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Energy Consumption and Thermal Performance in Different Residential Building Types in Hot-Summer and Cold-Winter Zone

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Abstract: In China, REC (residential energy consumption) is the second largest energy use category (10%) following the industry. 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, and Changzhou) in hot-summer and cold-winter regions, these three cities were selected to represent the most flourishing economic provinces. This region in China was selected for the evaluation of EETP (energy and thermal performance analysis), 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 and 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.

Key words: Hot-summer and cold-winter, thermal comfort, PMV, evaluation of energy and thermal performance, residential building type.

1. Introduction

The residential energy consumption of China in 2007 was almost 300 million tons of standard coal equivalent, 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 Figs. 1 and 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 is 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 [2].

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 calls 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 [3, 4].

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

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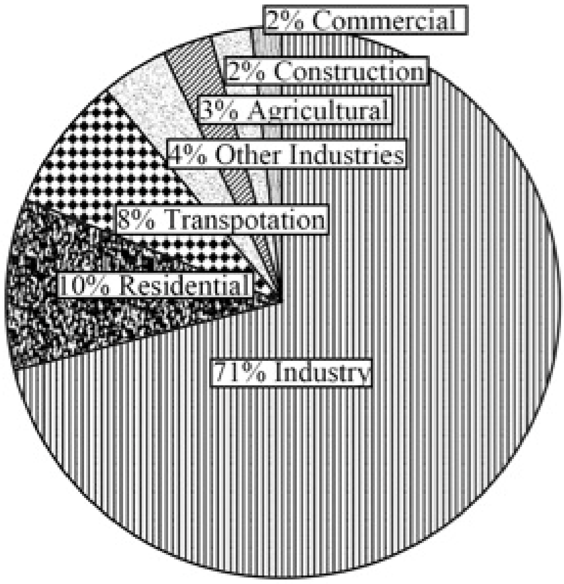

Fig. 1 China's total primary energy consumption in 2007.

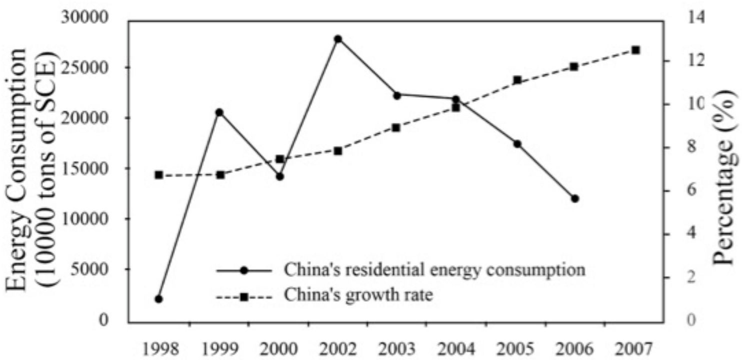

Fig. 2 Residential energy consumption and growth rate.

Source: China Statistical Yearbook (1999~2008), SCE—standard coal equivalent.

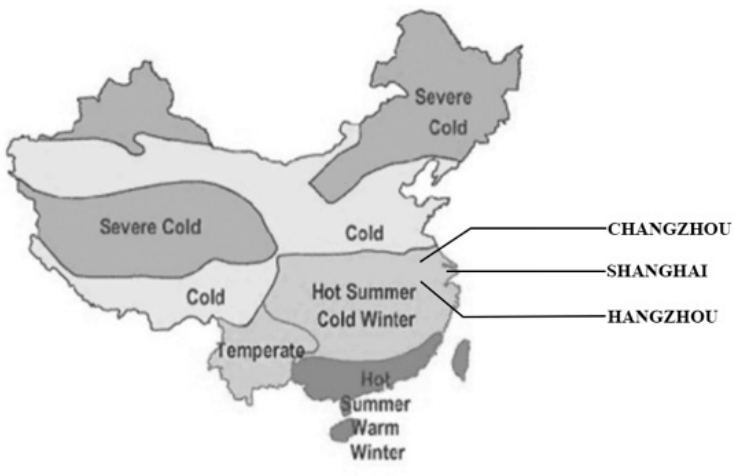

Fig. 3 Layout of five climate zones in China and the survey cities [1].

special administration regions. It is sultry in summer and wet, cold in winter; the mean temperature of July is about 2 °C higher than other places of the same latitude in the world while the mean temperature of January is about 8~10 °C lower, and the mean temperature of the hottest month and the coldest month is between 25~30 and 2~7 °C, respectively. Besides, the relative humidity in most cities here is 75%~80%, even 95%~100% sometimes (not in rainy days), which is another characteristic. The whole winter is cold and rainy, and is in great shortage of sunshine, take some cities, for example: the percentage of possible sunshine is 43% in Shanghai, as shown in Fig. 3. 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, and high-rise building), 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 still has a long way to go. Also, experiments were separately done in typical examples of three different building types. Systematic evaluation on EETP for three different residential building types, was put forward to assess the energy efficiency and thermal performance of three different building types.

2. Investigation

2.1 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 that are 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. Figs. 4 and 5 show the percentage and the construction year of each building type are consistent with the real situation.

2.2 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

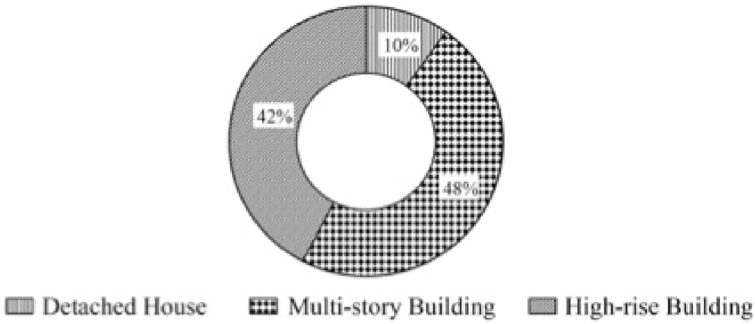

Fig. 4 Percentage of three building types.

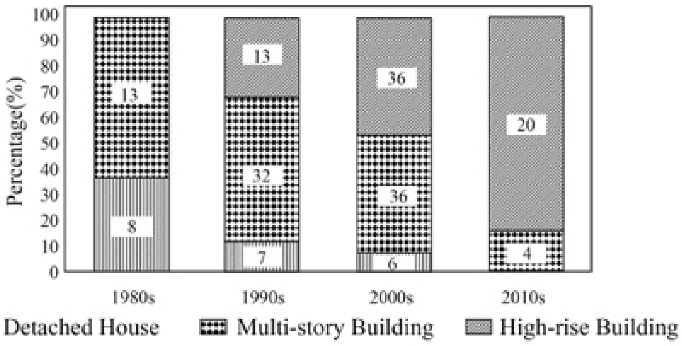

Fig. 5 Construction year of the investigated buildings.

Table 1 Items of the basic information.

Location: city, district, street	Building floor area
Family composition	Construction time
Building structure form	Area of windows

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.

3. Experiment

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

3.1 Introduction of Experiment

Based on the questionnaire above, three cases were selected for three residential building types. The experiment situations are in Fig. 6. As shown in Table 2, the basic information was listed.

3.2 Thermal Comfort Evaluation Method

The thermal comfort conditions of the human body as a whole can be evaluated by means of the PMV (predicted mean vote) index [5], 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 [6] (see Table 3).

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

(a) (b) (c)

Fig. 6 The pictures of experiment: (a) temperature sensor collector; (b) temperature sensor setting on window; (c) temperature-humidity on wall.

Table 2 Basic information of experiment subject.

	Detached house	Multi-story building	High-rise building
Location city	Changzhou	Shanghai	Changzhou
Area	220 m^2	81 m^2	140 m^2

Table 3 7-points ASHRAE thermal sensation scale [6].

Value	Sensation
+3	Hot
+2	Warm
+1	Slightly warm
0	Neutral
-1	Slightly cool
-2	Cool
-3	Cold

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	0-2,700	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

scale, it is expressed on a thermal sensation scale, and it also defines thermal comfort conditions (Table 4) 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 (heating ventilation air conditioning) system performances.

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 1 whose mathematical structure reveals that a little percentage of dissatisfied (5%) can be expected under thermal neutrality conditions (i.e., $PMV = 0$).

3.3 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 [6]:

$$PMV = \left(0.352e^{-0.042\left(M/A_{DU}\right)} + 0.032\right)\Big[M/A_{DU}(1-\eta) - 0.35\left(43 - 0.061\, M/A_{DU}(1-\eta) - p_a\right) - 0.42\left(M/A_{DU}(1-\eta) - 50\right) - 0.0023\, M/A_{DU}(1 - p_a) - 0.0014\, M/A_{DU}(34 - t_a) - 3.410^{-8} f_{c1}((t_{c1} + 273)^4 - (t_{mrt} + 273)^4) - f_{c1} h_c (t_{c1} - t_a)\Big] \quad (1)$$

where, M/ADU is the metabolic rate (W/m^2), 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:

$$t_{c1} = 35.7 - 0.032\, M/A_{DU}(1-\eta) - 0.18 I_{c1} \times [3.410^{-8} f_{c1}((t_{c1} + 273)^4 - (t_{mrt} + 273)^4) + f_{c1} h_c (t_{c1} - t_a) \quad (2)$$

And h_c by

$$h_c = \begin{cases} 2.05(t_{c1} - t_a)^{0.25} \text{for } 2.05(t_{c1} - t_a)^{0.25} > 10.4\sqrt{v} \\ 10.4\sqrt{v} \text{for } 2.05(t_{c1} - t_a)^{0.25} < 10.4\sqrt{v} \end{cases} \quad (3)$$

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 [7, 8].

In this paper, the setting parameters are in Table 5.

4. Analysis

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

As shown in Figs. 8 and 9, In these three building types, high-rise building has the best situation compared with the other two building types. At the same time, the temperature of the high-rise building is the highest, for the thermal performance, the high-rise building is best, and the second is the 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.

Additionally, as people who live in different building types, have different lifestyles, income level, and other differences, the requirements for thermal human comfort are always very different. Fig. 10 lists 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,

Table 5 Parameters setting

Air temperature (°C)	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

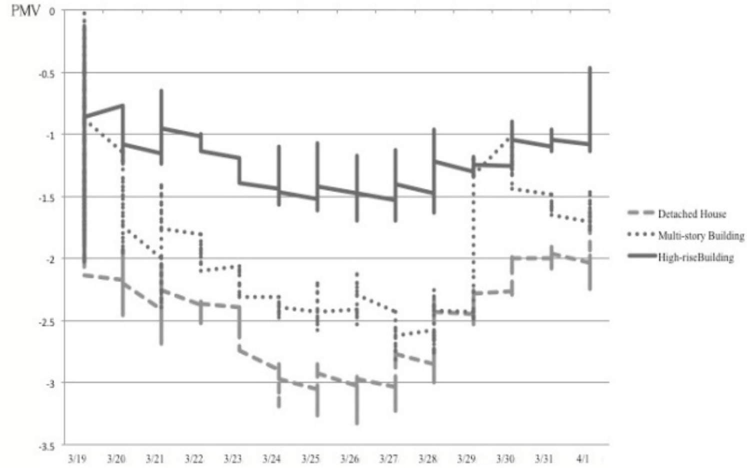

Fig. 7 PMV situation in three building types.

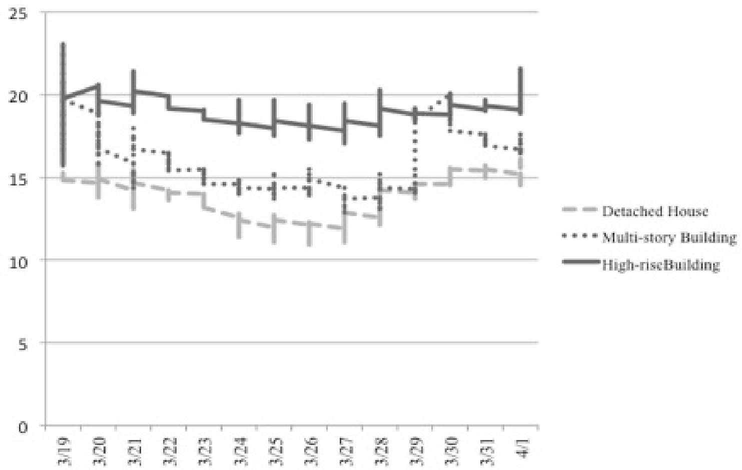

Fig. 8 Temperature changes in three building types.

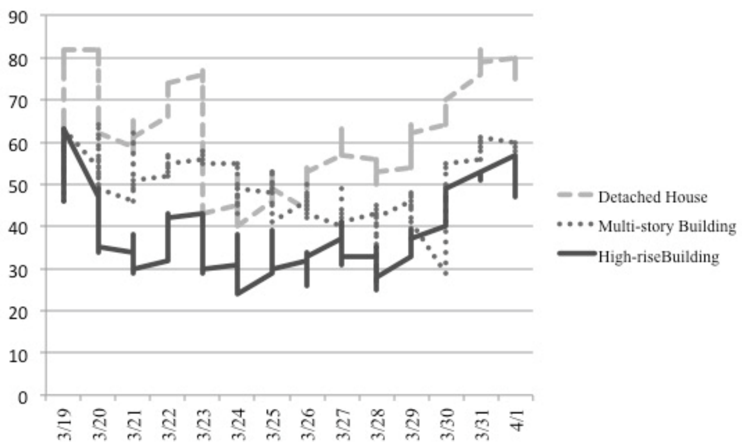

Fig. 9 Relative humidity changes in three building types.

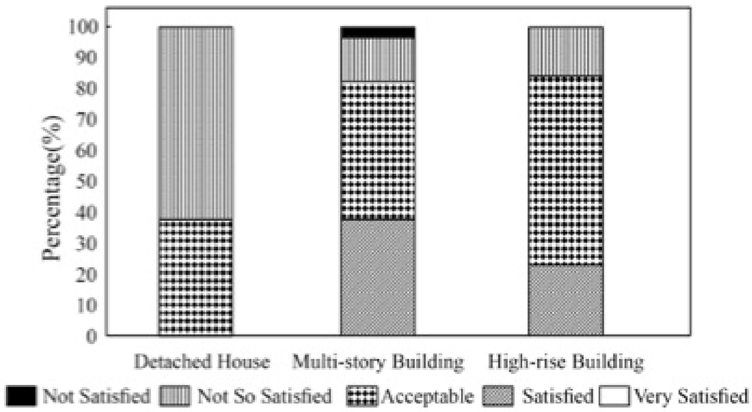

Fig. 10 Current thermal satisfaction use in different seasons for each type of situation.

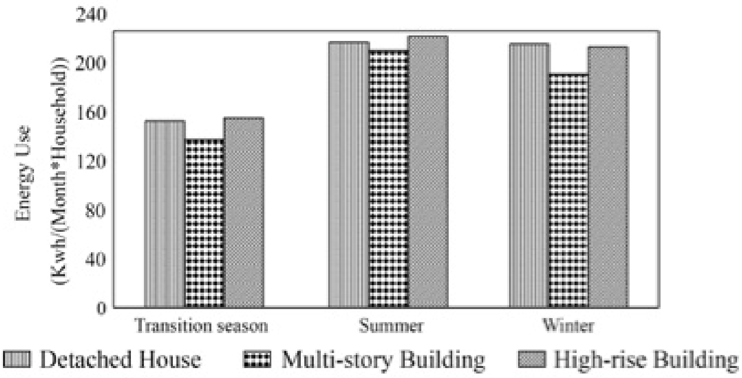

Fig. 11 Relationship between building type and energy use.

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. 11 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 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 always value energy saving, as a reason of saving money, and at the same time, they will bear a cold condition.

5. Conclusions

Without considering the envelope reasons, the energy use and the thermal comfort requirements 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 compared with the other two building types. At the same time, the temperature of the high-rise building is the highest, for the thermal performance, we consider that 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 attach importance to energy saving, as a reason of saving money, and at the same time, they will 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 that 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, people who live in high-rise building have a high thermal comfort requirement.

Acknowledgments

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