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Procedia Engineering 121 (2015) 1008 – 1015

Procedia Engineering

www.elsevier.com/locate/procedia

9th International Symposium on Heating, Ventilation and Air Conditioning (ISHVAC) and the 3rd International Conference on Building Energy and Environment (COBEE)

Determination of Optimum Insulation Thickness of Exterior Wall with Moisture Transfer in Hot Summer and Cold Winter Zone of China

Xiangwei Liu[a], Youming Chen[a,*], Hua Ge[b], Paul Fazio[b], Guojie Chen[a,c]

[a]College of Civil Engineering, Hunan University, Changsha, Hunan, 410082, China
[b]Centre for Zero-Energy Building Studies, Department of Building, Civil and Environment Engineering, Concordia University, Montreal, Quebec, H3G 1M8, Canada
[c]College of City Construction, University of South China, Hengyang, Hunan, 421001, China

Abstract

Thermal insulation plays an important role in achieving building efficiency. Many engineering investigations were carried out to determine the optimum insulation thickness. In this paper, a coupled heat and moisture transfer model is presented to calculate the annual energy consumption. Then, the lifecycle total cost is analyzed by the P1-P2 economic model. Based on lifecycle total cost analysis, the optimum insulation thickness is determined. Three representative cities, viz. Changsha, Chengdu and Shaoguan, are chosen as the sample cities. The optimum insulation thickness, lifecycle saving and payback period are estimated. The results show that the optimum thickness of extruded polystyrene (XPS) is between 0.053 and 0.069m and the optimum thickness of expanded polystyrene (EPS) is between 0.081 and 0.105m. The maximum lifecycle saving varies from 16.60 to 28.50$/m2 and the payback period varies from 1.89 to 2.56 years. EPS is more economical than XPS as insulation because of its lower lifecycle total cost.

Peer-review under responsibility of the organizing committee of ISHVAC-COBEE 2015

Keywords: Coupled heat and moisture transfer; Optimum insulation thickness; Lifecycle total cost; Lifecycle saving; Payback period

* Corresponding author.
E-mail address: ymchen@hnu.edu.cn

Peer-review under responsibility of the organizing committee of ISHVAC-COBEE 2015
doi:10.1016/j.proeng.2015.09.072

1. Introduction

Heating and cooling loads of buildings are mostly due to heat transmission across the building envelope. From energy conservation viewpoint, thermal insulation is an effective way to achieve energy conservation in buildings. On one hand, the energy consumption for space conditioning can be reduced by increasing the thickness of insulation. On the other hand, increasing the thickness of insulation will increase the investment cost. Thus, it is inevitable to determine an optimum insulation thickness by considering economic analysis.

Many studies have been carried out to study the optimum insulation thickness [1-10]. They can be classified into two categories according to the transmission load calculation method. Most of studies estimated the transmission load through the exterior wall into room by using the degree-time concept (degree-day/degree hour) which is one of the simplest methods that applied in static conditions [1-7]. A few studies estimated the transmission load through the exterior wall into room by using numerical method [8-10], which neglects the effect of moisture transfer on heat transmission.

However, the building envelopes are exposed to the hot-humid climate with intense temperature change and high humidity in the hot summer and cold winter zone of China. The moisture transfer and storage in the building exterior walls is common. Moisture transfer and accumulation in exterior wall can increase the heat capacity and buffering effect and reduce the thermal insulation resistance which plays an important role in the transmission load through the exterior wall into room. To accurately calculate the transmission load through the exterior wall into room, the effect of moisture transfer on heat transfer should be considered.

In this paper, a coupled heat and moisture transfer model is proposed to estimate the annual energy consumption. Then, the lifecycle total cost is analyzed by the P1-P2 economic model. Based on lifecycle total cost analysis, the optimum insulation thickness is determined. Three representative cities, Chengdu, Changsha, and Shaoguan are selected as the sample cities. Two commonly used insulation materials, expanded polystyrene (EPS) and extruded polystyrene (XPS), are selected to determine their optimum thickness for a commonly used wall construction in residential buildings of this region. The annual energy consumptions, lifecycle savings and payback periods are analyzed and presented as well.

2. Methodology for insulation thickness optimization

2.1. Coupled heat and moisture transfer model for an exterior wall

In this paper, the effect of moisture transfer on heat transmission is taken into consideration. The simultaneous heat and moisture transport model proposed by Liu et al [11] is selected. The governing equations are as follow:

$$\xi \cdot \frac{\partial \varphi}{\partial t} = \nabla \left(\left(\delta_p \cdot P_s + K_l \cdot \rho_l \cdot R_D \cdot \frac{T}{\varphi} \right) \cdot \nabla \varphi + \left(\delta_p \cdot \varphi \cdot \frac{dP_s}{dT} + K_l \cdot \rho_l \cdot R_D \cdot \ln(\varphi) \right) \cdot \nabla T \right) \tag{1}$$

$$\left(\rho_m \cdot c_{p,m} + \omega \cdot c_{p,l} \right) \cdot \frac{\partial T}{\partial t} = \nabla \left(\lambda \cdot \nabla T \right) + h_{lv} \cdot \nabla \left[\delta_p \cdot \left(\varphi \cdot \frac{dP_s}{dT} \cdot \nabla T + P_s \cdot \nabla \varphi \right) \right] \tag{2}$$

where ξ (J/m^3) is sorption capacity, φ is relative humidity, t (s) is the time coordinate, δ_p (s) is the water vapor permeability, P_s (Pa) is the saturated water vapour pressure, K_l (s) is the liquid water permeability, ρ_l (kg/m^3) is the density of liquid water, R_D (J/kg K) is the gas constant of water vapor, T (K) is temperature, ρ_m (kg/m^3) is the density of the dry material, $c_{p,m}$ (J/kg K) is the specific capacity of the dry material, ω (kg/m^3) is the moisture content, $c_{p,l}$ (kg/m^3) is specific heat of liquid water, λ (W/m K) is the thermal conductivity of the moisture building materials, h_{lv} (J/kg) is the latent heat of evaporation.

2.2. Cooling and heating energy consumption of exterior wall

The instantaneous transmission load is obtained as follows:

$$q_c = h_i \cdot \left(T_{surf,i} - T_i\right) \tag{3}$$

$$q_h = h_i \cdot \left(T_i - T_{surf,i}\right) \tag{4}$$

where q_c (W/m^2) is the instantaneous transmission load for cooling, q_h (W/m^2) is the instantaneous transmission load for heating.

The annual energy consumption per unit area of the exterior wall (E_h, kW h/m^2) for heating can be calculated by:

$$E_h = \frac{Q_h}{\eta} \tag{5}$$

where Q_h (kW h/m^2) is the total transmission load per unit area of the exterior wall for heating, η is the efficiency of the heating system.

The annual energy consumption per unit area of the exterior wall for cooling (E_c, kW h/m^2) is expressed as:

$$E_c = \frac{Q_c}{EER} \tag{6}$$

where Q_c (kW h/m^2) is the total transmission load per unit area of the exterior wall for cooling, EER is the energy efficiency ratio of the cooling system.

2.3. Economic analysis model

The present worth of capital is considered in the economic analysis. The P_1-P_2 economic model proposed by Duffie and Bechman [12] is applied. P_1 is the lifecycle energy related to market discount rate (d), electricity cost inflation rate (i), and economic analysis period (N_e); P_2 is the ratio of lifecycle expenditures caused by the additional capital investment to the initial investment.

$$P_1 = PWF\left(N_e, i, d\right) = \begin{cases} \dfrac{1}{d-i} \cdot \left[1 - \left(\dfrac{1+i}{1+d}\right)^{N_e}\right] & i \neq d \\ \dfrac{N_e}{1+i} & i = d \end{cases} \tag{7}$$

$$P_2 = D + \left(1 - D\right) \cdot \frac{PWF\left(N_{\min}, 0, d\right)}{PWF\left(N_L, 0, m\right)} + M_s \cdot PWF\left(N_e, i, d\right) - \frac{R_v}{\left(1+d\right)^{N_e}} \tag{8}$$

where D is the ratio of down payment to the initial investment, N_{min} is the number of years over which mortgage payments contribute to the analysis period, N_L is the term of loan, M_s is the ratio of first year miscellaneous costs to the initial investment, R_v is the ratio of resale value at the end of the analysis period to the initial investment.

The lifecycle total cost (LCT, W/m^2) can be estimated by using Eq. (9):

$$LCT = P_1 \cdot C_E \cdot \left(E_c + E_h\right) + P_2 \cdot C_{ins} \cdot x_{ins} \quad (9)$$

where C_E is the price of electricity (\$/kW h), C_{ins} is the price of insulation material (\$/m^3), x_{ins} is the thickness of the insulation material (m). The optimum insulation thickness is the value that gives the minimum lifecycle total cost.

The lifecycle saving (LCS, \$/m^2) is the difference between the saved energy cost over the lifetime and the insulation payout:

$$LCS = P_1 \cdot C_E \cdot \left(\Delta E_c + \Delta E_h\right) - P_2 \cdot C_{ins} \cdot x_{ins} \quad (10)$$

where ΔE_c and ΔE_h are the difference between the annual energy consumption per unit area of the wall without and with insulation under cooling and heating conditions, respectively.

The payback period N_p (year) can be obtained by setting LCS to zero.

$$N_p = \begin{cases} \dfrac{\ln\left[1 - \dfrac{P_2 \cdot C_{ins} \cdot x \cdot (d-i)}{C_E \cdot \left(\Delta E_c + \Delta E_h\right)}\right]}{\ln\left(\dfrac{1+i}{1+d}\right)} & i \neq d \\ \dfrac{P_2 \cdot C_{ins} \cdot x \cdot (1+i)}{C_E \cdot \left(\Delta E_c + \Delta E_h\right)} & i = d \end{cases} \quad (11)$$

The parameters used to analyze the lifecycle total costs are given in Table 1.

Table 1. The parameters used in calculation

Parameters	Value
a	0.6 [6]
Electricity	0.087 (\$/kW h) [13]
EER	2.3 [14]
η	1.9 [14]
i	1%
d	5%
D	1
M_s	0
R_v	0

3. Results and discussions

3.1. Exterior wall configuration

A typical exterior wall representing the construction practice in residential buildings is selected in hot summer and cold winter zone of China. From exterior to interior, the wall consists of 20mm cement plaster, thermal insulation, 240mm red brick, and 20mm lime plaster.

The hydrothermal properties of the wall components obtained from Kumaran [15] are shown in Table 2. The price of expanded polystyrene is 41.0\$/m^3 and the price of extruded polystyrene is 64.1\$/m^3 [13].

Table 2. Properties of the exterior wall components.

Component	ρ_m (kg/m^3)	$c_{p,m}$ (J/kg K)	δ_p (10^{-12}s)	ω (kg/m^3)	λ (W/m K)	D_w (m^2/s)
Cement plaster	1807	840	54.67	$\frac{\varphi}{-0.022\varphi^2+0.025\varphi+0.0001}$	$0.854+4.5\times10^{-3}\omega$	$1.4\times10^{-9}\exp(0.027\omega)$
Red brick	1918	840	26.00	$\frac{\varphi}{0.02451\varphi^2-0.2362\varphi+0.273}$	$1.035+4.2\times10^{-3}\omega$	$7.4\times10^{-9}\exp(0.0316\omega)$
Lime plaster	1500	840	13.57	$\frac{\varphi}{-0.052\varphi^2+0.052\varphi+0.005}$	$0.526+3.1\times10^{-3}\omega$	$2.7\times10^{-9}\exp(0.0204\omega)$
Expanded polystyrene	30	1470	11.00	$\frac{\varphi}{-0.5277\varphi^2+0.9647\varphi+0.07086}$	$0.0331+1.23\times10^{-3}\omega$	N/A
Extruded polystyrene	35	1470	1.200	$\frac{\varphi}{-4.462\varphi^2+18.96}$	$0.0241+1.3\times10^{-4}\omega$ $+5.9\times10^{-5}\omega^2$	N/A

where the moisture diffusive $D_w=\left(K_l\cdot\frac{\rho_l\cdot R_D\cdot T}{\varphi}+\delta_p\cdot P_s\right)\cdot\frac{1}{\xi}$ m^2/s

3.2. Climate conditions

Three representative cities, Chengdu, Changsha, and Shaoguan are selected as the sample cities. The outdoor conditions are taken from typical meteorological year data [16], which is generated based on the measured weather data of years 1971-2003. The cooling season is from June 15th to August 31st, and the heating season is from December 1st to February 28th [14]. The indoor conditions are set as 26°C and 60% relative humidity for cooling and 18°C and 50% relative humidity for heating according to the design code for heating ventilation and air conditioning of civil buildings [17].

3.3. Optimum wall insulation thickness

The optimum insulation thickness of a typical south-facing brick wall used in representative cities, Chengdu, Changsha, and Shaoguan, is determined for two types of insulation materials (XPS & EPS) over a life time of 20 years.

The variation of the annual energy consumption (*AEC*) of exterior wall facing south orientation with respect to the thickness of insulation is shown in Fig.1. As can been seen in Fig.1, the annual energy consumption decreases with the increase of insulation thickness, while the rate decreases with the continued increase of the insulation thickness. The annual energy consumption of exterior wall using XPS as insulation material is much lower than that using EPS as insulation material. The annual energy consumption of exterior wall in Changsha is the highest, and followed by Chengdu and Shaoguan.

The variation of the lifecycle total cost of exterior wall facing south orientation with respect to the thickness of insulation is shown in Fig.2 (XPS as insulation material) and Fig.3 (EPS as insulation material). The lifecycle total cost of the exterior wall using EPS as insulation material is lower than that using XPS as insulation material. It indicates that EPS is more economical than XPS. The insulation thickness at which the lifecycle total cost is the minimum (as shown in Fig.2 and Fig.3) is defined as the optimum thickness. The optimum thickness of XPS in Changsha, Chengdu and Shaoguan are 0.069, 0.064 and 0.053m, respectively. And the optimum thickness of EPS in Changsha, Chengdu and Shaoguan are 0.105, 0.097 and 0.081m, respectively. It is obvious that the optimum wall insulation thickness in Changsha is the highest, and followed by Chengdu and Shaoguan since the annual energy consumption of exterior wall in Changsha is the highest, and followed by Chengdu and Shaoguan.

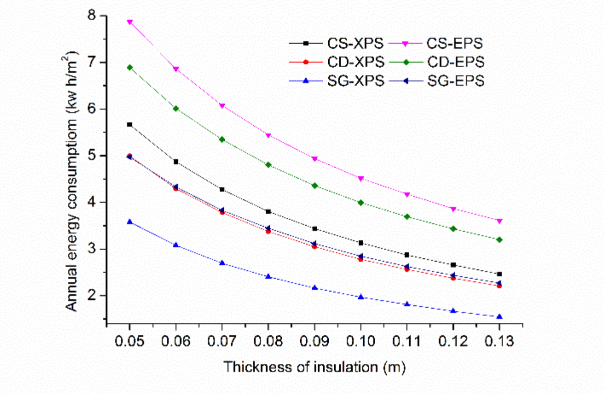

Fig.1. The annual energy consumption of exterior wall facing south orientation.

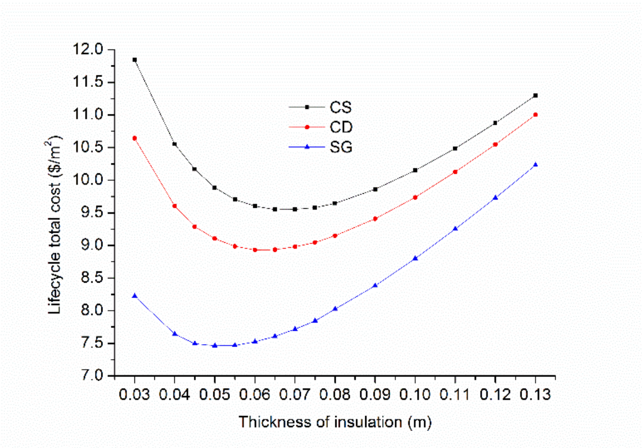

Fig. 2. Lifecycle total cost of exterior wall facing south orientation using XPS as insulation material.

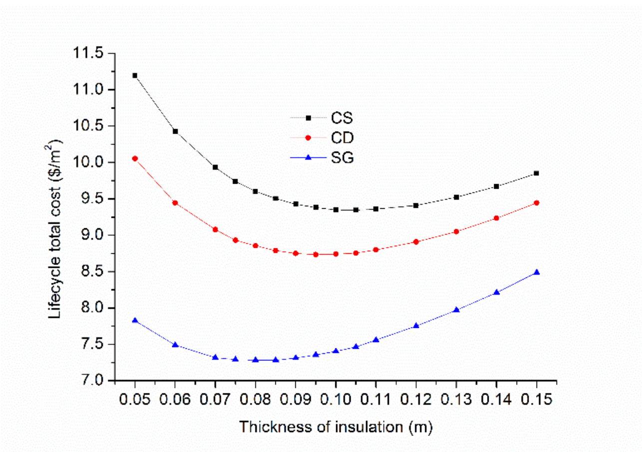

Fig. 3. Lifecycle total cost of exterior wall facing south orientation using EPS as insulation material.

The maximum lifecycle saving (the lifecycle saving corresponding to the optimum insulation thickness, LCS_{op}) is shown in Table 3. The maximum lifecycle saving varies from 16.60 to 28.50\$/m^2. The lifecycle saving of exterior wall using EPS as insulation is higher than that using XPS as insulation. It indicates that using EPS as insulation has higher saving potential than XPS.

Table 3. The maximum lifecycle saving (LCS_{op}) (\$/m^2).

Material	Changsha	Chengdu	Shaoguan
EPS	28.50	24.21	16.69
XPS	28.39	24.11	16.60

The payback period is shown in Table 4. The payback period is between 1.89 and 2.56 years. The payback period of exterior wall using EPS as insulation is lower than that using XPS as insulation.

Table 4. The payback period (years).

Material	Changsha	Chengdu	Shaoguan
EPS	1.89	2.00	2.52
XPS	1.97	2.14	2.56

4. Conclusions

In this paper, a coupled heat and moisture transfer model that considers the effect of moisture transfer on heat transfer is used to estimate the annual energy consumption. The lifecycle total cost is analyzed by P_1-P_2 economic model. The optimum insulation thickness, lifecycle saving, and payback period are estimated in three representative cities, Changsha, Chengdu and Shaoguan, in hot summer and cold winter zone of China. The result shows that the lifecycle total cost of exterior wall using EPS as insulation material is lower than that using XPS as insulation. It indicates that EPS is more economical than XPS. The optimum thickness of XPS is between 0.053 and 0.069m and the optimum thickness of EPS is between 0.081 and 0.105m. The maximum lifecycle saving varies from 16.60 to 28.50\$/m^2 and the payback period varies from 1.89 to 2.56 years.

Acknowledgements

This work was supported by Natural Science Foundation of China (Grant No.51078127, 51408294) and China Scholarship Council. Support was also received from Concordia University.

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