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A study on optimum insulation thicknesses of external walls in hot summer and cold winter zone of China

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ABSTRACT

The employ of thermal insulation is one of the most effective ways of building energy conservation for cooling and heating. Therefore, the selection of a proper insulation material and the determination of optimum insulation thickness are particularly vital. Four typical cities of Shanghai, Changsha, Shaoguan and Chengdu are selected to represent A, B, C and D subzone of hot summer and cold winter zone in China, respectively. The optimum thicknesses of five insulation materials including expanded polystyrene, extruded polystyrene, foamed polyurethane, perlite and foamed polyvinyl chloride are calculated with a typical residential wall using solar-air cooling and heating degree-days analysis and P_1–P_2 economic model. And then, life cycle total costs, life cycle savings and payback periods are calculated based on life cycle cost analysis. Considering different orientations, surface colors, insulation materials and climates, optimum thicknesses of the five insulations vary from 0.053 to 0.236 m, and the payback periods vary from 1.9 to 4.7 years over a lifetime of 20 years. The maximum life cycle savings are 54.4 $/m^2 in Shanghai, 54.8 $/m^2 in Changsha and 41.5 $/m^2 in Shaoguan (with a deep-colored northeast wall), and 39.0 $/m^2 in Chengdu (with a light-colored northwest wall). Finally, an approach to analyze economical efficiency of insulation materials is developed, result shows that expanded polystyrene is the most economic insulation material of the five because of the highest life cycle saving and lowest payback period.

1. Introduction

With the increase of population and the improvement of living standard, the demand for energy in China is steadily increasing, total energy use rose from 603 million tons of standard coal equivalent in 1980–2656 in 2007, representing an average annual increase of 5.64% during that 27 year period [1,2]. It was estimated that the residential sector consumed 11.3% of total national energy [3]. The energy consumption of heating, ventilation, and air conditioning accounts for about 50–60% of total in residential buildings and will increase dramatically in the future [4]. Moreover, the level of energy efficiency in residential buildings remains low [5]. Effective thermal insulation of residential envelope plays an important role in the reduction of heat flow rate and energy consumption for space cooling and heating. The selection of insulation material is based on the thermal conductivity and price, the lower the thermal conductivity and price are, the higher the economical efficiency of insulation material is. The increase of insulation thickness will decrease the energy consumption for cooling and heating, however, the investment for the insulation will increase as well, and then there must be an optimum point where the total investment cost for the insulation and energy consumption can be minimized over the lifetime. Therefore, the selection of proper insulation material, as well as the determination of optimum insulation thickness is very critical for the economic analysis.

Hot summer and cold winter zone locates at south center of China. The weather here is severe, The mean temperature of the hottest month July is between 25 °C and 30 °C, about 2 °C higher than other places of the same latitude in the world; while, the mean temperature of the coldest month January is between 2 °C and 7 °C, which is about 8–10 °C lower than other places of the same latitude in the world. Besides, the relative humidity in most cities of this region is 75–80%, even more than 95% some times [6]. Additionally, the heat-insulating level for residential buildings is extremely poor, indoor temperature is usually higher than 30 °C in summer and less than 12 °C in winter in non air-conditioned buildings. To maintain indoor thermal comfort, buildings need long time cooling in summer and heating in winter. According to a related data, 80 million kW of cooling load in summer and 0.2 billion kW of heating load in winter are required in this zone to maintain indoor thermal comfort, the total energy consumption for cooling and heating per unit floor area in this zone is higher than those in cold zones [7]. The conditions of rigorous climatic, huge energy consumption and poor heat-insulating level in hot summer and cold winter zone make the energy conservation program in residential buildings be much more crucial and imply that

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it has great significance to determine the most economic insulation material and optimum insulation thickness of external walls.

Cooling degree-days (CDD) and heating degree-days (HDD) using the base temperature and outdoor temperature are applied as a major reference for climate classification, and also as a proper method for forecasting the energy consumption of residential heating and cooling. Several studies have applied the degree time method to calculate the optimum insulation thickness from different aspects. Hasan [8] reported a study in 1999, the optimization of insulation thickness which was regarded as a function of degree-days and wall thermal resistance was studied using life cycle cost analysis in Palestine. Life cycle savings of the insulated buildings were computed and results showed that the saving went up to 21 $/m^2 when rock wool and polystyrene insulation were adopted. Payback periods were 1–1.7 years for rock wool and 1.3–2.3 years for polystyrene insulation, depending on the wall structures. Comakli and Yuksel [9] studied the optimum insulation thickness for the coldest cities of Turkey, and when the optimum insulation thickness was applied, a considerable energy saving of 12.113 $/m^2 of wall was obtained in Erzurum. In the study by Al-Khawaja [10], the optimum thicknesses of four insulation materials were calculated considering the solar energy radiation in Qatar, a comparison of total costs among four different insulation materials with light-colored and deep-colored surfaces during the lifetime was carried out in terms of average solar-air temperature of all orientations.

Dombaycı [11] reported a study in 2006, in which five different energy-sources and two insulation materials were compared when calculating the optimum insulation thickness of wall for Denizli in Turkey. According to the results, the optimum case was obtained when using coal as the energy source and expanded polystyrene as the insulating material based on a life cycle cost analysis. When the optimum insulation thickness was adopted, the life cycle saving and payback period were 14.09 $/m^2 and 1.43 years, respectively. Dombaycı [12] later focused on the environmental impact of optimum insulation thickness in external walls for the case of Denizli, Turkey. In the calculations, coal was used as the fuel source and expanded polystyrene as the insulation material. The results proved that when the optimum insulation thickness was used, energy consumption was decreased by 46.6% and the emissions of CO_2 and SO_2 were reduced by 41.53%. At the same time, Ozel and Pihtili [13] investigated the optimum location and distribution of insulation in a wall from the consideration of time lag and decrement factor for various wall orientations in both summer and winter conditions in Elazıg, Turkey. Results showed that the best thermal performance was obtained in the case that one of three equal pieces insulation layers was placed in the outdoor surface of wall, the second piece of insulation was placed in the middle of wall and third piece of insulation was placed in the indoor surface of wall.

Bolatturk [14] in 2006 selected 16 cities from four climate zones of Turkey to analyze the optimum insulation thicknesses, energy savings and payback periods of various fuels and climate zones. Five different fuels (including coal, natural gas, fuel oil, liquefied petroleum gas and electricity) and polystyrene insulation material are considered. Results show that, optimum insulation thicknesses vary between 2 and 17 cm, energy savings vary between 22% and 79%, and payback periods vary between 1.3 and 4.5 years, depending on the city and the type of fuel. Another study was later reported by the same author [15] in 2008, the effects of different base temperatures on the optimum insulation were analyzed in Turkey's warmest zone with respect to the cooling and heating degree-hours. For cooling load, the optimum insulation thicknesses vary between 3.2 and 3.8 cm, the energy savings vary between 8.47 and 12.19 $/m^2 and the payback periods vary between 3.39 and 3.81 years, depending on the cooling degree-hours; for heating load, insulation thicknesses vary between 1.6 and 2.7 cm, energy savings vary between 2.2 and 6.6 $/m^2 and payback periods vary between 4.15 and 5.47 years. Simultaneously, Kaynakli [16] investigated the variation of annual energy requirement of buildings for various architectural design properties considering long term and current outdoor air temperature records in Bursa. The optimum insulation thicknesses for Bursa vary between 5.3 and 12.4 cm depending on fuel types. In a subsequent study in 2009 [17], the optimum insulation thicknesses of the external walls, energy savings and payback periods over a lifetime of 10 years were calculated using the P_1–P_2 method for five different fuels, four different insulation materials and various cities in Turkey. The results show that optimum insulation thicknesses vary between 1.06 and 7.64 cm, energy savings vary between 19 $/m^2 and 47 $/m^2 and payback periods vary between 1.8 and 3.7 years, depending on the city and the type of fuel.

In China, there are only few studies on the optimum insulation thickness, especially in hot summer and cold winter zone. Fang [18] presented a technical-economic model for optimizing the thermal insulation thickness using Lagrange's method of undetermined multipliers. The approach was applied to a residential building in Shanghai in hot summer and cold winter zone and showed that the insulation on the west wall provided the largest savings while the insulator on the south wall provided the smallest. Huang and Ye [19] established a mathematics model of optimum insulation thickness of external wall to estimate the life cycle cost including energy consumption and investment of insulation materials, the optimum insulation thicknesses of six walls referred in *Design Standard of Residential Building for Energy Efficiency in Hunan Province (DBJ43/001-2004)* were calculated and some influence factors of the optimum insulation thickness were analyzed.

Hot summer and cold winter zone of China is divided into four subzones according to HDD18 and CDD26, which are, A subzone (1000 °C d $\leqslant$ HDD18 < 2000 °C d and 50 °C d < CDD26 $\leqslant$ 150 °C d), B subzone (1000 °C d $\leqslant$ HDD18 < 2000 °C d and 150 °C d < CD- D26 $\leqslant$ 300 °C d), C subzone (600 °C d $\leqslant$ HDD18 < 1000 °C d and 100 °C d < CDD26 $\leqslant$ 300 °C d), and D subzone (1000 °C d $\leqslant$ HDD18 < 2000 °C d and CDD26 $\leqslant$ 50 °C d). In this study, four typical cities of Shanghai, Changsha, Shaoguan, and Chengdu are selected to represent A, B, C, and D subzone of hot summer and cold winter zone, respectively. Five insulation materials including expanded polystyrene, extruded polystyrene, foamed polyurethane, perlite, and foamed polyvinyl chloride are chosen to determine the optimum insulation thickness of external walls in residential buildings. This study has three objectives: (i) calculate solar-air cooling and heating degree-days which consider the effects of solar radiation on wall orientation and surface color during cooling and heating seasons; (ii) analyze the optimum insulation thicknesses, life cycle total costs, life cycle savings and payback periods of five insulation materials with a typical residential wall based on life cycle cost analysis in four selected cities; and (iii) develop an approach for selecting the most economic insulation material.

2. Calculation for solar-air cooling degree-days (CDD*) and heating degree-days (HDD*)

2.1. Concepts of solar-air cooling degree-days and heating degree-days

In China, cooling and heating degree-days method is the simplest and most efficient way to calculate the envelope heat transfer, which assumes that the energy requirement is proportional to the difference between outdoor temperature and indoor base temperature. But for opaque surfaces, solar radiation absorbed by outside surfaces should be taken into account by considering the solar-air temperature which is regarded as the outdoor temperature to be higher by an amount equivalent to the effect of solar