermal resistances depend on indoor thermal environmental conditions so as to reach a comfortable state. The residential indoor temperature in summer of cold zone was slightly lower than those of the other zones, leading to the slightly higher indoor clothing insulation of residents with 0.31clo. The clothing thermal resistance values of residents in Hangzhou and Guangzhou were almost the same with about 0.2clo.

4. Comparison of thermal neutral temperature




| | C | HSCW | HSWW |
|---|---|---|---|
| Thermal neutral temperature | 25.3 | 27.3 | 28.4 |

Figure 6-14 Comparison of thermal neutral temperature in summer

Figure 6-14 shows the comparison of thermal neutral temperature in summer. It can be seen that the thermal neutral temperature was higher in the hotter zone in summer. This also because of thermal adaptability of human body, the higher the indoor temperature, the thermal neutrality temperature was higher. The heat dissipation mechanism, clothing adjustment, etc. of human body caused the thermal adaptability when prolonged stay in a relatively hot environment.

Therefore, the thermal neutral temperature of residents was higher in Guangzhou with higher residential indoor temperature, while the thermal neutral temperature of residents was lower in Qingdao with lower residential indoor temperature.

5. Comparison of monthly energy consumption

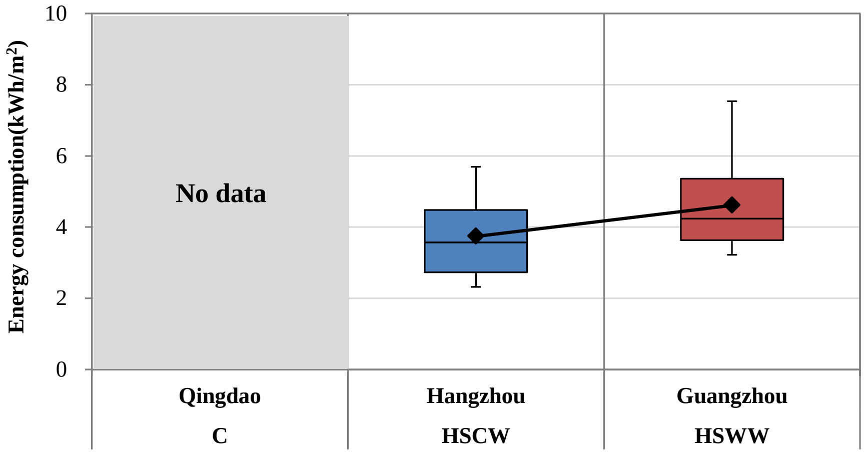



Figure 6-15 Comparison of monthly energy consumption in summer

Figure 6-15 shows the comparison of monthly energy consumption in summer. The monthly energy consumption in Guangzhou was larger than that in Hangzhou. In summer, the electricity consumption of air conditioning accounted for the major part, the electricity shortage even occurred during the peak hours of air conditioning. The average daily service time of air conditioning in Guangzhou was longer, and the higher outdoor temperature led to the larger cooling load, causing that the energy consumption of air conditioning was higher than that in Hangzhou.

### 6.2.3 Comparison of simulation results

In the Severe Cold and Cold Zones where required greater heating levels in winter, air tightness of residential building should be considered a priority as a better air tightness can deliver a significant heating energy reduction. This is mainly because that the outdoor temperatures in these two zones were both lower than those of the other climate zones, the larger difference in indoor and outdoor temperature, the indoor heating loads caused by the exchange of indoor and outdoor air through the gaps between doors and windows were bigger. The correlational research indicated that for the typical multi-residential buildings in Harbin zone, the air heat loss caused by the gaps of doors and windows accounted for about 29% of total heat loss, while 23%(14) for the buildings in Cold Zone. As a result, the air tightness of residences had great influence on the energy consumption of heating in these two climatic zones.

However, the quality of external wall insulation performance was the main contributor to the indoor thermal environment in winter for the colder climate zones. This is because that the indoor comfort not only depended on indoor temperature and humidity but also had a direct relationship with radiation temperature, and the facade area of exterior wall covered the main radiation part. For example, under the conditions of same indoor temperature and humidity in winter, the inner surface temperature of exterior wall with better insulation performance was relatively higher and the radiation temperature was far higher than that of residence without the insulation of exterior wall, which led to the increase of human body comfort. In addition, there were also studies indicated that the thermal sensation of human body in the residences with insulation of exterior wall was on the upper edge of comfort zone and near the hotspots, with feeling warm; while the thermal sensation of human body in residence without insulation of exterior wall was on the lower edge of comfort zone. In winter, the surface temperature of indoor wall in residence with insulation of exterior wall was relatively higher, and there was no cold wall effect (15). Therefore, the insulation performance of residential exterior wall had the greatest effect on indoor comfort in winter.

In the Hot Summer and Warm Winter Zone where the comfort in summer was the main concern, the improvement of external window performance and the addition of external shading were the key issues that affected the cooling energy demand and indoor thermal comfort. This is because that for the energy consumption of air-conditioning in summer, the exterior window of envelope structure had the largest proportion with up to around 70%, which was the main part of residential energy consumption in summer(16). In addition, the shading of exterior window had a significant influence on indoor comfort in summer. The reasons were that the solar radiation was relatively strong in summer of Hot Summer and Cold Winter Zone, the residential indoor heat through the exterior window was relatively more, resulting in the higher surface temperature of residential exterior window and the obvious baking sensation for the indoor residents. Therefore, in Hot Summer and Cold Winter Zone, the improvement on insulation of exterior window and sunshade performance had a significant influence on indoor thermal environment and energy consumption of air conditioning.

Compared with the poor effects of lowering heating temperature in the north of China, rising cooling temperature in the south was relatively effective method to save energy without causing a sharp deterioration of the indoor thermal environment. It is likely to be that compared to Severe Cold Zone and Cold Zone, the outdoor temperature hovered at around 28ºC for a part of time, rising the cooling temperature to 28ºC resulted in the little or even no difference in indoor and outdoor temperature for a part of time, which can significantly reduce the cooling energy demand. However, the outdoor temperature was below 10ºC all the time in Severe Cold Zone and Cold Zone, reducing the heating temperature to 16ºC could not stop heating for a part of time. Therefore, the heating energy consumption at energy saving was only the energy efficiency caused by reducing 2ºC of heating temperature. In addition, in terms of indoor thermal comfort, because the temperature sensitivity in winter was far higher than that in summer, rising the cooling temperature by 2ºC could not cause the sharp deterioration of indoor thermal environment. On the other hand, it can be obtained from the experimental results of this paper that the residential indoor neutral temperature of human body in summer of Hot Summer and Warm Winter Zone was higher than those of the other zones. In contrast, the residential indoor neutral temperature of human body in winter of Severe Cold Zone and Cold Zone was higher than those of southern zones. Therefore, lowering the heating temperature in the Severe Cold Zone and Cold Zone could cause the sharp deterioration of indoor thermal environment. However, rising the cooling temperature in southern zones could reduce the energy consumption of air-conditioning and would not cause the sharp deterioration of indoor thermal environment.

### 6.2.4 Comparison of improvement proposals in different climate zones

Table 6-3 shows the comparison of improvement proposals in different climate zones. At first, the insulation performance of external wall should be optimized to improve the indoor thermal environment for all climate zones.

In winter, for the Severe Cold Zone and the Cold Zone, the district heating temperature should be appropriately reduced to improve indoor comfort and save the energy. At the same time, the household heat-regulating system should be put into practice as soon as possible to avoid the overheating phenomenon. In addition, corresponding measures should be adopted for indoor humidification. Moreover, due to the lower outdoor temperature, air tightness improvement should be considered to save energy demand in these two colder zones. In contrast with these zones, the indoor environment in the Hot Summer and Cold Winter Zone which had no district heating system was in a cold condition, so the envelope performance should be improved to reduce heat dissipation. Meanwhile, the economy and comfort should be simultaneously taken into account to decide whether to adopt the district heating system or not.

In summer, because the natural ventilation became the main cooling method in the Cold Zone, so the proper room layout and direction of residence that are better for summer natural ventilation should be constructed in this zone. For the other two hotter zones, the external window insulation performance should be considered to improve indoor thermal environment and save cooling energy demand. In addition, the thermal environment and energy consumption should be comprehensively considered to design the usage pattern of air conditioning depend on human thermal sensation. Rising the cooling temperature should be considered to save cooling temperature. Measures should be taken to reduce indoor humidity in summer for all climate zones.

Table 6-3 Comparison of improvement proposals in different climate zones

<table>
<tr><th>Climate zone</th><th>SC</th><th>C</th><th>HSCW</th><th>HSWW</th><th>T</th></tr>
<tr><th>Investigation city</th><th>Harbin</th><th>Qingdao</th><th>Hangzhou</th><th>Guangzhou</th><th>Kunming</th></tr>
<tr><td rowspan="5">Improvement proposals</td><td rowspan="2"></td><td>◎Vertical-pipe type hot water circulation heating method should be changed;<br>◎Radiant floor heating method should be adopted;<br>◎ Proper room layout and direction of residence that are better for summer natural ventilation should be constructed.</td><td>◎ Envelope performance should be improved so as to reduce heat loss.<br>◎ Economy and comfort should be simultaneously taken into account to decide whether to adopt the district heating system.</td><td>The doors and the windows should be shut tight when using the air conditioning.<br>◎ An air conditioning should be avoided to conduct the cooling for more than one room at the same time.</td><td rowspan="2"></td></tr>
<tr><td colspan="3">◎Measures should be taken to reduce indoor humidity in summer.</td></tr>
<tr><td colspan="2" rowspan="2">◎District heating temperature should be appropriately reduced;<br>◎Household heat-regulating system should be put into practice;<br>◎ Corresponding measures should be adopted for indoor humidification in winter;<br>◎ Air tightness improvement should be considered to save energy demand;</td><td colspan="2">◎Frequency of using air conditioning should be increased to effectively reduce indoor temperature and relative humidity in summer.<br>◎ Thermal environment and energy consumption should be comprehensively considered to design the usage pattern of air conditioning depend on human thermal sensation.<br>◎ External window insulation performance should be considered to improve indoor thermal environment and save cooling energy demand.</td><td></td></tr>
<tr><td colspan="3">◎Raising cooling temperature should be considered to save cooling temperature.</td></tr>
<tr><td colspan="5">◎External wall insulation performance should be considered to improve indoor thermal environment in all climate zones.</td></tr>
</table>

## 6.3 Conclusion

This chapter compared the results of literature survey (chapter 2), field investigation (chapter 3 and 4) and simulation study (chapter 5), and analyzed the reasons for different results in different climate zones. The main conclusions were obtained as follows:

1) Because of the better condition of envelope structure performance and district heating system in winter as well as the higher penetration rate and using frequency of air conditioning in summer in field investigated residences, the indoor environment of field investigation was better than that in literature result.

2) The indoor temperatures in winter in SC Zone and C Zone were far higher than that in HSCW Zone. The district heating system in these two zones played a decisive role. However, the outdoor temperature had the most important influence on the indoor temperature in summer. The indoor temperature in summer in HSWW was higher than that in C Zone and HSCW Zone.

3) Because of the higher indoor temperature, the clothing insulation of residents was lower in the colder zone in winter. However, it was approximately similar in summer in three hotter zones.

4) Because the thermal sensation of human body has thermal adaptability, the thermal neutral temperature was higher in the colder zone which has higher indoor temperature in winter. And it was higher in the hotter zone in summer.

5) Due to the energy demand of district heating system, the monthly energy consumption in winter in SC Zone and C Zone were far larger than that in Hangzhou. However, except for Qingdao, there was no big difference between HSCW Zone and HSWW Zone in the monthly energy consumption in summer.

6) Because of the lower outdoor temperature and larger heating load, Air tightness of building has the most significant effect on energy saving for the SC Zone and C Zone.

7) Because the better insulation performance of external wall can improve the radiation temperature of inner wall, so it becomes the main contributor to the indoor thermal environment for all climate zones.

8) Because of the stronger solar radiation in summer, the improvement of external window performance and the addition of external shading are the key issues that affect the cooling energy demand and indoor thermal comfort in HSCW Zone and HSWW Zone.

9) Because the weaker temperature sensitivity and higher thermal neutral temperature in summer, raising cooling temperature in hotter zones is relatively effective method to save energy without causing a sharp deterioration of the indoor thermal environment.

10) In addition, according to the above results, from the point of view of energy saving and indoor environment improvement, the key improvement proposals in all five climate zones was presented.

## References

(1)Yiza XIA, Effects of airflow pulsation intensity and frequency on human thermal sensation, Master Thesis, Tsinghua University, 2000.

(2) J.G. Li, L. Yang, J.P. Liu, A thermal comfort field survey in residential buildings in hot summer and cold winter area, Sichuan Building Science 4(2008) 200-205.

(3)Y.Z. Xia, R.Y. Zhao, Y. Jiang, Study on thermal comfort of residential environment in Beijing, Journal of HV&AC 2(1999).

(4)Yiza XIA, Study on indoor thermal environment and thermal sensation of human body, Doctoral Thesis, Harbin Institute of Technology, 2012.

(5)Peng ZHANG, Xi-ping ZHAO, Study on indoor thermal environment comfort of residential buildings in cold zone in winter, Urban Buildings, 2015, 26:199~200.

(6)Hai-yan YAN, Liu YANG, Field study on occupant thermal comfort in residential buildings in Jiaozuo city in winter, HV&AC, 2011, 41(11):119~125.

(7)Feifei PENG, Study on indoor thermal environment and adaptability of occupants in residential buildings in cold zone in winter, Master Thesis, Dalian University of Technology, 2003.

(8)Yaya LI, The indoor thermal environment in winter of the residential for the hot summer and cold winter context- take Hangzhou and Hefei for example, Master Thesis, XI'AN University of Architecture and Technology, 2013.

(9)Yaya LI, Study on indoor thermal environment comfort of residential buildings in Hangzhou city in winter, Architectural Engineering Technology and Design, 2015, 19:2093.

(10)Wenjing LI, Human thermal sensations in different thermal environments, Master Thesis, Hunan University, 2006.

(11)Lin ZHANG, Study on adaptation and thermal comfort of residents in Harbin, Master Thesis, Harbin Institute of Technology University, 2010.

(12)M.A. Humphreys, Field studies of thermal comfort compared and applied. U.K, Department of environmental building research establishment current paper, 1975.

(13)Baker. N, Standeven. M, Comfort Criteria for Passively Cooled Building-A Pass cool task, Renewable Energy, 1994,5.

(14)Dong LIU, Peilin CHEN, Building environment and HVAC energy saving, Energy Conservation Technology, 2001, 19(2):17~19.

(15)Jiachun WANG, Peiyu YAN, Influence of exterior wall insulation system on indoor thermal comfort. Insulation Materials and Building Energy Saving, 2004 (11):36~38.

(16)Heng FU, Influence of external window on low energy resident building consumption, Master Thesis, Nanjing University of Technology, 2011.

# CHAPTER 7 CONCLUSION

This study mainly researched the actual condition of thermal environment and energy demand in multi-unit residences of five different climate zones in China through literature investigation, field measurement, questionnaire analysis and simulation analysis. On such basis, rational improvement proposals and measures to improve the comfort of indoor thermal environments and energy conservation in multi-unit residences in China are discussed. Section of 7.1 summarized the conclusions of each chapter and section of 7.2 advanced the direction of future research.

## 7.1 Summry of This Paper

**「Chapter 1 Introduction」**

This chapter mainly introduced the background and significance of this study which includes the risk of global climate change and energy shortages all over the world as well as the process of energy saving of urban multi-unit residences in China. The previous researches on multi-unit residences were also described. The limitation of existing research and the purpose of this study were proposed.

**「Chapter 2 Literature survey on multi-unit residences based on different climate zones」**

This chapter summarized the relevant previous literature pertaining to the multi-unit residences published over the past 15 years in five climate zones. Through reviewing about 99 articles, the data recorded in each article was extracted and statistical analyzed. The main conclusions can be drawn as follows:

1) The previous literatures about the multi-unit residences mainly concentrated in the C Zone and HSCW Zone. And the research mainly focused on the measurement of indoor thermal environment, performance optimization of envelope structure, statistics and simulation of energy consumption and evaluation of thermal sensation.

2) Compared with northern regions, there were few wall and window insulation measures and the thermal performance of envelope structures was poor in southern regions. However, the external windows were usually equipped with the sunshade measures in HSCW Zone and HSWW Zone.

3) According to the extracted average data of literature, the indoor temperature was summarized. In winter, the indoor average temperature of HSCW Zone was the lowest than the other climate zones, only about 15ºC. In summer, that of HSWW Zone was the highest, about 30.6ºC. Therefore, improving the indoor environment of multi-unit residences in winter of HSCW Zone and in summer of HSWW Zone became a priority among priorities.

4) The annual energy consumption of five climate zones was also summarized. The energy consumption of SC Zone was far higher than other climate zones, reached up to 51.8kWh/m$^2$.

**「Chapter 3 Field investigation of indoor thermal environment and energy consumption in multi-unit residences in winter」**

This chapter mainly researched the actual condition of indoor thermal environments and energy consumption in winter in multi-unit residences in three colder climate zones (Harbin, Qingdao and Hangzhou) in China through field measurement and questionnaire survey. Based on the obtained data such as the indoor thermal environment, thermal sensations of residents, energy consumption and so on, the current status and improvement proposals in these three colder climate zones in winter were clarified as follows:

1) Due to the effect of district heating, the indoor temperature was relatively high in SC Zone and C Zone. The average temperatures were 23.5ºC and 20.9ºC, respectively. In contrast, the indoor average temperature of Hangzhou in the HSCW Zone where has no district heating system and mainly uses the air conditioning was only 13.7ºC.

2) Compared with that in HSCW Zone, the relative humidity in the SC Zone and C Zone was low, only about 27.9% and 38.2%.

3) The clothing insulation of residents in winter in SC Zone, C Zone and HSCW Zone was 0.5clo, 0.9clo, and 1.5clo, respectively. It was relatively lower in the colder zone.

4) The indoor thermal neutral temperature in winter in SC Zone, C Zone and HSCW Zone was 22.1ºC, 20.6ºC and 18.1ºC, respectively. It was relatively higher in the colder zone.

5) The monthly total energy consumption in the SC Zone and C Zone was higher, about 10.1kWh/m2 and 8.9 kWh/$m^2$, respectively. Energy consumption of district heating was the major part of total energy consumption in these two zones. However, the monthly total energy consumption was low in HSCW Zone, only about 3.2kWh/$m^2$.

6) Therefore, the district heating temperature in the SC Zone and C Zone should be appropriately reduced to improve indoor comfort and save energy. At the same time, the household heat-regulating system should be put into practice as soon as possible to avoid the overheating phenomenon. For the HSCW Zone, the envelope performance should be improved to reduce heat dissipation. Meanwhile, the economy and comfort should be simultaneously taken into account to decide whether to adopt the district heating system.

**「Chapter 4 Field investigation of indoor thermal environment and energy consumption in multi-unit residences in summer」**

This chapter mainly researched the actual condition of indoor thermal environments and energy consumption in summer in multi-unit residences in three hotter climate zones (Qingdao, Hangzhou and Guangzhou) in China through field measurement and questionnaire survey. Based on the obtained data such as the indoor thermal environment, thermal sensations of residents, energy consumption and so on, the current status and improvement proposals in these three hotter climate zones in summer were clarified as follows:

1) The actual data of indoor thermal environment in summer of multi-unit residence of Guangzhou in HSWW Zone which has few previous researches as well as Qingdao in C Zone and Hangzhou in HSCW Zone was obtained.

2) The average indoor temperatures of Qingdao, Hangzhou and Guangzhou were 26.6ºC, 27.8ºC and 29.6ºC, respectively. Although the cooling equipment was seldom used and natural ventilation became the main cooling method, the indoor temperature was the lowest in C Zone.

3) Because all belonged to coastal cities with greater rainfall in summer, the indoor relative humidity was high in these three cities. The average relative humidity of Qingdao, Hangzhou and Guangzhou was 68.6%, 74.8% and 70.1%, respectively.

4) The risk of heatstroke was higher in HSCW Zone and HSWW Zone. The proportion in the danger zone of heat stroke was 13% and 31%, respectively.

5) The monthly energy consumption in HSWW Zone was slightly higher, about 4.6kWh/m2. The usage pattern of air conditioning including the service time and setting temperature can directly affect the cooling energy consumption.

6) Therefore, for the C Zone, the proper room layout and direction of residence that are better for summer natural ventilation should be constructed. For the HSCW Zone and HSWW Zone, frequency of using air conditioning should be increased to effectively reduce indoor temperature, and the thermal environment and energy consumption should be comprehensively considered to design the usage pattern of air conditioning depend on human thermal sensation. In addition, the measures should be taken to reduce indoor humidity in summer in all these three hotter climate zones.

**「Chapter 5 Simulation study on the energy saving potential of current conditions and influential parameter in different climate zones」**

This chapter compiled four different parameters (wall, window, air tightness and setting temperature) and performed dynamic building energy simulations on the basis of new energy saving standard (energy saving targets -65%). The energy saving potential of current heating and cooling system and building envelope performance were analyzed based on the actual data of indoor temperature and building envelope structure obtained from chapter 3 and 4. Meanwhile, the influential parameter on energy demand and indoor thermal comfort was clarified in all five climate zones. Based on the simulation results, the improvement proposals are suggested for each climate zone. The main conclusions can be drawn as follows:

1) The energy consumption of current status based on the actual results of field investigation was larger than that of new energy saving standard, and the energy saving potentials of current district heating system in SC Zone and C Zone was large, about 27% and 25%, respectively.

2) Changing the thermal insulation performance of envelope structure from current status to new energy saving standard had a significant energy saving effect on the heating energy demand in SC Zone and C Zone, about 24% and 37%, respectively.

3) The quality of the wall insulation is the main contributor to the indoor thermal environment for all climate zones.

4) In the SC Zone and C Zone that require greater levels of heating in winter, the air tightness of buildings should be considered a priority, because better air tightness can deliver a significant heating energy reduction.

5) On the contrary, in HSCW Zone and HSWW Zone where comfort in summer is regarded as the main concern, the improvement of external window performance and the addition of external shading are the key issues that need to be addressed.

6) Compared with the poor effects of lowering the heating temperature in the colder climate zones, raising the cooling temperature in the hotter climate zones is relatively an effective method to save energy without causing a sharp deterioration of indoor thermal environment.

**「Chapter 6 Comparison analysis of investigation and simulation results in different climate zones」**

This chapter compared the results of literature survey (chapter 2), field investigation (chapter 3 and 4) and simulation study (chapter 5), and analyzed the reasons for different results in different climate zones. The main conclusions were obtained as follows:

1) Because of the better condition of envelope structure performance and district heating system in winter as well as the higher penetration rate and using frequency of air conditioning in summer in field investigated residences, the indoor environment of field investigation was better than that in literature result.

2) The indoor temperatures in winter in SC Zone and C Zone were far higher than that in HSCW Zone. The district heating system in these two zones played a decisive role. However, the outdoor temperature had the most important influence on the indoor temperature in summer. The indoor temperature in summer in HSWW was higher than that in C Zone and HSCW Zone.

3) Because of the higher indoor temperature, the clothing insulation of residents was lower in the colder zone in winter. However, it was approximately similar in summer in three hotter zones.

4) Because the thermal sensation of human body has thermal adaptability, the thermal neutral temperature has a proportional relationship with indoor temperature. It was higher in the colder zone which has higher indoor temperature in winter. And it was higher in the hotter zone in summer.

5) Due to the energy demand of district heating system, the monthly energy consumption in winter in SC Zone and C Zone were far larger than that in Hangzhou in HSCW Zone. On the other hand, except for Qingdao, there was no big difference between HSCW Zone and HSWW Zone in the monthly energy consumption in summer.

6) Because of the lower outdoor temperature and larger heating load, Air tightness of building has the most significant effect on energy saving for the SC Zone and C Zone.

7) Because the better insulation performance of external wall can improve the radiation temperature of inner wall, so it becomes the main contributor to the indoor thermal environment for all climate zones.

8) Because of the stronger solar radiation in summer, the improvement of external window performance and the addition of external shading are the key issues that affect the cooling energy demand and indoor thermal comfort in HSCW Zone and HSWW Zone.

9) Because the weaker temperature sensitivity and higher thermal neutral temperature in summer, raising cooling temperature in hotter zones is relatively effective method to save energy without causing a sharp deterioration of the indoor thermal environment.

10) In addition, according to the above results, from the point of view of energy saving and indoor environment improvement, the key improvement proposals in all five climate zones was presented.

## 7.2 Future issues and prospects

This paper puts forward targeted suggestions to improve the comfort of indoor thermal environments and energy conservation in multi-unit residences in China according to the investigation results. It has a guiding significance for reducing energy consumption and improving indoor thermal comfort for Chinese multi-unit residences. However, due to the limitation of time and actual investigation conditions, this paper has some shortcomings and needs further more in-depth study:

- The basic situation of multi-unit residences and the income of residents have a greater impact on energy consumption. Due to the limitations of the investigation, residences in various situations were not investigated at all levels. Therefore, the investigated residences should be diversified.
- In the analysis of residential terminal energy consumption, due to the lack of a measuring instrument, only rough statistics of total electricity consumption and district heating expenses can be carried out, so the energy consumption of heating and cooling cannot be measured accurately. Therefore, the accuracy of energy consumption statistics needs to be improved.
- Simulation research mainly focused on the effect of building performance and heating or cooling temperature on the energy demand and indoor thermal comfort, and the model is unitary. However, the numerical simulation results are not compared with the measured data. Therefore, the next simulation study should be simulated according to the actual situation of investigative multi-unit residences.
- Despite this, the influence of different climatic characteristics on indoor thermal environment and energy demand is significant. Although it is also a climate zone, there is a obvious climate difference between coastal areas and inland areas. However, this study has limitations in selecting only one city in each climate zone. Therefore, the scope of the investigated cities should be expanded.

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**Meinan WANG**

# Appendix

# Appendix-1

# External Envelope Construction of Investigated Residences

**(1)Harbin**

<table>
<tr><th></th><th>External wall<br>(From outside to inside)</th><th>External window<br>(From outside to inside)</th><th>Roof<br>(From outside to inside)</th></tr>
<tr><td>SC-1</td><td colspan="3">—</td></tr>
<tr><td>SC-2</td><td>30mm Cement mortar<br>360mm Brick<br>120mm Asphalt expanded perlite<br>30mm Cement mortar</td><td>6mm Plate glass<br>12mm Air<br>6mm Plate glass</td><td>10mm Waterproof layer<br>30mm Cement mortar<br>150mm Polystyrene board<br>30mm Cement mortar<br>100mm Cement slag<br>120mm Reinforced concrete<br>25mm Cement mortar</td></tr>
<tr><td>SC-3</td><td rowspan="7">30mm Cement mortar<br>200mm Reinforced concrete<br>50mm Polyurethane foam plastics<br>30mm Cement mortar</td><td rowspan="7">6mm High transparency Low-e glass<br>12mm Rare gas<br>6mm High transparency Low-e glass</td><td rowspan="7">10mm Waterproof layer<br>30mm Cement mortar<br>150mm Polystyrene board<br>30mm Cement mortar<br>100mm Cement slag<br>120mm Reinforced concrete<br>25mm Cement mortar</td></tr>
<tr><td>SC-4</td></tr>
<tr><td>SC-5</td></tr>
<tr><td>SC-6</td></tr>
<tr><td>SC-7</td></tr>
<tr><td>SC-8</td></tr>
<tr><td>SC-9</td></tr>
</table>

(2)Qingdao

| | External wall (From outside to inside) | External window (From outside to inside) | Roof (From outside to inside) |
|---|---|---|---|
| **C-1** | 20mm Cement mortar<br>240mm Brick<br>40mm Asphalt expanded perlite<br>20mm Cement mortar | 6mm Plate glass<br>6mm Air<br>6mm Plate glass | 30mm Concrete capping plate<br>60mm Polystyrene board<br>10mm Waterproof layer<br>20mm Cement mortar<br>100mm Cement slag<br>120mm Reinforced concrete<br>25mm Cement mortar |
| **C-2** | — | | |
| **C-3** | 20mm Cement mortar<br>200mm Reinforced concrete<br>50mm Rubber powder EPS thermal insulation mortar<br>20mm Cement mortar | 6mm Plate glass<br>6mm Air<br>6mm Plate glass | 10mm Waterproof layer<br>30mm Cement mortar<br>110mm Polystyrene board<br>30mm Cement mortar<br>100mm Cement slag<br>120mm Reinforced concrete<br>25mm Cement mortar |
| **C-4** | 20mm Cement mortar<br>200mm Reinforced concrete<br>55mm Polystyrene board<br>20mm Cement mortar | 6mm Low-e glass<br>9mm Air<br>6mm Low-e glass | 10mm Waterproof layer<br>30mm Cement mortar<br>120mm Polystyrene board<br>30mm Cement mortar<br>100mm Cement slag<br>120mm Reinforced concrete<br>25mm Cement mortar |
| **C-5** | 20mm Cement mortar<br>240mm Brick<br>50mm Asphalt expanded perlite<br>20mm Cement mortar | 6mm Plate glass<br>6mm Air<br>6mm Plate glass | 30mm Concrete capping plate<br>50mm EPS extrusion plate<br>10mm Waterproof layer<br>20mm Cement mortar<br>100mm Cement slag<br>120mm Reinforced concrete<br>25mm Cement mortar |
| **C-6** | 20mm Cement mortar<br>200mm Reinforced concrete<br>50mm Rubber powder EPS thermal insulation mortar<br>20mm Cement mortar | 6mm Plate glass<br>6mm Air<br>6mm Plate glass | 10mm Waterproof layer<br>30mm Cement mortar<br>110mm Polystyrene board<br>30mm Cement mortar<br>100mm Cement slag<br>120mm Reinforced concrete<br>25mm Cement mortar |
| **C-7** | — | | |
| **C-8** | 20mm Cement mortar<br>200mm Reinforced concrete<br>45mm Foamed EPS thermal insulation mortar<br>20mm Cement mortar | 6mm Plate glass<br>6mm Air<br>6mm Plate glass | 10mm Waterproof layer<br>20mm Cement mortar<br>140mm Hydrophobic perlite board<br>20mm Cement mortar<br>100mm Cement slag<br>120mm Reinforced concrete<br>25mm Cement mortar |
| **C-9** | — | | |

### (3)Hangzhou

| | External wall<br>(From outside to inside) | External window<br>(From outside to inside) | Roof<br>(From outside to inside) |
|---|---|---|---|
| **HSCW-1**<br>**HSCW-2** | 20mm Cement mortar<br>200mm Reinforced concrete<br>20mm Rubber powder EPS thermal insulation mortar<br>10mm Cement mortar | 6mm Low-e glass | 10mm Waterproof layer<br>30mm Cement mortar<br>50mm Polystyrene board<br>30mm Cement mortar<br>100mm Cement slag<br>120mm Reinforced concrete<br>25mm Cement mortar |
| **HSCW-3** | 20mm Cement mortar<br>190mm Double row hollow concrete block<br>30mm Rubber powder EPS thermal insulation mortar<br>20mm Cement mortar | 6mm Plate glass<br>9mm Air<br>6mm Plate glass | 10mm Waterproof layer<br>30mm Cement mortar<br>50mm Polystyrene board<br>30mm Cement mortar<br>100mm Cement slag<br>120mm Reinforced concrete<br>25mm Cement mortar |
| **HSCW-4** | 20mm Cement mortar<br>200mm Reinforced concrete<br>20mm Rubber powder EPS thermal insulation mortar<br>10mm Cement mortar | 6mm Plate glass | 10mm Waterproof layer<br>30mm Cement mortar<br>30mm Polystyrene board<br>30mm Cement mortar<br>100mm Cement slag<br>120mm Reinforced concrete<br>25mm Cement mortar |
| **HSCW-5** | 20mm Cement mortar<br>220mm Aerated concrete<br>20mm Cement mortar | 6mm Plate glass<br>6mm Air<br>6mm Plate glass | 10mm Waterproof layer<br>30mm Cement mortar<br>50mm Polystyrene board<br>30mm Cement mortar<br>100mm Cement slag<br>120mm Reinforced concrete<br>25mm Cement mortar |
| **HSCW-6** | 20mm Cement mortar<br>200mm Reinforced concrete<br>35mm Rubber powder EPS thermal insulation mortar<br>20mm Cement mortar | 6mm Low-e glass | 10mm Waterproof layer<br>30mm Cement mortar<br>50mm Polystyrene board<br>30mm Cement mortar<br>100mm Cement slag<br>120mm Reinforced concrete<br>25mm Cement mortar |
| **HSCW-7** | — | | |
| **HSCW-8** | 20mm Cement mortar<br>220mm Aerated concrete<br>20mm Cement mortar | 6mm Plate glass<br>6mm Air<br>6mm Plate glass | 10mm Waterproof layer<br>30mm Cement mortar<br>50mm Polystyrene board<br>30mm Cement mortar<br>100mm Cement slag<br>120mm Reinforced concrete<br>25mm Cement mortar |
| **HSCW-9** | 20mm Cement mortar<br>240mm Brick<br>20mm Cement mortar | 6mm Plate glass | 10mm Waterproof layer<br>30mm Cement mortar<br>20mm Polystyrene board<br>30mm Cement mortar<br>100mm Cement slag<br>120mm Reinforced concrete<br>25mm Cement mortar |

**(4)Guangzhou**

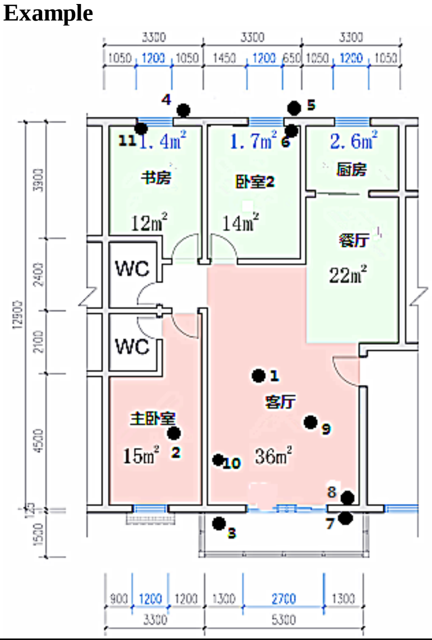
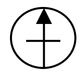
| | External wall<br>(From outside to inside) | External window<br>(From outside to inside) | Roof<br>(From outside to inside) |
|---|---|---|---|
| **HSWW-1** | 20mm Cement mortar<br>240mm Brick<br>20mm Cement mortar | 6mm Plate glass<br>16mm Air<br>6mm Plate glass | 10mm Waterproof layer<br>30mm Cement mortar<br>50mm Polystyrene board<br>30mm Cement mortar<br>100mm Cement slag<br>120mm Reinforced concrete<br>20mm Cement mortar |
| **HSWW-2** | Face brick<br>10mm Cement mortar<br>200mm Reinforced concrete<br>10mm Cement mortar | 6mm Plate glass | 10mm Waterproof layer<br>30mm Cement mortar<br>20mm Polystyrene board<br>30mm Cement mortar<br>100mm Cement slag<br>120mm Reinforced concrete<br>20mm Cement mortar |
| **HSWW-3** | 20mm Cement mortar<br>250mm Aerated concrete<br>20mm Cement mortar | 6mm Low-e glass<br>9mm Air<br>6mm Low-e glass | 30mm Concrete capping plate<br>50mm EPS extrusion plate<br>10mm Waterproof layer<br>20mm Cement mortar<br>100mm Cement slag<br>120mm Reinforced concrete<br>20mm Cement mortar |
| **HSWW-4** | — | | |
| **HSWW-5** | 20mm Cement mortar<br>240mm Brick<br>20mm Cement mortar | 6mm Plate glass | 10mm Waterproof layer<br>30mm Cement mortar<br>50mm Polystyrene board<br>30mm Cement mortar<br>100mm Cement slag<br>120mm Reinforced concrete<br>20mm Cement mortar |
| **HSWW-6** | — | | |
| **HSWW-7** | 20mm Cement mortar<br>240mm Brick<br>20mm Cement mortar | 6mm Low-e glass | 10mm Waterproof layer<br>30mm Cement mortar<br>50mm Polystyrene board<br>30mm Cement mortar<br>100mm Cement slag<br>120mm Reinforced concrete<br>25mm Cement mortar |
| **HSWW-8** | 20mm Cement mortar<br>190mm Double row hollow concrete block<br>30mm Rubber powder EPS thermal insulation mortar<br>20mm Cement mortar | 6mm Low-e glass | 10mm Waterproof layer<br>30mm Cement mortar<br>50mm Polystyrene board<br>30mm Cement mortar<br>100mm Cement slag<br>120mm Reinforced concrete<br>20mm Cement mortar |
| **HSWW-9** | 20mm Cement mortar<br>240mm Brick<br>20mm Cement mortar | 6mm Low-e glass | 10mm Waterproof layer<br>30mm Cement mortar<br>50mm Polystyrene board<br>30mm Cement mortar<br>100mm Cement slag<br>120mm Reinforced concrete<br>20mm Cement mortar |

# Appendix-2

# Residential Questionnaire

**Name** **Date**

## 1、Main information of residence

| Location | | | | | | | |
|---|---|---|---|---|---|---|---|
| Completion/Reform year | | | | Floor area（$m^2$） | | | |
| Structure (Circle) | BC / RC / Frame / Others | | | Window shade | | | |
| Floor / Total | | | | Orientation | | | |
| Overall of Family | | | | Location of residence | | Middle / Both ends | |
| Age structure | ~10 years: | 10~20: | 20~30: | 30~40: | 40~50: | 50~60: | 60~: |
| Plan and Measuring Points<br><br>1-Living room<br>2-Bedroom<br>3-Non-air conditioning room<br>4-Outdoor<br>5- Outer surface of exterior wall<br>6- Inner surface of exterior wall<br>7- Outer surface of Interior wall<br>8- Inner surface of Interior wall<br>9-Floor<br>10-Celling<br>11- Inner surface of exterior window | Example<br> | | | Plan and measuring points<br><br>—Wall ═ Window ● Measuring points<br>*1 Mark the sizes of window and wall and locations of measuring points.<br>*2 No need to paint the doors or windows which are open at all times. | | | |
| Size | Living room | Main bedroom | Bedroom | Study | Kitchen | Toilet | Others |
| Height of window | | | | | | | |
| Height of wall | | | | | | | |

## 2、Insulation structure of residence（Fill in it if clear）

| | | Material and thickness（mm）（inner→outer）<br>(One of the wall structure and insulation layer shall be chosen from the corresponding internal and external wall) |
|---|---|---|
| Example | | Cement paste（20mm）+ Brick / perforated brick / reinforced concrete / others（240mm）+ Insulation layer (aerated concrete, /EPS board / polyurethane rigid foam / cement expanded perlite / other)（50mm）+cement mortar（20mm） |
| Wall | Exterior | |
| | Interior | |
| Floor | | |

| Circle the corresponding materials and thickness | | | |
|---|---|---|---|
| Exterior Window | Frame | Structure | 1layer/2layer/3layer |
| | | Material | Steel / aluminum alloy / plastic / wood window |
| | Glass | Structure | Single / double layer / others |
| | | Material | Ordinary transparent glass / Low-E glass |
| | | Thickness | 3mm/6mm/9mm |
| | | Air thickness | 3mm/6mm/9mm/12mm |
| Indoor Window | Frame | Structure | 1layer/2layer/3layer |
| | | Material | Steel / aluminum alloy / plastic / wood window |
| | Glass | Structure | Single / double layer / others |
| | | Material | Ordinary transparent glass / Low-E glass |
| | | Thickness | 3mm / 6mm/ 9mm |
| | | Air thickness | 3mm / 6mm/ 9mm/ 12mm |

# 3、Heating/Cooling

## 1）Heating/Cooling method

| | Heating | | Cooling |
|---|---|---|---|
| 例 | District heating (Circle)<br>Radiator / Floor heating / Others | Non district heating (Circle)<br>AC/ Electric heater / Oil /Gas stove/Others | AC / Electric fan / Others (Circle) |
| Living room | | | |
| Main bedroom | | | |
| Bedroom2 | | | |
| Study | | | |
| Kitchen | | | |
| Dining room | | | |
| Washing room | | | |
| Toilet | | | |
| Bathroom | | | |
| others | | | |

## 2）Heating / Ventilation (ventilation with open window) / Humidifier Servicing time

**Weekday**

| Room | Device | Setting temperature /Intensity | Servicing time 0:00 | 3:00 | 6:00 | 9:00 | 12:00 | 15:00 | 18:00 | 21:00 |
|---|---|---|---|---|---|---|---|---|---|---|
| Example | District heating | Mid-range | | | | | | | | |
| | AC | 23℃ | | | | | | | | |
| | Ventilation | | | | | | | | | |
| | Humidifier | weak | | | | | | | | |
| Living room | | | | | | | | | | |
| Main bedroom | | | | | | | | | | |
| Bedroom2 | | | | | | | | | | |
| Study | | | | | | | | | | |
| Kitchen | | | | | | | | | | |
| Dining room | | | | | | | | | | |
| Washing room | | | | | | | | | | |
| Toilet | | | | | | | | | | |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Bathroom** | | | | | | | | | | |
| | | | | | | | | | | |
| | | | | | | | | | | |
| | | | | | | | | | | |
| **Others** | | | | | | | | | | |
| | | | | | | | | | | |
| | | | | | | | | | | |
| | | | | | | | | | | |

**Weekend**

| Room | Device | Setting temperature /Intensity | Servicing time 0:00 | 3:00 | 6:00 | 9:00 | 12:00 | 15:00 | 18:00 | 21:00 |
|---|---|---|---|---|---|---|---|---|---|---|
| **Example** | District heating | Mid-range | | | | | | | | |
| | AC | 23℃ | | | | | | | | |
| | Ventilation | | | | | | | | | |
| | Humidifier | weak | | | | | | | | |
| **Living room** | | | | | | | | | | |
| | | | | | | | | | | |
| | | | | | | | | | | |
| | | | | | | | | | | |
| **Main bedroom** | | | | | | | | | | |
| | | | | | | | | | | |
| | | | | | | | | | | |
| | | | | | | | | | | |
| **Bedroom2** | | | | | | | | | | |
| | | | | | | | | | | |
| | | | | | | | | | | |
| | | | | | | | | | | |
| **Study** | | | | | | | | | | |
| | | | | | | | | | | |
| | | | | | | | | | | |
| | | | | | | | | | | |
| **Kitchen** | | | | | | | | | | |
| | | | | | | | | | | |
| | | | | | | | | | | |
| | | | | | | | | | | |
| **Dining room** | | | | | | | | | | |
| | | | | | | | | | | |
| | | | | | | | | | | |
| | | | | | | | | | | |
| **Washing room** | | | | | | | | | | |
| | | | | | | | | | | |
| | | | | | | | | | | |
| | | | | | | | | | | |
| **Toilet** | | | | | | | | | | |
| | | | | | | | | | | |
| | | | | | | | | | | |
| | | | | | | | | | | |
| **Bathroom** | | | | | | | | | | |
| | | | | | | | | | | |
| | | | | | | | | | | |
| | | | | | | | | | | |
| **Others** | | | | | | | | | | |
| | | | | | | | | | | |
| | | | | | | | | | | |
| | | | | | | | | | | |

## 4、Thermal comfort

**1）Thermal sensation (please mark ○ at the corresponding number)**

| | Room | -3 | -2 | -1 | 0 | +1 | +2 | +3 |
|---|---|---|---|---|---|---|---|---|
| | | Very cold | Cold | Slight cold | Common | Slight hot | Hot | Very hot |
| Example | Living room | -3 | -2 | -1 | 0 | +1 | (+2) | +3 |
| | Living room | -3 | -2 | -1 | 0 | +1 | +2 | +3 |
| | Main bedroom | -3 | -2 | -1 | 0 | +1 | +2 | +3 |
| | Bedroom2 | -3 | -2 | -1 | 0 | +1 | +2 | +3 |
| | Study | -3 | -2 | -1 | 0 | +1 | +2 | +3 |
| | Kitchen | -3 | -2 | -1 | 0 | +1 | +2 | +3 |
| | Dining room | -3 | -2 | -1 | 0 | +1 | +2 | +3 |
| | Washing room | -3 | -2 | -1 | 0 | +1 | +2 | +3 |
| | Toilet | -3 | -2 | -1 | 0 | +1 | +2 | +3 |
| | Bathroom | -3 | -2 | -1 | 0 | +1 | +2 | +3 |
| | others | -3 | -2 | -1 | 0 | +1 | +2 | +3 |
| | Others | -3 | -2 | -1 | 0 | +1 | +2 | +3 |

**2）Thermal comfort (please mark ○ at the corresponding number)**

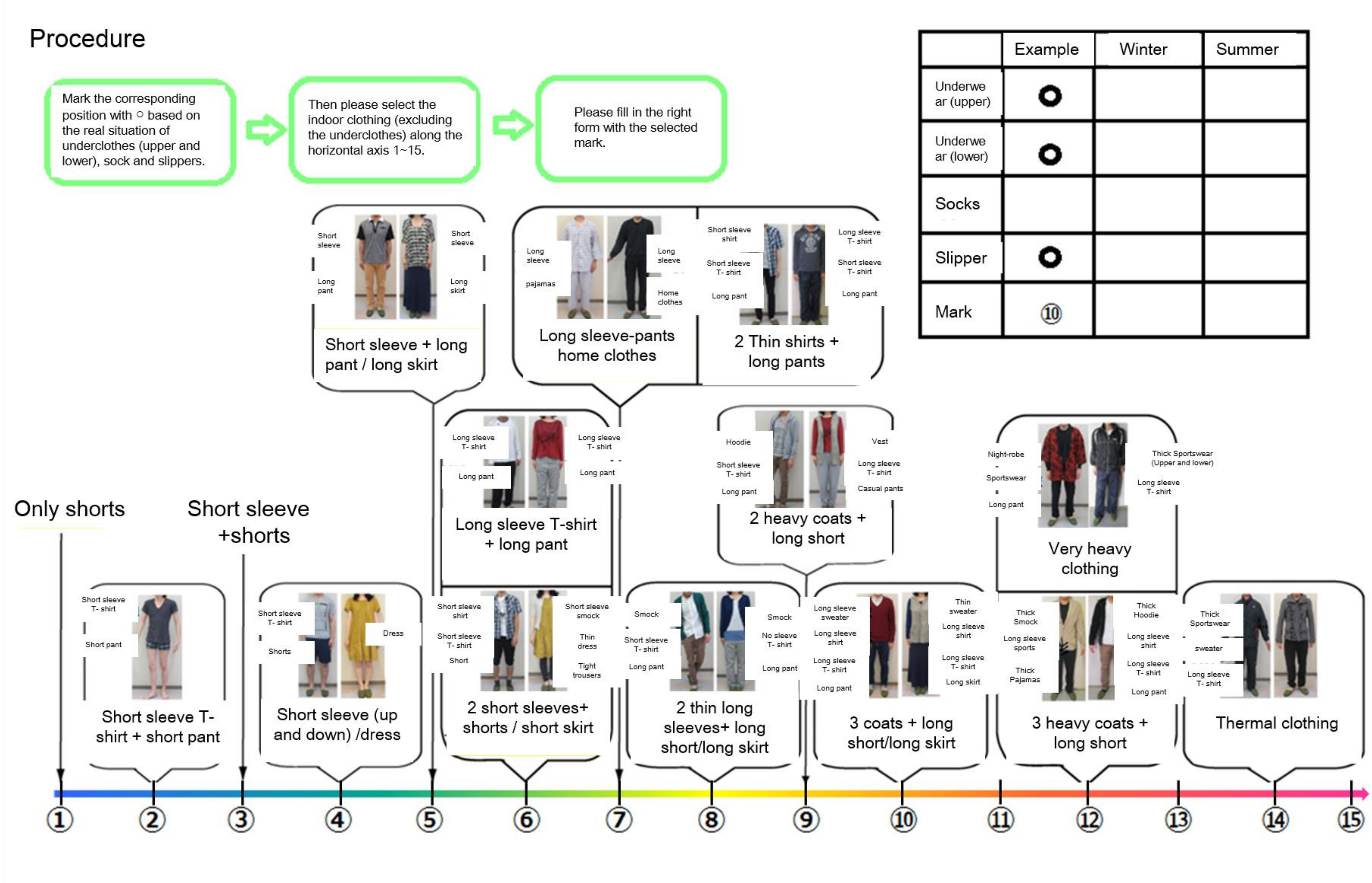
Reasons for「－1．Slight discomfort」～「-3．Very discomfort」

| | |
|---|---|
| A | Room is cold overall |
| B | Feel hot, because of the very good effect of Air conditioning/ district heating |
| C | Feet feel cold |
| D | Feel cold-blast air |
| E | The effect of air conditioning is poor, it works after a long time with open |
| F | Indoor temperature drops rapidly after stopping the heating equipment |
| G | Feel flushed face with hot when using air conditioning |
| H | Feel sweaty |
| I | Feel dry |
| J | Others |

| | Room | -3 | -2 | -1 | 0 | 1 | 2 | 3 | Reasons for discomfort | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Very discomfort | Discomfort | Slight discomfort | Common | Slight comfort | Comfort | Very comfort | Mark | Others |
| Example | Living room | -3 | -2 | -1 | 0 | +1 | +2 | +3 | A、J | Air leakage |
| | Living room | -3 | -2 | -1 | 0 | +1 | +2 | +3 | | |
| | Main bedroom | -3 | -2 | -1 | 0 | +1 | +2 | +3 | | |
| | Bedroom2 | -3 | -2 | -1 | 0 | +1 | +2 | +3 | | |
| | Study | -3 | -2 | -1 | 0 | +1 | +2 | +3 | | |
| | Kitchen | -3 | -2 | -1 | 0 | +1 | +2 | +3 | | |
| | Dining room | -3 | -2 | -1 | 0 | +1 | +2 | +3 | | |
| | Washing room | -3 | -2 | -1 | 0 | +1 | +2 | +3 | | |
| | Toilet | -3 | -2 | -1 | 0 | +1 | +2 | +3 | | |
| | Bathroom | -3 | -2 | -1 | 0 | +1 | +2 | +3 | | |
| | Others | -3 | -2 | -1 | 0 | +1 | +2 | +3 | | |
| | Others | -3 | -2 | -1 | 0 | +1 | +2 | +3 | | |

## 5、Clothing amount

Please fill in the clothing situation which is closest to that at home in winter and summer. From the choice straight line, please find the closest clothing (Excluding underwear) and record it (The righter the more thick).




| | Example | Winter | Summer |
|---|---|---|---|
| Underwear (upper) | ○ | | |
| Underwear (lower) | ○ | | |
| Socks | | | |
| Slipper | ○ | | |
| Mark | ⑩ | | |

## 6、The time in room

**A Living room  B Main bedroom  C Bedroom2  D Study  E Kitchen  F Dining room  G Washing room  H Toilet  I Bathroom  J Others**

| | Relation | Profession | | | The time at home 0:00 | 3:00 | 6:00 | 9:00 | 12:00 | 15:00 | 18:00 | 21:00 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Example | Father | Teacher | Weekday | Time in room | | | | | | | | |
| | | | | Place | | B | G F | | | | F | A B |
| | | | Weekday | Time in room | | | | | | | | |
| | | | | Place | | | | | | | | |
| | | | Weekend | Time in room | | | | | | | | |
| | | | | Place | | | | | | | | |
| | | | Weekday | Time in room | | | | | | | | |
| | | | | Place | | | | | | | | |
| | | | Weekend | Time in room | | | | | | | | |
| | | | | Place | | | | | | | | |
| | | | Weekday | Time in room | | | | | | | | |
| | | | | Place | | | | | | | | |
| | | | Weekend | Time in room | | | | | | | | |
| | | | | Place | | | | | | | | |
| | | | Weekday | Time in room | | | | | | | | |
| | | | | Place | | | | | | | | |
| | | | Weekend | Time in room | | | | | | | | |
| | | | | Place | | | | | | | | |
| | | | Weekday | Time in room | | | | | | | | |
| | | | | Place | | | | | | | | |
| | | | Weekend | Time in room | | | | | | | | |
| | | | | Place | | | | | | | | |
| | | | Weekday | Time in room | | | | | | | | |
| | | | | Place | | | | | | | | |
| | | | Weekend | Time in room | | | | | | | | |
| | | | | Place | | | | | | | | |

## 7、Energy consumption amount

**Electricity bills, Gas, Other fees, and Usage amount**

| Month | Electricity bills（Cost・Usage） | Gas fees（Cost・Usage） | Others（Cost・Usage） |
|---|---|---|---|
| 11 | Yen kWh | Yen ㎥ | Yen ℓ |
| 12 | Yen kWh | Yen ㎥ | Yen ℓ |
| 1 | Yen kWh | Yen ㎥ | Yen ℓ |
| 2 | Yen kWh | Yen ㎥ | Yen ℓ |

**District heating cost**

_______________Yen/$m^2$ _______________Yen/Year

# Thank you for your answer and cooperation!