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Numerical Study of Effects of Wall's Insulation Thickness on Energy Performance for Different Climatic Regions of China

Zhang Lianying*[a,b] , Wang Yuan[a], Zhang Jiyuan[a], Liu Xing[a], Zhang Linhua[b]

[a]School of Human Settlements and Civil Engineering, Xi'an Jiaotong University, Xi'an, Shaanxi Province and 710049, PR China
[b]Key Laboratory of Renewable Energy Utilization Technologies in Building of the National Education Ministry, Jinan, Shandong Province and 250101, PR China

Abstract

Building energy consumption plays a significant role in total energy consumption in China. It is well-known that the insulation performance of the external walls of a building is a critical factor for energy consumption of air conditioning system. In this study, the effects of building external wall's insulation thickness on the heating and cooling loads of commercial buildings of five cities in China, namely Harbin, Xi'an, Shanghai, Kunming and Guangzhou, have been investigated numerically. Meanwhile, the wall's optimum insulation thicknesses of typical buildings in five cities are calculated by the life cycle cost analysis (LCCA) method. The results show that the increase of insulation thickness has a significant effect on the building heating load, inversely it exhibits a relatively small effect on the building cooling load. The analysis indicates that building energy savings are different from cities for given wall insulation and the same building conditions. For the investigated cities, Harbin achieves the largest building energy savings, and then follows the order of Xi'an, Shanghai, Kunming and Guangzhou. For the buildings in Guangzhou, the variation of energy savings is also insignificant as the insulation thickness increases. Using expanded polystyrene as insulation layer material, the optimum insulation layers of Harbin, Xi'an, Shanghai, Kunming and Guangzhou are founded to be 80mm, 60mm, 40mm, 40mm, and 20mm, respectively.

Keywords: External wall; insulation layer; heating load; cooling load

1. Introduction

General building energy consumption included three parts: construction, employment and demolishment. Energy consumption in employment (namely energy consumption of HVAC, lighting, power and water supply and drainage) is larger than construction and demolishment. The most effective

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* Corresponding author. Tel.: +86-029-83395127; fax: +86-029-83395127.
E-mail address: zhangly@mail.xjtu.edu.cn.

measure, which achieves building energy efficient, is to reduce employment energy consumption. Energy-efficiency renovation for existing building and designing energy-efficient buildings are based on accurate energy consumption calculation, which is the way to alleviate the disparities between energy shortage and economic development. As "building energy efficiency" is put forward in recent years, more and more scholars pay attention to accurate calculation of building energy consumption, and many software of building energy consumption, such as DOE-2, EnergyPlus, eQUEST and DeST, were developed. The software De-ST developed by Tsinghua university is used to calculate and analyzes the yearly cooling and heating loads at different outdoor climate conditions, external wall configuration and insulation layer thickness.

Many authors have studied optimum insulation thickness on energy performance, the option of optimum insulation thickness depended on the accurate heating and cooling loads. The early studies used degree-days concept which is simple and crude model to calculate loads [1-5], and this method ignores the solar radiation and thermal inertia of the building. As we all known, many researchers interested in analytical methods, but only limited number of cases can be solved [6-10]. The accurate results are needed to select the optimum insulation thickness. Sanea [11] used a dynamic heat-transfer model to study the optimum insulation-thickness in building walls. This method provided an accurate solution for transient heat transfer. Analytical and dynamic methods are believed to obtain highly accurate results on the determination of optimum insulation thickness. The DeST employs accurate dynamic time-dependent model which considers the solar radiation and the effect of the different room and uses the State-Space method to calculate the daily transmission loads through the wall.

The foundation of the optimum insulation thickness obtained is different. Life cycle costs analysis (LCCA) which was applied to calculate the optimum thickness was widely employed by researchers [1,10,12-14]. Moreover, the energy sources and energy savings were used to obtain the optimum insulation thickness [15-17].

The main objective of the present work is to study the effects of building external wall's insulation thickness on the heating and cooling loads of commercial buildings of five cities in China, namely Harbin, Xi'an, Shanghai, Kunming and Guangzhou. Meanwhile, the wall's optimum insulation thicknesses of typical buildings in five cities are calculated by the life cycle cost analysis (LCCA) method.

2. The building model and mathematical formulation

The studied object is a commercial building in Xi'an as shown in Fig. 1. This is a three-floors building. The length of each floor from the first to third is 45.5m, 40.9m and 30.9m, respectively. The height of each floor is 5.0m, 4.5m and 3.9m, and the width of all floors is 4.5m.

This paper investigated numerically on yearly heating load and cooling load of commercial building in five cities of China for uninsulated wall and the composite wall with 20mm, 40mm, 60mm, 80mm and 100mm thermal insulation thickness. The plaster layer faces indoor side and the cement layer faces outdoor side. The parameters of the enclosure configurations are shown in Table 1.

The indoor temperature is 18℃ in winter and 26℃ in summer respectively. The humidity is ranged from 40% to 60%. The air infiltration rate is considered to be 0.5 times per hour as the air conditioning is operated, while the air infiltration rate is 2 times per hour as the air conditioning is switched off in summer night. The parameters of indoor thermal disturbance of major room in the building are given in Table 2
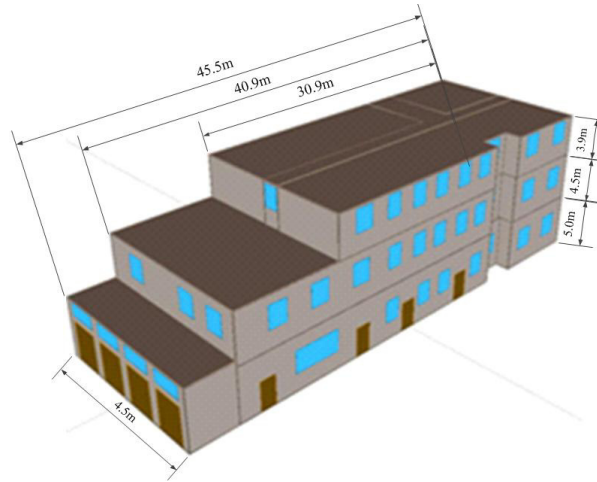
Fig. 1 Graphic model of the commercial building

Table 1 Constitution and heat transfer coefficient of enclosure structure of the building

Name	Constitution of enclosure Structure	Heat transfer coefficient/W·m^{-2}·K^{-1}	
External wall	20mm lime mortar +200mm solid clay brick + polystyrene board+ 20mm cement mortar	Polystyrene board 0mm	2.224
		Polystyrene board 20mm	1.143
		Polystyrene board 40mm	0.769
		Polystyrene board 60mm	0.579
		Polystyrene board 80mm	0.465
		Polystyrene board 100mm	0.388
Roof	20mm cement mortar + 200mm reinforced concrete + 46 polystyrene board + 20mm cement mortar	0.595	
External windows	Common insulating glass	3.100	

Table 2 Thermal disturbance of the major room

Type of room	Maximum number of people/person·m^{-2}	LPD(lighting power density)/W·m^{-2}	Equipment power density/W·m^{-2}
office	0.25	11	20
Conference room	0.4	11	5
Passageway	0.02	2	0
Control room	0.05	11	5

In this study, the wall is assumed to be one dimensional in x direction and time dependent. The one dimensional transient heat conduction equation for this problem is as follows:

$$\frac{\partial T(x,t)}{\partial t} = \frac{\lambda}{\rho c_p}\frac{\partial^2 T(x,t)}{\partial x^2}$$

（1）

where λ is the thermal conductivity, ρ is the density and c_p is the specific heat of the wall material. To solve this problem, two boundary conditions and one initial condition are required. On both sides of the wall, convection boundary conditions are present. On the inner surface, the boundary condition is:

$$-\lambda\left(\frac{\partial T(x,t)}{\partial x}\right)_{x=0} = h_i\left[T_{x=0}(t) - T_i\right]$$

（2）

whereas on the outer surface of the wall, the boundary condition can be written as:

$$-\lambda\left(\frac{\partial T(x,t)}{\partial x}\right)_{x=L} = h_o\left[T_o(t) - T_{x=L}(t)\right]$$

（3）

here, h_i is the heat transfer coefficient of wall inner surface; h_o is the heat transfer coefficient of wall outer surface ; T_i is the indoor air temperature; $T_0(t)$ is the outdoor air temperature; $T_{x=0}(t)$ is the wall inner surface temperature, and $T_{x=L}(t)$ is the wall outer surface temperature, respectively.

Under an initial condition, the steady-state solution of the problem at t=0 is taken. In the computations, the indoor temperature of a room is taken to be constant. The function of outdoor temperature which is assumed to show sinusoidal variations during a 24-hour period is written by UDF(user-defined function) procedure of software FLUENT.

In the numerical calculation, some assumptions are made: (1) the thickness of the composite wall is small compared to other dimensions. So one-dimensional temperature variation is assumed; (2) the layers are in good contact, hence the interfacial resistance is negligible; (3) there is no heat generation; (4) the variation of thermal properties is negligible; (5) the convection coefficient is constant.

3. Results and discussion

3.1 Annual cooling and heating loads

The climatic zones of China are divided into five regions mainly depending on average temperature degree-days of the coldest month and of the hottest month, namely, severe cold zone(the average temperature degree-days of the coldest month is not more than -10℃), cold zone(the average temperature degree-days of the coldest month is from -10℃ to 0℃), hot summer and cold winter zone(the average temperature degree-days of the coldest month is from 0℃ to 10℃, and the average temperature degree-days of the hottest month is from 25℃ to 30℃), hot summer and warm winter zone(the average temperature degree-days of the coldest month is more than 10℃, and the average temperature degree-days of the hottest month is from 25℃ to 29℃) and mild zone(the average temperature degree-days of the coldest month is from 0℃ to 13℃, and the average temperature degree-days of the hottest month is from 18℃ to 25℃). Different zones require different parameters in heating and air conditioning systems. In this study, the five different cities of China Harbin, Xi'an, Shanghai, Guangzhou and Kunming are chosen from five different climatic zones. Therefore, this study as the results of selected cities may be conveniently used to make reasonable estimation for other cities.

Figure 2 shows the relationship between the external insulation thickness and yearly heating or cooling loads in five cities. From Fig. 2(a) it can be learned that Harbin has the largest building heating load, and then follows the order of Xi'an, Shanghai, Kunming and Guangzhou. The increase of the

insulation thickness results in the most significant reduction on the yearly-heating-load for buildings in Harbin, followed by Xi'an, then Shanghai and Kunming. Guangzhou is located in the hot summer and warm winter zone with little heating load, where the insulation layer thickness has a little influence on the heating load. From Fig. 2(b), it can be seen that Harbin has the smallest cooling load, and then follows the order of Kunming, Xi'an, Shanghai and Guangzhou. For the selected cities, the insulation layer thickness affects the building cooling load insignificantly.

The reason of different effects of the insulation layer thickness on heating and cooling loads is that the outdoor temperature is very low in winter, far less than the indoor temperature of 18℃. An increase of insulation layer thickness effectively reduces the heat dissipation through the wall caused by the great temperature difference between indoor and outdoor. So the heating load is affected significantly by insulation thickness. On the contrary, the temperature difference between indoor and outdoor is small in summer, and sometimes heat flows from indoor to outdoor as the outdoor temperature is lower (i.e. the summer night). The thicker insulation layer is, the harder heat flows from outdoor into indoor, at the same time, the harder heat flows from indoor to outdoor in summer night. Therefore, an increase of insulation thickness has less effect on cooling load for summer.
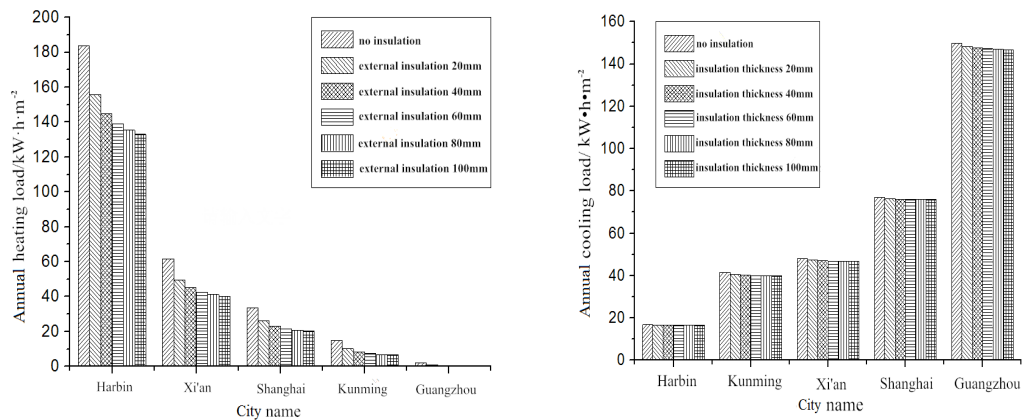

Fig. 2 Annual heating and cooling load in five cities

3.2 The energy savings

Over the past few years, external wall thermal insulation technology has been widely used in the severe cold and cold areas in China. The remarkable energy saving effect has been obtained. However, there are great climate differences between different climatic zones in China. Different heat preservation and heat insulation methods are needed, and so does indoor heating and air-conditioning methods. It is unreasonable to keep increasing the insulation layer thickness for reducing building energy consumption in all climatic zones. It is necessary to investigate the energy-saving caused by different insulation thicknesses of the external wall in the selected five cities which represent five climatic zones of China.

Figure 3 shows the relationship between annual energy saving of the commercial building heating and cooling and the insulation layer thickness. The calculation of energy savings is shown in Equation (4).

$$E=E_1-E_2 \tag{4}$$

where E (kW·h·m^{-2}) is the energy savings of annual building heating and cooling with thermal insulation, E_1 is the annual building heating and cooling loads without thermal insulation and E_2 is the annual building heating and cooling loads with thermal insulation.

It can be seen from Fig. 3 that Harbin achieves the largest energy savings with the fixed insulation thickness, and then follows the order of Xi'an, Shanghai, Kunming and Guangzhou. The building energy savings increase the most in Harbin with an increase of insulation thickness. For the buildings in Guangzhou, the variation of energy savings is insignificant as the insulation thickness increases. Harbin is located in severe cold zone, which the heating load accounts for a large proportion in the total load; while Guangzhou is in hot summer and warm winter zone, which the heating load is very small and the annual load is mainly composed of cooling load.
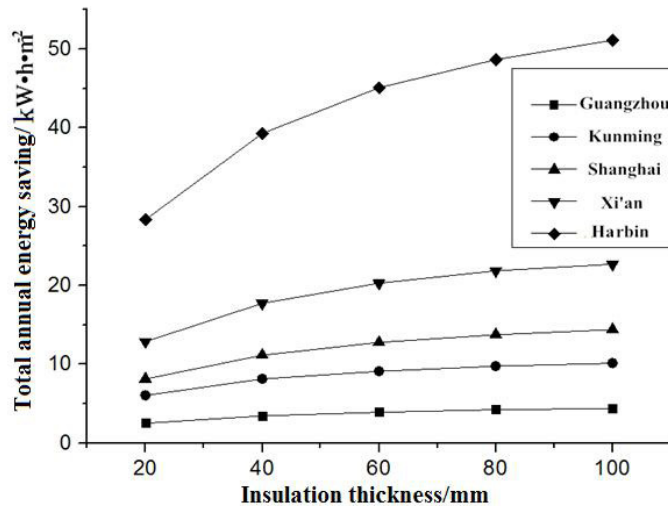

Fig. 3 Total annual energy savings at different insulation thicknesses

It also can be seen from Fig. 3 that the energy savings are leveled off along with an increase of the insulation thickness in five cities. As the insulation thicknesses approach to a certain value, the effect of adding insulation thickness on the reduction of building energy consumption becomes inoperative. On the other side, the cost of the thermal insulation layer increases with the insulation thickness. Therefore the each city has the optimum thermal insulation thickness of the building external wall.

3.3 Economic analysis

On one hand, an increase of the insulation layer thickness can reduce the cost of energy consumption of buildings. But on the other hand, it also can increase the initial investment of exterior walls. So it is unreasonable to reduce building energy consumption through unlimited increase of insulation thickness. It is necessary to find out the optimum insulation layer thickness with consideration of the heating and air conditioning energy consumption and thermal insulation layer costs during the insulation life cycle. There are many kinds of method to calculate the optimum insulation thickness. The commonly used life cycle cost analysis (LCCA) was adopted in this study.

Life-cycle cost analysis is often applied to energy technologies and building projects. A life-cycle cost analysis shows that spending more initially on additional building insulation produces a net savings (due to reduce heating and cooling costs) over the lifetime of a building. The concept of life-cycle can be used to determine the optimum insulation thickness in order to take effects of the change in interest and inflation that directly affect both the cost of insulation and fuels [18].

The sum present value of the cost of insulation, heating and cooling during the insulation life cycle, C in dollar/m^2, is as follows:

$$C = C_t + P_2 C_a$$

（5）

where C_t in dollar/m^2 is the sum cost of heating and cooling during the insulation life cycle, P_2 is the cost scale factor because of the extra investment within the insulation life cycle, and C_a in dollar/m^2 is the cost of thermal insulation layer. The insulation thickness leading to the value C obtained the minimum is called optimum insulation thickness.

In this study, the heating and cooling loads, which are as a basis of calculating the optimum insulation thickness of the building exterior wall, were calculated by DeST. The software DeST calculates the heating and cooling load of the building hourly. It fully considers the heat conduction of the retaining structure, the change of solar radiation intensity, the heat storage of the wall and night ventilation in summer. The calculated heating and cooling loads are more accurate.

Generally, the insulation maintenance cost is not considered, that is $P_2=1$. The relationship between the total cost during the insulation life cycle and the insulation thickness of the commercial building in five cities are shown in Table 3.

Table 3 Total cost during the insulation life cycle of the building（dollar/m^2）

Insulation thickness/mm	City names				
	Harbin	Xi'an	Shanghai	Kunming	Guangzhou
0	74.37	47.02	57.63	29.51	78.87
20	65.14	43.20	54.28	27.24	78.46
40	62.16	42.35	53.62	27.09	78.9
60	61.02	42.34	53.7	27.49	79.58
80	60.67	42.69	54.12	28.09	80.35
100	60.72	43.33	54.7	28.8	81.18

Table 3 presents the total cost achieves the minimum during the insulation life cycle as the insulation thickness is 80mm in Harbin. The total cost increases as the insulation thickness increase to 100mm. Therefore the optimum insulation thickness of the commercial building is around 80mm in Harbin. Similarly, the optimum insulation thicknesses of the building exterior wall in Xi 'an, Shanghai, Kunming and Guangzhou are 60 mm, 40 mm, 40 mm and 20 mm respectively.

4 Conclusions

This paper investigates numerically on the annual heating and cooling loads of commercial building in five cities of China for uninsulated wall and different insulation thickness walls. The simulation results indicate that, the increase of the insulation layer thickness on the influence of building heating load is bigger than that on the cooling load of the building. In different cities for the same exterior insulation measures of the same type building, Harbin achieves the largest energy savings. The increase of insulation thickness results in the most building energy savings in Harbin, and then follows the order of Xi'an, Shanghai, Kunming and Guangzhou. For the buildings in Guangzhou, the variation of energy savings is insignificant with the insulation thickness increase.

It is necessary to perform the energy simulation to find yearly heating and cooling loads as using the thermal insulation to the building. This simulation should be coupled with an economic analysis that takes

into account the investment in thermal insulation and the money savings generated by the decrease in the heating and cooling loads. As using expanded polystyrene as insulation layer material, the optimum insulation layers of Harbin, Xi'an, Shanghai, Kunming and Guangzhou are founded to be 80mm, 60mm, 40mm, 40mm, and 20mm, respectively.

Acknowledgements

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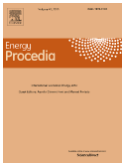
Biography

Dr. Zhang is currently an Associate Professor working at the Department of Building Environment and Energy Engineering of Xi'an Jiaotong University, China. She was a visiting scholar of the Department of Built Environment of the University of Nottingham, UK. Her research interests include building energy analysis, absorption refrigeration and thermal performance of building envelope.