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Evaluation on the energy consumption and thermal performance in different residential building types during mid-season in hot-summer and cold-winter zone in China

Haiqiang Liu[a],Shoichi Kojima[b]

[ab]*Department of Civil Engineering and Architecture*
Graduate School of Science and Engineering, Saga University,NO.1 honjomachi, Saga, Japan

Abstract

As a result of rapid urban development and economic growth in China, the energy issue is becoming more and more important today because of a possible energy shortage in the future. In China, residential energy consumption (REC) is the second largest energy use category (10%) following the industry (Residential energy consumption in urban China: A decomposition analysis, as shown in Fig.1), and is likely to continue its rapid growth. In order to fulfill the Chinese government`s commitment that Chinese CO_2 emissions would peak in 2030, as a result, improving the energy efficiency and reducing the emissions from the building sector is significantly important.
A survey, in the form of a questionnaire, of energy consumption and thermal situation in different residential building types (detached house, Multi-story building, high-rise building), was undertaken in three cities (Shanghai, Hangzhou in Zhejiang province, Changzhou in Jiangsu province) in hot-summer and cold-winter region, these three cities were selected to represent the most flourishing economic provinces. Hot-summer and cold-winter region in China was selected for the evaluation of energy and thermal performance analysis (EETP), because of its special weather conditions, huge energy consumption (as both heating in winter and cooling in summer are necessary), and other regional characteristics. 183 households were sampled during the survey. Energy consumption analyses showed that the amounts of energy use, in different building types were very different as their distinct characteristics. Also, experiments were separately done in typical examples of three different building types. Systematic evaluation on EETP for three different residential building types, were put forward to assess the energy efficiency and thermal performance of three different building types.

Keywords: Hot-summer and cold-winter, Thermal comfort,PMV,Evaluation of energy and thermal performance,Residential building type;

- Corresponding author. Tel.: +81 080-6470-0372; fax: +81 0952-28-8490.
- *E-mail address:* liu.haiqiang@hotmail.com

1. Introduction

The residential energy consumption of China in 2007 was almost 300 million tons of standard coal equivalent (Fig.2), which approximately equals the total amount of energy consumption of Brazil in the same year and comprises 10% of the year's total energy consumption, as in Fig.1 and Fig.2. China is a fast developing country with a vast size, and there are great differences in both the amount and structure of residential energy consumption at the unit level.

At the same time, with its rapid economic growth, people`s human thermal comfort requirement are improving. In the past, during the transition season (spring and autumn), people never used air conditioner even there was someday severely cold or hot. But this situation has changed in the recent years.

And for a long term, residential household energy consumption and the thermal performance in China are analyzed based on the intuitive sense. The researcher, always does qualitative analysis based on the "China Energy Statistics Book", a big data for an industrial classification, and call for energy saving, but it is meaningless if the reason cannot be found and how is the thermal performance. For these reasons, quantitative analysis of energy consumption in China is an important basis for research into improving the energy efficiency and thermal performance of the residential households.

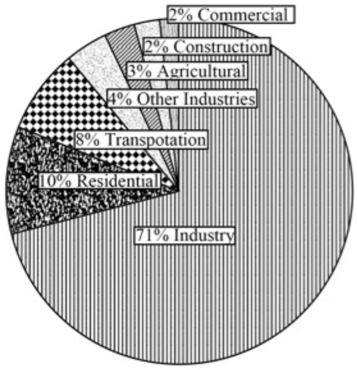

Fig. 1. China's total primary energy consumption in 2007.

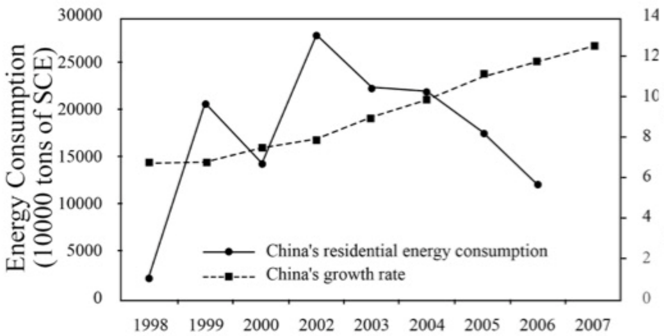

Fig. 2. Residential energy consumption and growth rate

(Data source: CSYs (1999–2008), SCE—standard coal equivalent.)

China has various types of climate due to its vast territory, complicated topography and a great disparity in elevation， hot summer and cold winter zone located at south center of China. Hot-summer and cold-winter zone in China includes 16 provinces, municipalities and special administration regions. It is sultry in summer and wet, cold in winter; the mean temperature of July is about 2℃ higher than other places of the same latitude in the world while the mean temperature of January is about 8~10℃ lower, and the mean temperature of the hottest month and the coldest month is between 25~30 and 2~7 ℃, respectively; Besides, the relative humidity in most cities here is 75~80%, even 95~100% sometimes (not in the rainy days), which is another characteristic. The whole winter is cold and rainy and is in great short of sunshine, take some cities, for example: the percentage of possible sunshine is 43% in Shanghai. This kind of climate brings huge load to the air conditioning system (data from the China Meteorological Bureau).

The purpose of this paper is to classify the energy and thermal situation in three different residential building types (detached house, multi-story building, high-rise building) and hoping to give higher thermal performance design methods and energy-efficient equipment advices. In hot summer and cold winter zone, both the architectural quality and the usage way have many problems. How to lead the people to a better lifestyle is still needing a long way to go.

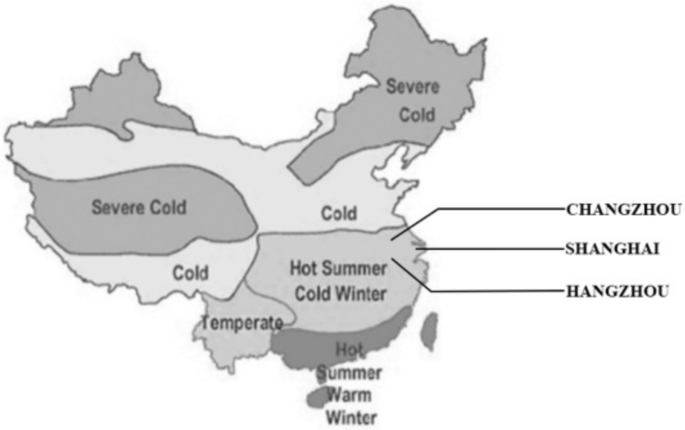

Fig. 3. Layout of five climate zones in China and the survey cities

2. Previous Studies

Residential energy consumption has been studied primarily through questionnaire surveys. Brounen [2] studied residential energy consumption behavior from the perspective of resource conservation. The sample data of more than 300,000 households in the Netherlands reveal that residential natural gas consumption is mainly determined by residence features, such as construction year, building type, etc.; while electricity consumption is determined by residential factors, such as income, age structure of family members, etc. Using the U.S. 2009 residential energy consumption survey (RECS) micro-data, Tsoand and Guan [3] confirmed the statistically significant impacts of division groups, single-family detached housing, house size, usage of space heating equipment, household size and usage of air-conditioners on residential energy consumption [3]. Heinonen and Junnila [4] employed the household budget survey data of Finland and demonstrate that behavioral differences seem significant between different housing modes and that each housing mode appears to be less energy-intensive in rural areas.

Regarding the residential energy consumption issues of China, Chen [5] conducted a co-integration analysis and argued that actual expenditure is a dominant factor among the factors the affecting residential energy demand and that urbanization and changes in energy consumption structure have little effect on residential energy consumption. Nie et al. [6] undertook a decomposition analysis of changes in energy consumption by Chinese households and argued that the increase in energy-using appliances is the biggest contributor followed by floor space per capita, while population is the most stable factor and energy mix is the least important factor. Zhao et al. [7] and Qin [8] decomposed the factors that have an impact on residential energy consumption by using the logarithmic mean Divisia index and conclude that population, household income, energy efficiency and structure directly affect residential energy consumption, and especially, the factor of income contributes the most. Particularly, Zhao et al. [7] also pointed out that the current energy structure is undergoing an intensive change promoting the usage of high-quality and cleaner energy, such as electricity and natural gas. Chen et al. [9] analyzed the data of residential energy consumption in Hangzhou and find that the resident age structure has more influence than income. Fu et al. [10] conducted a micro-demographic analysis of residential energy consumption in China and indicated that population changes, urbanization and aging are sensitive, while population age is not, except for the 60+ age group. Golley [11] extended the notion of household energy consumption by including indirect energy requirements, then examined the extent of variation in total energy requirements and emissions across households with different income levels in China and, finally, identified that, while richer households do indeed emit more per capita, poorer households tend to be more emissions-intensive.

With regards to rural areas of China, Xu [12] analyzed the residential energy consumption and its structural changes and suggested that income level, merchantability, energy quality and renewability determine the residential energy consumption level of rural households and the consumption structure in China. Lou [13] and Zhang et al. [14] studied rural residents' selection behavior in energy consumption, and the results reveal that household wealth, resource availability and the level of education and other household characteristics are the principal factors that determine the level and the structural change of China's energy consumption. Li et al. [15] discussed the current status and the regional differences of residential energy consumption in rural China and indicated that significant regional differences exist in the level of residential energy consumption in rural areas, with a gradually decreasing trend along the north-southwest axis of China. Lun et al. [16] reported the findings of field surveys in forest villages in Weichang County as a case study of rural energy consumption in northern China and find that local climate, family size and household income have strong influences on rural residential energy consumption. Suo [17] analyzed the residential energy consumption of rural Beijing, implying that the population is a major influence factor and that the energy-saving transformation can effectively reduce the energy consumption quantity.

3. Investigation

3.1. Introduction of Investigation

A survey, in the form of a questionnaire, of energy consumption and thermal performance in urban residential households in hot-summer and cold-winter zone in China was undertaken. Three cities, namely Shanghai, Hangzhou city in Zhejiang province, Changzhou city in Jiangsu province, from the most developed areas of China were analyzed. In the survey, 183 residential households were sampled and classified.

For historic reasons, the three different building types have many characteristics what different from the other two types. Around eighty years ago, most Chinese people lived in the detached house as a basic lifestyle rule. But after the 1970s, especially after the Chinese economic reform, large population rushed into the urban region from the rural area. To meet the housing demands of newcomers, the government began to build an amount of economical apartments in the form of multi-story building because of a lower cost. As the economics developed, started from the end of 1990s, high-rise building gradually became popular as the better location, good scene, and many other benefits. Of course, the larger expense must be paid. Like in Fig.4 and Fig.5 show the percentage and the construction year of each building type are consistent with the real situation.

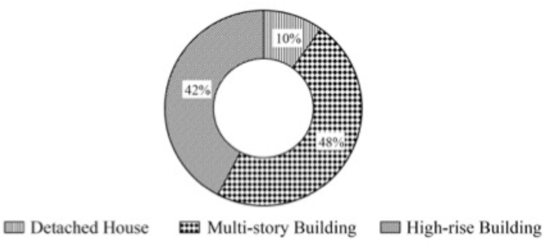

Fig. 4. Percentage of three building types

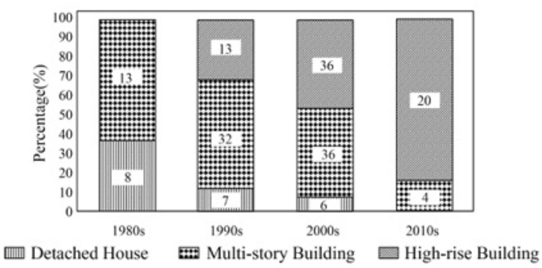

Fig. 5. Construction year of the investigated buildings

3.2. Investigation method

Table 1 lists the content of basic information for the investigated households. Sampling method was designed in a scientific way so as to obtain representative samples in each city. Three-phase sampling method was adopted, where investigated cities were decided firstly, and residential districts were selected in each investigated city secondly, and families in each selected residential district were finally taken out thirdly. In the first phase, all the cities with a population over than 1 million in hot-summer and cold-winter zone are classified. Typical cities were selected in each province based on the way of representative sampling. In this way, it is possible to reflect the respective characteristics of both residential energy use and thermal performance of the building by the investigators, and the adoption of representative sampling can help to the detail statistical analysis so that residential energy use and its relationship with important ingredients can be revealed. In the second phase, in order to ensure the representativeness and the universality of the selected samples, several typical residences were selected in the future in each investigated cities, and each residence was required to represent the common situation of energy use. In the third phase, households were finally chosen by random. It should be pointed out that attention was also paid on samples, selecting which bear different household backgrounds and domestic economic levels estimated by the basic information in Table 1.

Table 1. Items of the basic information

Location: City, District, Street	Building Floor Area
Family Composition	Construction Time
Building Structure Form	Area of Windows

3.3. The way to process missing data

Around 200 families are taken as the samples, and all the items in the questionnaires are taken as the variables when processing the missing data. There are usually two kinds of missing data. One is no answer for all the variables in the questionnaires, and the other is no answer for some items in the questionnaires. Sample delete, partial delete and interpolation are three different ways to deal with missing data:

(1) Sample delete is usually used for no answers for the whole questionnaire. If the families refuse to fill in the questionnaires, these samples should be deleted from the whole sample collectivity. In addition, if the families just fill in a very small part of the questionnaire so that the questionnaires are useless for the analyses, this kind of samples should also be deleted.

(2) Partial delete and interpolation are usually used for no answers for some items in the questionnaires. Partial delete means those samples with the missing data of one variable are invalid for the statistics of this variable, but they are still valid for the statistics of other variables. Thus, this will result in the different sample capacities for different variables.

(3) Interpolation is a way of using another value to replace the missing values. As for one variable, if the ratio of missing values is less than 5% of total samples, the overall average value of this variable can be used to replace the missing values. If the ratio of missing value is more than 5% of total samples, the way of ‘‘hot deck’’ is recommended, in which similar samples are classified into a group and the mean value of this group is used to substitute the missing data in this group.

Except the missing data, there are 183 families samples were used in this research.

4. Experiment

Actually, the experiment will last one year for data collection process. In this paper, we will take the mid-season as an example. As data is so large, we just selected the typical period.


（a）


（b）


（c）

Fig. 6. The pictures of experiment a,b,c

4.1. Introduction of Experiment

Based on the questionnaire above, three cases were selected for three residential building types. As shown in Table.1, the basic information was listed.

Table 2. Basic information of experiment subject

	Detached House	Multi-story Building	High-rise Building
Location City	Changzhou	Shanghai	Changzhou
Area	220 m^2	81m^2	140 m^2

4.2. Thermal comfort evaluation method

The thermal comfort conditions of the human body as a whole can be evaluated by means of the PMV index [18], which integrates the influence of the thermal comfort factors (air temperature, air velocity, mean radiant temperature, humidity, clothing and activity) into a value on a 7-point scale [19] (see Table 3).

Table 3. 7-points ASHRAE thermal sensation scale [20]

+3	Hot
+2	Warm
+1	Slightly Warm
0	Neutral
-1	Slightly Cool
-2	Cool
-3	Cold

The PMV-index is an objective method based on an analysis of the heat balance equation of the human body together with the influence of the physical environment and expressed as a subjective sensation. Although PMV index is expressed on a thermal sensation scale, it defines thermal comfort conditions rather than the thermal sensation. Therefore, it can be used as an index for the thermal environment assessment from the perspective of building and HVAC system performances.

Table 4. Ranges of application for the PMV model

Parameter	Value	Unit
Air Temperature	10-30	◦C
Mean Radiant Temperature	10-40	◦C
Water Vapor Partial Pressure	0-2700	Pa
Air Velocity	0-1.0	m/s
Metabolic Rate	0.8-4.0	Met
	46-232	Wm^{-2}
Clothing Thermal Insulation	0-2.0	Clo
	0-0.310	m^2kW^{-1}
PMV	-2 to 2	1

When PMV is zero, thermal comfort is maintained; + 1, + 2 and + 3 indicate slightly warm, warm and hot conditions, while - 1, - 2 and - 3 stand for slightly cool, cool and cold.

To express the quality of the thermal environment as a quantitative prediction of the percentage of thermally dissatisfied (i.e. people who feel too cold or too hot) the PPD-index (predicted percentage of dissatisfied) is also used. The PPD correlates to the PMV value by means of Eq. (1) whose mathematical structure reveals that a little percentage of dissatisfied (5%) can be expected under thermal neutrality conditions (i.e. PMV = 0).

4.3. PMV equation

In this study, the time-dependent PMV, which is a complex mathematical expression involving activity, clothing and the four environmental parameters, was generated from Fanger's expression:

$$PMV = \left(0.352e^{-0.042(M/A_{DU})} + 0.032\right)\left[M/A_{DU}(1-\eta) - 0.35\left(43 - 0.061\, M/A_{DU}(1-\eta) - p_a\right) - 0.42\left(M/A_{DU}(1-\eta) - 50\right) - 0.0023\, M/A_{DU}(1 - p_a) - 0.0014\, M/A_{DU}(34 - t_a) - 3.4\,10^{-8} f_{cl}\left((t_{cl}+273)^4 - (t_{mrt}+273)^4\right) - f_{cl}h_c(t_{cl} - t_a)\right] \quad (1)$$

where M/A_{DU} is the metabolic rate (W/m^2), η the mechanical efficiency, p_a the pressure of water vapor in ambient air (mm Hg), t_a the air temperature (◦C); f_{cl} the ratio of the surface area of the clothed body to the surface area of the nude body, t_{cl} the temperature of the clothing surface (◦C), t_{mrt} the mean radiant temperature (◦C), h_c the convection coefficient.

The t_{cl} is determined by the equation:

$$t_{cl} = 35.7 - 0.032\, M/A_{DU}(1-\eta) - 0.18 I_{cl} \times \left[3.4\,10^{-8} f_{cl}\left((t_{cl}+273)^4 - (t_{mrt}+273)^4\right) + f_{cl}h_c(t_{cl} - t_a)\right] \quad (2)$$

And h_c by

$$h_c = \{ \text{[illegible]} \quad (3)$$

where t_{c1} is insulation of clothing in clo unit and v is relative air velocity (m/s).
Eq. (1) is a transcendental equation, which can only be solved by an iterative process.
In this paper, the setting parameters are as follows.

Table 5. Parameters setting

Air temperature (℃)	RH (%)	Radiant temperature (°C)	Air speed (m/s)	Met.	Clo
Real-time temperature	Real-time humidity	Real-time temperature	0.1	1.1	1.0

5. Analysis

PMV is one of the most important indexes to evaluate the thermal situation. According to PMV equation and the temperature，humidity data from the experiment，PMV can be calculated. PMV analysis result was shown in the Fig. 7, all the three building types are in a very low situation in spring season. It is saying that in this season, the weather condition is still very cold.

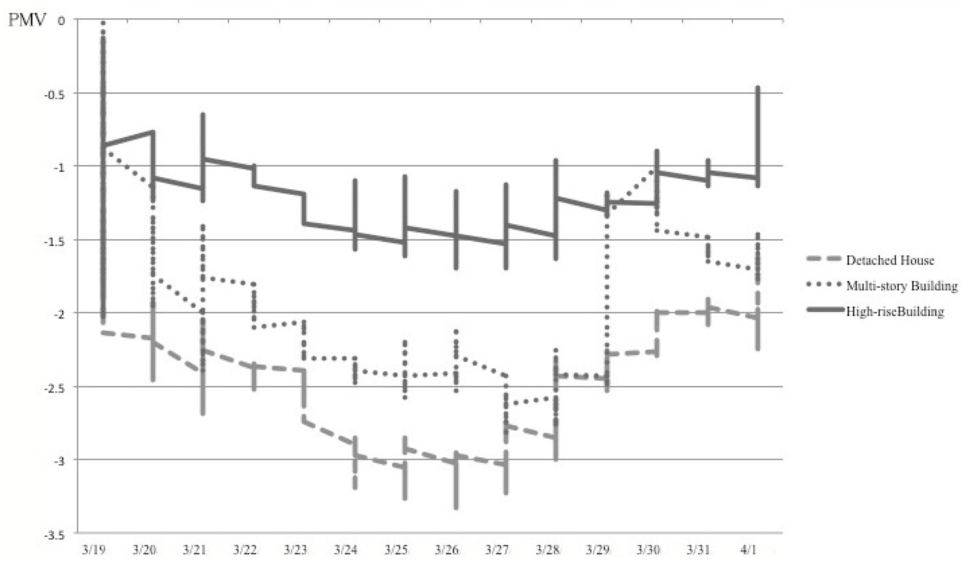

Fig. 7 PMV situation in three building types

In these three building types, high-rise building has the best situation compare to the other two building types. At the same time, the temperature of the high-rise building is the highest, for the thermal performance, we can get the high-rise building is best, and the second is multi-story building. The worst one is the detached house. Of course, that is not to say the insulation property is bad or not. And we can see the range of the PMV changes in one-day, the high-rise building type change range is the biggest as the biggest window size.

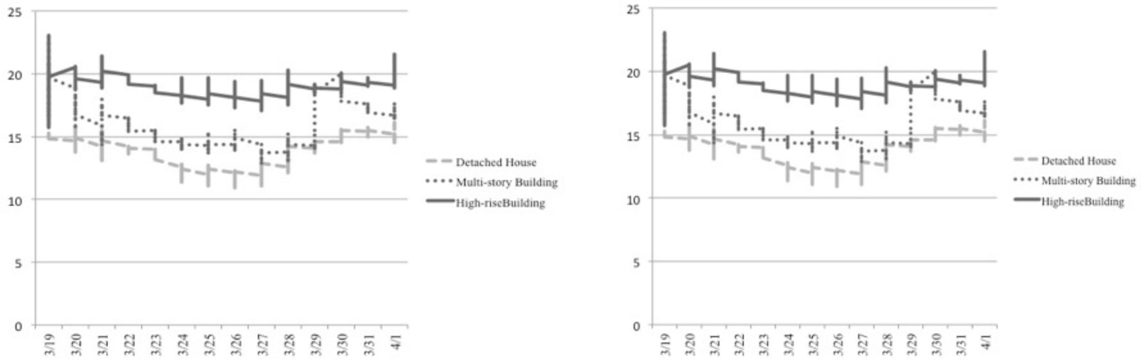

Fig. 8. Temperature (left) and Humidity (right) of three building types

Additionally, as people who live in different building types, have different lifestyles, income level, and other differences, the requirement for thermal human comfort are always very different. Figure 9 lists that the satisfaction degree of the residents to their thermal situation of their houses. "Very satisfied" was chosen by nobody, the percentage of above "acceptable" for detached house was only about 35%, the other two types are more than 80%. In another way, as shown in Fig.5, the high-rise building is the newest built type, the material, building craft and construction technologies are all better than before, so the thermal satisfaction of the high-rise building is better than the other two building types.

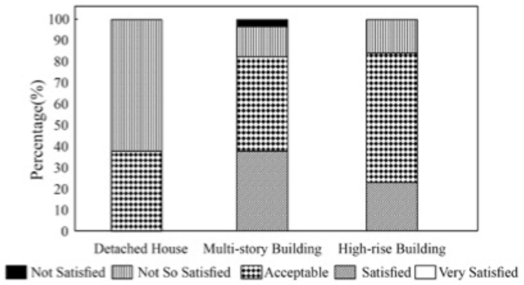

Fig. 9. Current thermal satisfaction use in different seasons for each type of situation

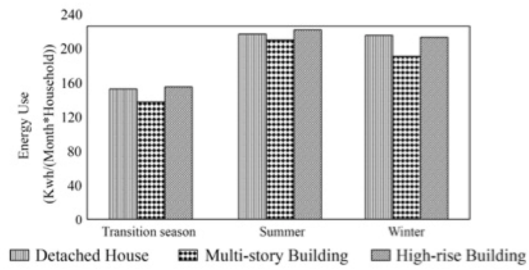

Fig. 10. Relationship between building type and energy use

Figure 10 shows the energy use in different building types. The multi-story building is the most energy saving type, the highest energy use type is a high-rise building, and the multi-story building is the most energy saving type. To combine with the Fig.7, the multi-story building type has bad thermal performance and the lowest energy using type, we can see people who live in this type is always see high of energy saving, as a reason of saving money, and at the same time, they can bear a cold condition.

6. Conclusion

Without considering the envelope reasons, the energy use and the thermal comfort requirement are always proportional. The three buildings all show the different characteristics of the building time. People in different building types have different human comfort requirements. And the energy consumption is very different in different building types. For the thermal comfort situation in these three building types, high-rise building has the best situation compare to the other two building types. At the same time, the temperature of the high-rise building is the highest, for the thermal performance, we can get the high-rise building is best, and the second is multi-story building.

The worst one is the detached house. For the energy use, the highest energy use type is a high-rise building, and the multi-story building is the most energy saving type. The multi-story building type has bad thermal performance and the lowest energy using type, we can see people who live in this type is always see high of energy saving, as a reason of saving money, and at the same time, they can bear a cold condition. In hot summer and cold winter zone, even in the mid-season, the extremely critical. For the thermal performance of three building types, we can get the high-rise building is best, and the second is multi-story building. On the other hand, for energy use, high-rise building has the best thermal performance, at the same time, is people who live in high-rise building have a high thermal comfort requirement.

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