ANALYSIS OF LIFE CYCLE ENERGY CONSUMPTION AND ENVIRONMENTAL LOAD OF INSULATION DESIGN FOR RESIDENTIAL BUILDINGS IN CHINA

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ABSTRACT

Increasing insulation thickness may reduce the energy consumption and environmental load in building operation phase, but may also increase those in insulation production phase. Therefore, the life cycle energy consumption and environmental load of insulation design for a typical residential building were analyzed in this paper. Cases in four typical cities -Harbin, Beijing, Shanghai and Guangzhou- in four different climate zones in China were compared. The results indicate that increasing insulation thickness based on the active design standards for buildings in Harbin, Beijing and Shanghai, is helpful to reduce building life cycle energy consumption and environmental load. But for buildings in Guangzhou, the insulation thickness should not be increased any more.

KEY WORDS

insulation, life cycle assessment, energy conservation, environmental load, residential building

INTRODUCTION

Currently, building operating energy consumption accounts for nearly 25% of the total energy consumption in China (Building Energy Research Center of Tsinghua University, 2008). The energy consumption of building materials production, transportation and building construction has also been close to 20% of the total social energy consumption (Jiang, 2006). Therefore, building energy saving plays a vital role in the realization of sustainable development in China. The current energy saving work only focuses on reducing building operating energy consumption. One of the main measures for energy saving of building envelope is to improve the thermal performance of insulation and windows. However, the production and transportation of these building materials also consume a lot of energy and resources and produce pollutants. Improving the performance of building envelope often causes the increase in the energy consumption and environmental load of building material production. From the perspective of building's life cycle, the increase of energy consumption and environmental load in building material production phase may balance out those saved in building operation phase. This will be more likely to occur for the area where the heating period is not long and the effects of energy-saving by using insulation are not obvious. In order to take energy-saving measures in accordance with local conditions and to avoid hypercorrectness of energy-saving work, the life cycle assessment (LCA) methodology was adopted in this paper. The life cycle energy consumption and environmental load of different insulation designs for a typical residential building in China were studied, and cases for buildings in different climate zones were analyzed and compared.

METHODOLOGY

Case Introduction

In this paper, a typical high-rise residential building was selected as a study case. It is a 12-storey building, with a total floor area of 6000 m^2 and a height of each floor of 2.9 m. There are four houses on each floor. Its layout is shown in Figure 1. The total area of its external walls is 3654 m^2 and the total area of its roof is 500m^2.

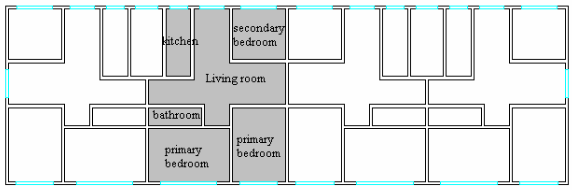

Figure 1 Layout of building standard floor

China is a country with a vast territory and various climates. For different climate zones, there are great difference of building cooling and heating load, so the insulation strategies to be taken should also be different. In this paper, four representative cities, Harbin, Beijing, Shanghai and Guangzhou, respectively in four different climate zones of China were selected, and the effect of increasing insulation thickness on the life cycle energy consumption and environmental load of the above typical residential building in these four cities were analyzed respectively. The climate zones and the locations of the cities are shown in Figure 2.

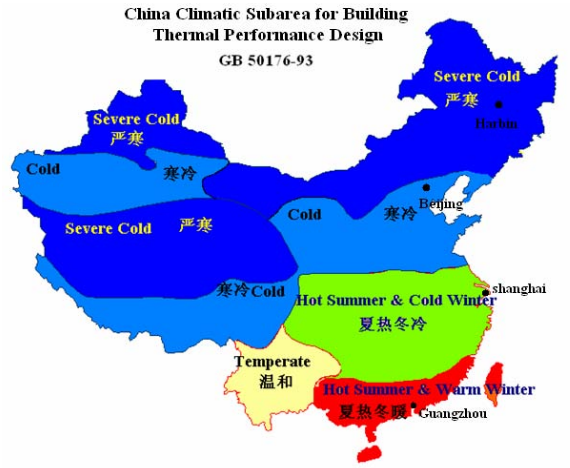

Figure 2 Climate zones and cities' locations

The difference of the shape of the residential buildings throughout the country is not large, but there are some differences on the area ratio of window over wall. Therefore when the above typical building was placed in different zones, its area ratio of window over wall was set according to the active local design standard for energy efficiency (China Building Science Research Institute, 1997, 2001; Beijing Institute of Architecture Design, 2004; Guangdong Construction Department, 2006), as shown in Table 1. The thermal performance of external windows required in the energy efficiency design standards of different zones are also different, so it was set differently as shown in Table 1. The mode of heating and cooling and the energy used in different cities are shown in Table 2. For intermittent heating and cooling, the air-conditioners will be turned on only when there is someone in the room. The operation schedules of air conditioners for different types of rooms are shown in Figure 3. The heating temperature of living room and bedroom was set as 18 ℃ and cooling temperature was set as 26 ℃. The turn-on temperature was 16 ℃ for intermittent heating and 29 ℃ for intermittent cooling. The inner heat gain from the equipment of living room and bedroom was set as 4.3 W/m^2, their schedules are shown in Figure 4. There were no heating and cooling for kitchens and bathrooms.

In addition, considering that the ventilation mode has bigger influence on the energy consumption of the residential building, cases for two ventilation modes, variable and invariable ventilation, were calculated respectively. The ventilation time ranged from 0.5 to 5 per hour for variable ventilation and was 0.5 per hour for the whole year for invariable ventilation.

The case with the lower limit of insulation thickness that can meet the requirement of the active building design standards was taken as the base case.

Table 1 Area ratio of window over wall and window thermal performance

	AREA RATIO OF WINDOW OVER WALL				K[a]	SC[b]
	EAST	SOUTH	WEST	NORTH		
Harbin	0.1	0.35	0.1	0.25	2.5	0.75
Beijing	0.1	0.45	0.1	0.3	2.8	0.75
Shanghai	0.1	0.45	0.1	0.4	2.5	0.6
Guangzhou	0.1	0.45	0.1	0.4	5.7	0.6

a: "K" is the thermal transfer coefficient of window, W/(m^2·K), b: "SC" is the shading coefficient of window.

Table 2 the mode of heating and cooling and the energy used

	HEATING	COOLING
Harbin	Central heating, continuous, coal	Room air conditioner, intermittent, electricity
Beijing	Central heating, continuous, natural gas	Room air conditioner, intermittent, electricity
Shanghai	Room air conditioner, intermittent, electricity	Room air conditioner, intermittent, electricity
Guangzhou	Room air conditioner, intermittent, electricity	Room air conditioner, intermittent, electricity

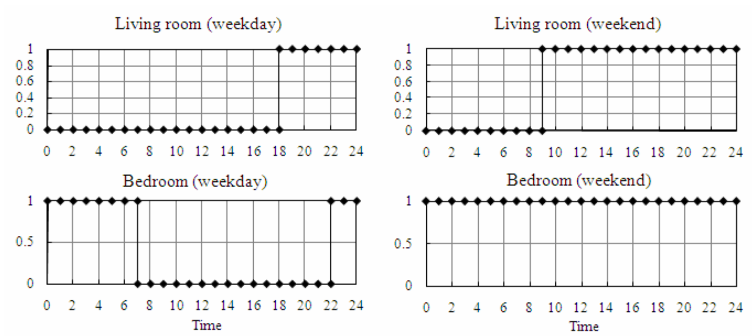

Figure 3 Operation schedules of air conditioners for intermittent heating and cooling

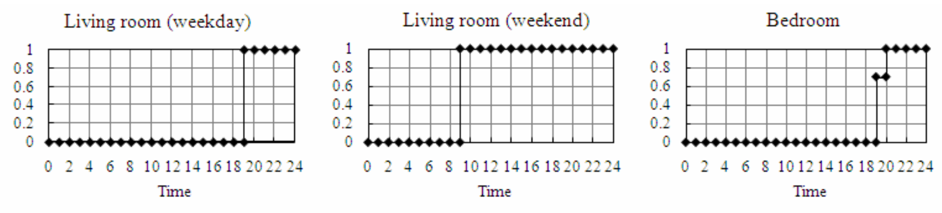

Figure 4 Schedules of inner heat gain

Energy Payback Time

The energy consumption of building's life cycle contains the energy consumed for building material production and transportation, building construction and operation, building material replacement and maintenance and building demolishment. This paper mainly studied the changes of energy consumption in each phase of building's life cycle when different insulation schemes were used for the same building. Therefore, the differences of energy consumption for different schemes mainly came from the insulation production phase (here and in the following text, "production phase" also includes the transportation and demolishment phase of the insulation) and building operation phase. The difference of energy consumption in construction phases for different schemes were also mainly caused by the difference of insulation thickness, but was much less than that in insulation production phase, so they were neglected in this study.

The energy consumption of building material production can be described by embodied energy. A product's embodied energy refers to the sum of energy consumption of all relevant processes before the product leaves factory, including processes of raw material extraction, transportation, processing, and assembly and so on (Laoson, 1996). In calculation, the consumption of different types of energy is all converted into the consumption of primary energy. Generally, the embodied energy per unit mass of the product is used to represent its energy consumption density. Expended polystyrene (EPS) board is a kind of commonly used insulation in China currently, so it was chosen for study in this paper. According to Chen's study (Chen et al., 2004; Hong et al., 2001), the embodied energy of EPS in China was 173 MJ/kg, among which about 90MJ is production energy consumption and the rest is the energy contained in raw material, oil. The density of EPS used for building insulation is about 22 kg/m^3. The heat conduction coefficient of EPS is 0.042 W/(m·K). The lifespan of EPS was considered as 15 years in this paper.

Firstly, building loads were simulated hour by hour by an energy simulation tool, DeST (Yan, 2004). Then the annual building operating energy consumption can be calculated, and the electricity consumption was converted into primary energy consumption according to the coal consumption of power generation. Here, the efficiency of coal-fired boiler was assumed as 0.78; the efficiency of gas-fired boiler was assumed as 0.89; the coefficient of performance (COP) of air-conditioner was assumed as 2.4 in summer in Harbin (Li, 2007), 2.3in summer in Beijing (Li, 2007), 1.9 in winter and 2.3 in summer in Shanghai (China Building Science Research Institute, 2001), and 2.7 in summer in Guangzhou (Guangdong Construction Department, 2006); the efficiency of the central heating net was assumed as 0.9; and the coal consumption of power generation was 0.35 kgce/kWh according to the statistical data in 2005.

For residential buildings, the increase of insulation thickness may reduce the energy consumption of building operation, but at the same time will increase the energy consumption of insulation production. This study analyzed how long the energy consumption increased in insulation production phase can be paid back by that reduced in building operation phase, and called this time the energy payback time (EPT) of the insulation, which can be calculated with equation (1):

$$EPT = \frac{OEC_b - OEC}{EE - EE_b} \qquad (1)$$

Where *EPT* is the EPT of insulation, a; *OEC* is the annual operating energy consumption per unit floor area, MJ/(m^2·a); *EE* is the total embodied energy of all the insulation of building envelope per unit floor area, MJ/m^2; subscript "b" refers to the corresponding variables of the base case. If the EPT is shorter than the insulation's lifespan, it means that increasing insulation thickness based on the base case is helpful to reduce the energy consumption throughout the building's life cycle.

Environmental Load Payback Time

Building activities consume not only energy but also a lot of mineral resources. In addition, the process such as energy production and use, building material production, product transportation and so on, also produce various pollutants. Therefore the impact building has on the environment is various and complicated. LCA is a method to quantifying the comprehensive environmental impact of a product or activity's life cycle. Some Chinese scholars have put forward the LCA systems to analyze the environmental impact of buildings in China. In this paper, the system, Building Environmental Load Evaluation System (BELES), founded by Dr. Gu (Gu, 2006), was adopted to analyze the comprehensive environmental impact of the study case. The evaluating indicator in BELES is the Environmental

Load with unit "point" and "pt" for short. In this study, only insulation thickness differs among different cases in the same city, so only the environmental load of the insulation production was considered when calculating the environmental load in building material production phase. The environmental load in building operation phase mainly comes from the process of energy production and use. The life cycle inventory of insulation and energy were all from the database of BELES. The calculation with BELES showed: the environmental load of EPS production is 8.55×10^{-3} pt/kg, the environmental load of coal-fired heating is 5.10×10^{-5} pt/MJ of boiler heat consumption, the environmental load of gas-fired heating is 5.69×10^{-5} pt/MJ of boiler heat consumption, and the environmental load of power generation and distribution is 6.05×10^{-4} pt/kWh.

The increase of insulation thickness may reduce the energy consumption of building operation, and accordingly reduce the environmental load of building operation, but at the same time will increase the environmental load of insulation production. This study analyzed how long the environmental load increased in insulation production phase can be paid back by that reduced in building operation phase, and called this time the environmental load payback time (ELPT) of the insulation, which can be calculated with equation (2):

$$ELPT = \frac{OEL_b - OEL}{IEL - IEL_b} \quad (2)$$

Where *ELPT* is the ELPT of insulation, a; *OEL* is the annual operating environmental load per unit floor area, pt/(m^2·a); *IEL* is the total environmental load of all the insulation of building envelope per unit floor area, pt/m^2; subscript "b" refers to the corresponding variables of the base case. If the ELPT is shorter than the insulation's lifespan, it means that increasing insulation thickness based on the base case is helpful to reduce the environmental load throughout the building's life cycle.

RESULTS

Harbin

Harbin locates in the Severe Cold Zone of China. For the base case in Harbin, the insulation thickness of wall and roof were both 80 mm, and the corresponding heat transfer coefficient of wall and roof were 0.52 W/(m^2·K) and 0.50 W/(m^2·K) respectively. With the increase of insulation thickness, the energy consumption and environmental load in building operation phase and the two kinds of payback times changed, which are shown in Figure 5.

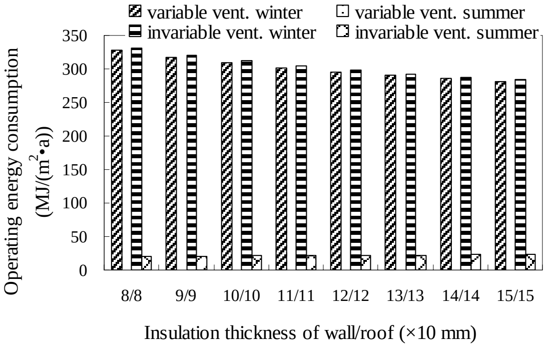

Figure 5-a operating energy consumption

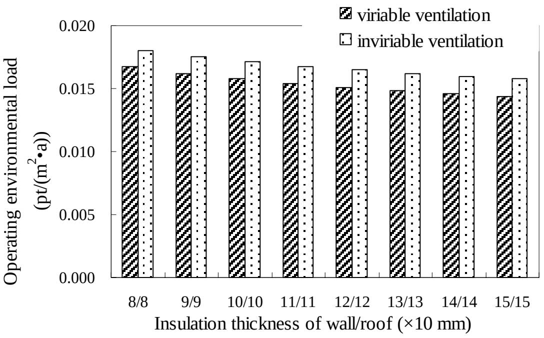

Figure 5-b operating environmental load

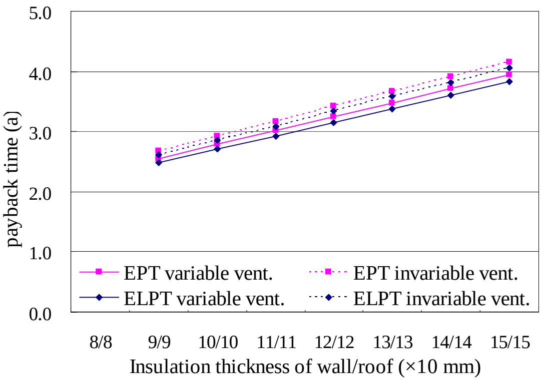

Figure 5-c payback time

Figure 5 Results of Harbin

The residential building in Harbin has almost no cooling energy consumption. Invariable ventilation will obviously increase the energy consumption of cooling in summer, and accordingly increase building's operating energy consumption and environmental load. The energy consumption and environmental load of building operation reduced with the increase of insulation thickness. The two kinds of payback times of insulation are short. Within the range of the insulation thickness that has been analyzed, the energy consumption increased in insulation production can be paid back within 2.6-4.1 years and the environmental load can be paid back within 2.5-4.1 years.

Beijing

Beijing locates in the Cold Zone of China. For the base case in Beijing, the insulation thickness of wall and roof were 30 mm and 45 mm respectively, and the corresponding heat transfer coefficient of wall and roof were 1.13 W/(m^2·K) and 0.77 W/(m^2·K) respectively. The change of the energy consumption and environmental load in building operation phase and the two kinds of payback times with the increase of insulation thickness are shown in Figure 6.

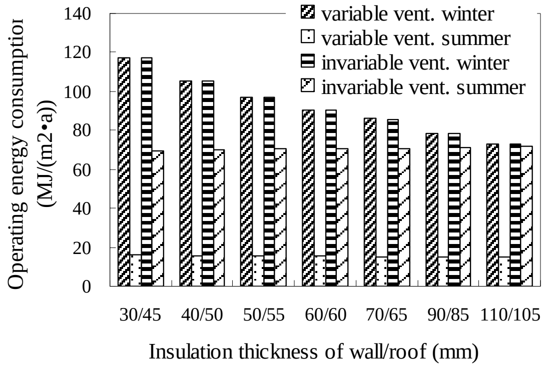

Figure 6-a operating energy consumption

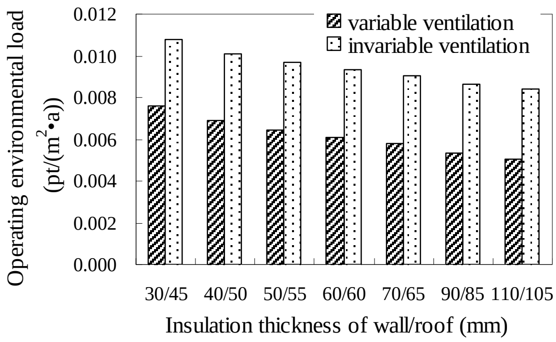

Figure 6-b operating environmental load

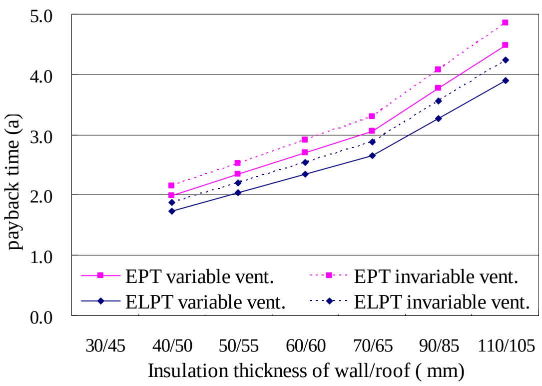

Figure 6-c payback time
Figure 6 Results of Beijing

The energy consumption of the residential building in Beijing mainly comes from heating. Invariable ventilation will obviously increase the energy consumption of cooling in summer, and accordingly increase building's operating energy consumption and environmental load. The energy consumption and environmental load of building operation reduced with the increase of insulation thickness. Within the range of the insulation thickness that has been analyzed, the energy consumption increased in insulation production can be paid back within 2.0-4.9 years and the environmental load can be paid back within 1.7-4.2 years.

Shanghai

Shanghai locates in the Hot Summer & Cold Winter zone of China. For the base case in Shanghai, the insulation thickness of wall and roof were both 25 mm, and the corresponding heat transfer coefficient of wall and roof were 1.02 W/(m^2·K) and 1.01 W/(m^2·K) respectively. Figure 7 shows the changes of the energy consumption and environmental load in building operation phase and the two kinds of payback times with the increase of insulation thickness.

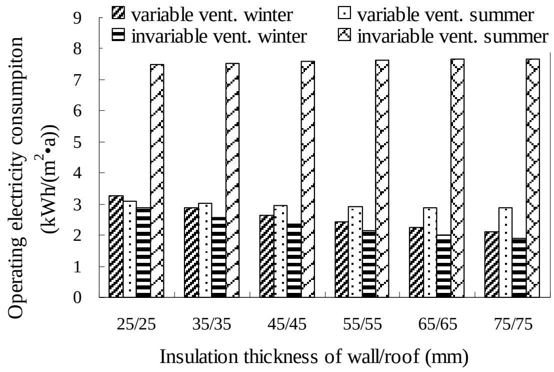

Figure 7-a operating energy consumption

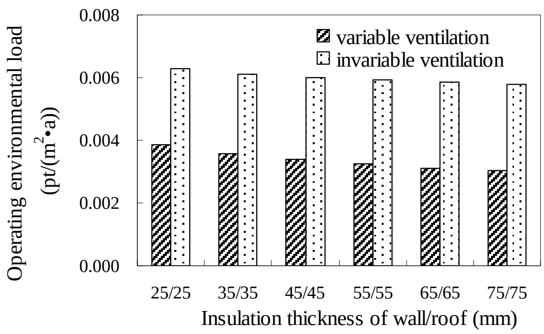

Figure 7-b operating environmental load

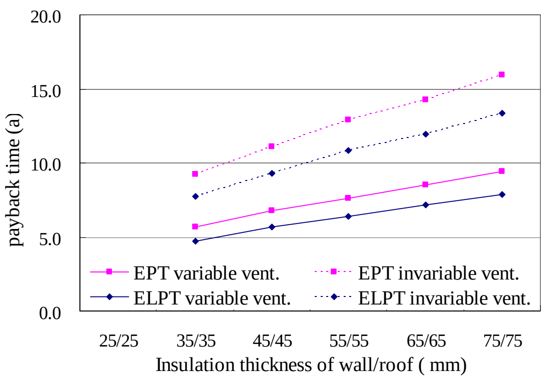

Figure 7-c payback time
Figure 7 Results of Shanghai

When ventilation times are variable, the heating energy consumption of the residential building in Shanghai is more or less the same as the cooling energy consumption. Invariable ventilation will obviously increase the energy consumption of cooling in summer, and accordingly increase building's operating energy consumption and environmental load. Except case 75/75 with invariable ventilation, the increase of insulation thickness is helpful to reduce the energy consumption and environmental load of building operation. Within the range of the insulation thickness that has been analyzed, the energy consumption increased in insulation production can be paid back within 5.6-14.2 years and the environmental load can be paid back within 4.7-13.4 years.

Guangzhou

Guangzhou locates in the Hot Summer & Warm Winter Zone of China. For the base case in Guangzhou, the insulation thickness of wall and roof were 30 mm and 30 mm respectively, the corresponding heat transfer coefficient of wall and roof were both 1.00 W/(m^2·K). With the increase of insulation thickness, the energy consumption and environmental load in building operation phase and the two kinds of payback times changed, which are shown in Figure 8.

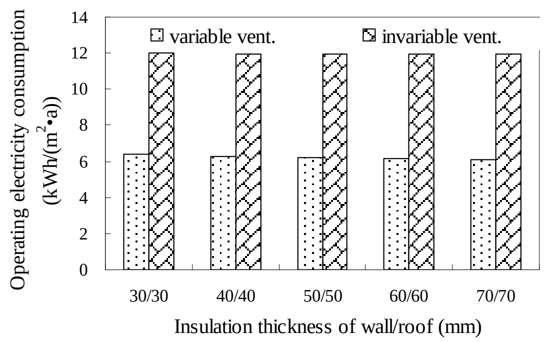

Figure 8-a operating energy consumption

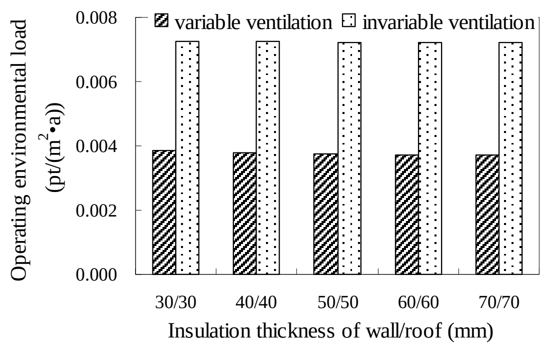

Figure 8-b operating environmental load

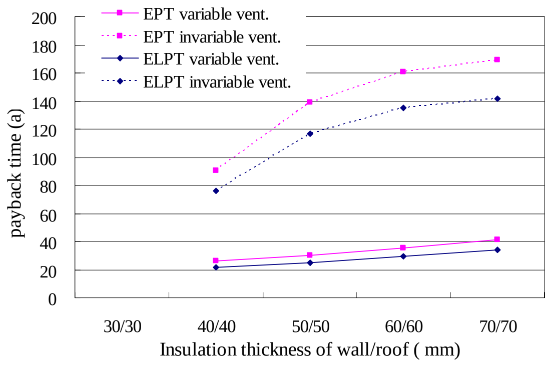

Figure 8-c payback time

Figure 8 Results of Guangzhou

The residential building in Guangzhou only has cooling energy consumption. Invariable ventilation will double the energy consumption of cooling in summer, and accordingly double building's operating energy consumption and environmental load. The increase of insulation thickness has very slight effect on the energy consumption and environmental load of building operation. The two kinds of payback times for all the options are longer than the insulation's lifespan, the payback times for some cases with invariable ventilation mode are even longer than one hundred years. This means the energy consumption and environmental load increased in insulation production can not be paid back for any case of Guangzhou.

ANALYSIS

From the above results, the following conclusions can be drawn:

1. For all these cities, the operating energy consumption and environmental load of buildings reduce with the increase of insulation thickness, but the reduction becomes less and less. In addition, the lower the latitude of the city, the less obvious the reduction is. There is only very slight reduction for cases in Guangzhou.
2. For all the cities, the cooling energy consumption in summer under invariable ventilation mode are higher than those under variable ventilation mode, and the lower the latitude of the city, the more obviously the cooling energy consumption increased by invariable ventilation.
3. The lower the latitude of the city, the longer two kinds of the payback times. Within the range of insulation thickness that has been analyzed, the payback times of cases in Harbin and Beijing are shorter than 5 a. The payback times of cases in Shanghai is 4.7 a at least, but the longest one exceeds the insulation's lifespan. The payback times of cases in Guangzhou are all longer than the insulation's lifespan, which means the increased energy consumption and environmental load in insulation production can not be paid back for any case in Guangzhou.
4. No matter in which area, the two kinds of

payback times will become longer and longer with the increase of insulation thickness. This is because the increase of energy consumption and environmental load of insulation production has a direct ratio with the increase of insulation thickness, but the reduction of operating energy consumption and environmental load decrease with the increase of insulation thickness. Thus it becomes more and more difficult to pay back the increased energy consumption and environmental load for insulation production when the insulation getting thicker and thicker.

5. As for a specific insulation scheme, the EPT is longer than the ELPT. This is because the energy consumption as raw material of insulation only has impact of energy exhaustion, but other energy consumption for insulation production or for building operation also has the impact of pollutant emission from energy combustion. Thus when only energy consumption is considered, the raw material energy consumption will has more contribution and make the EPT longer than the ELPT.
6. For a specific insulation scheme, the payback times of invariable ventilation mode is longer than that of variable ventilation mode. The lower the latitude of the city, the more effect the invariable ventilation has on the payback times. In the south part of China, it can be concluded that good natural ventilation design in residential building has much better effect on energy saving than increasing insulation's thickness.

CONCLUSIONS

In this paper the effect of increasing insulation thickness on the life cycle energy consumption and environmental load of a typical residential building were analyzed. The case with the lower limit of insulation thickness that can meet the requirement of active building design standards was taken as the base case. The insulation thickness was increased gradually from the lower limit and the EPT and ELPT were calculated for each case. Cases for buildings in the representative cities, Harbin, Beijing, Shanghai and Guangzhou, respectively from the four climate zones in China were analyzed and compared. In addition, two scenarios, variable and invariable ventilation, were calculated respectively. Within the range of the insulation thickness that has been analyzed, the energy consumption and environmental load increased in insulation production can be paid back in short time in Harbin and Beijing. The payback times in Shanghai are relatively long, but all the cases with variable ventilation can be paid back. However in Guangzhou, the two kinds of payback times are longer than the insulation's lifespan for all the cases. These indicate that increasing insulation's thickness is helpful to reduce the life cycle energy consumption and environmental load for residential buildings in Harbin and Beijing. But in Shanghai, the insulation's thickness should be controlled to avoid being too thick. However, for cities in Hot Summer & Warm Winter Zone, like Guangzhou, the insulation's thickness should not be increased any more based on the active design standard. In addition, proper ventilation can reduce the operating energy consumption and environmental load for the residential building in all the cities and meanwhile proper ventilation may not increase environmental impact in production phase. As for Hot Summer & Warm Winter Zone and Hot Summer & Cold Winter Zone, the benefit of proper ventilation is more obvious and much better than the benefit of insulation. Therefore, it should be encouraged in priority to make good ventilation design for buildings in the south part of China.

When the payback time of a case is shorter than the insulation's life span, it only means the insulation scheme for this case is better than the base case. But which scheme has the best life cycle environmental performance should be judged by the total amount of the environmental load it has throughout building's life cycle. This will be studied in the future to find the optimal insulation thickness for residential buildings in different climate zones.

What should be stated is that the specific value of the result are obtained based on the specific setting in this paper, including indoor heat gain, the way and the schedule of heating and cooling, energy type, insulation type and its physical performance, et al. When these parameters change, the result value may accordingly change. So the specific problem needs specific analysis. But the conclusions about the changing trend or relative magnitude of the payback times are universal.

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