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Calculation of Optimum Insulation Thickness Using the Heating Degree-Days Method for the Different Cost Approaches

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Abstract—*In this study, the optimum insulation thickness to be applied to external walls was determined by using the heating degree days method for the different cost approaches. Calculations were made for a sample city in Turkey and extruded polystyrene (XPS) was used as an insulation material. By applying the simple payback method and life-cycle cost analysis, optimum insulation thickness, saving amount and payback period were calculated according to increased insulation thickness. As a result, the optimum insulation thickness was determined as 0.0689 m and 0.0558 m for simple payback method and life-cycle cost analysis, respectively. For the determined insulation thicknesses, the payback periods were varied between 7.09 and 9.23 years. Also, at the optimum insulation thickness, the saving amount was obtained between 20.35 USD/m^2 and 35.58 USD/m^2 depending on the cost analyses.*

Keywords— *Heating degree days, life-cycle cost analysis, optimum insulation thickness, simple payback period.*

I. Introduction

Energy consumption has been increased rapidly in recent years due to factors such as population growth, industrialization and urbanization, and has become one of the most important problems of the countries. This situation increases the importance of energy conservation day by day. Applying the optimum insulation thickness to the exterior building walls is one of the primary ways in terms of energy conservation.

There are many studies on optimum insulation thickness in the literature [1-5]. Bademlioglu et al. [6] calculated the optimum insulation thickness for the vertical surfaces of the buildings facing different directions by considering the effect of solar radiation. They determined the optimum insulation thicknesses as 4.65 cm, 4.95 cm, 5.11 cm, 4.96 cm and 6.68 cm respectively on the vertical walls facing south, west, north, east and on the horizontal wall. Cay and Gurel [7] examined the optimum insulation thickness, energy saving and payback period for four cities in different climate regions of Turkey based on life-cycle cost analysis.

Kurekci [8] calculated optimum insulation thickness and repayment periods in 81 provinces of Turkey for four different fuels and five different insulation materials using heating and cooling degree-day values and life-cycle cost analysis. Dombayci [9] calculated the optimum insulation thickness using two different insulation materials for provinces located in four different climate regions of Turkey. The minimum insulation thickness is obtained for the province in the hot climate zone, while the maximum insulation thickness is provided for the province in the cold climate zone.

In this study, optimum insulation thickness was calculated using the heating degree days method for the simple payback method and life-cycle cost analysis. Firstly, heating degree days value was determined for Bursa as 1954.9. Then, optimum insulation thickness, saving amount and Payback period were calculated according to increased insulation thickness for the different cost analyses. As a result, the results obtained for both cost analysis are given comparatively.

II. Mathematical Model

A. Heating Degree-Days Method

In general, degree-days method is one of the most reliable methods for estimating the energy consumption in buildings. This method assumes that the difference between the average outdoor temperature and the base temperature (T_b) is directly proportional to the energy requirement of the building.

The heating degree days (*HDD*) value describes the density of the cold by taking into account the outdoor air and base temperature in a given period (month, year, etc.). HDD values can be expressed as follow,

$$HDD = \sum_{1}^{365} (T_b - T_o)^+ \qquad (1)$$

where T_o is the outside air temperature, and T_b is the base temperature. The plus sign above the parenthesis indicates that only positive values are to be counted, and thus the temperature difference is to be taken to be zero when $T_o > T_b$. In this study, the base temperature, T_b was taken 18°C.

B. Annual Heating Energy Requirements

The overall heat transfer coefficient (U) of a typical external wall that includes a layer of insulation can be given as follow,

$$U = \frac{1}{1/h_i + R_w + x/k + 1/h_o} \qquad (2)$$

$$U = \frac{1}{R_{t,w} + x/k} \qquad (3)$$

where h_i and h_o are the inside and outside heat transfer coefficients respectively, R_w is the total thermal resistance of the composite wall materials without insulation, $R_{t,w}$ is the total wall thermal resistances excluding the insulation layer, x and k are the thickness and thermal conductivity of insulation

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material, respectively. The annual heating energy requirement per unit area can be expressed as follow,

$$q_{A,H} = \frac{86400HDDU}{h} \quad (4)$$

where η is the efficiency of the heating system. In this study, the efficiency of the system was taken as 0.93.

C. Calculation of Optimum Insulation Thickness and Cost Analyses

As the insulation thickness increases, the cost for heating decreases, while the cost of insulation increases. Therefore, the cost of insulation and the cost for heating should be calculated for determining the optimum insulation thickness. As a result of these calculations, the optimum insulation thickness is the thickness at which the total cost is a minimum.

The cost of insulation ($C_{t,ins}$) for the external wall can be calculated as follow,

$$C_{t,ins} = C_{ins}x + C_{inst} \quad (5)$$

where C_{ins} is the cost of insulation material per unit volume and C_{inst} is the installation cost. The annual cost of heating (C_H) for the unit surface area can be given as follow,

$$C_H = \frac{86400HDDC_fPWF}{(R_{t,w} + x/k)Hu\eta} \quad (6)$$

where C_f is the cost of fuel, *Hu* is the Lower heating value of the fuel and PWF is the present worth factor. The PWF is a coefficient used for life-cycle cost analysis and which based on the lifetime of the building or the insulation material (*LT*), the interest rate (*g*) and the inflation rate (*i*), can be calculated as follow,

$$PWF = \left(\frac{1+i}{g-i}\right)\left[1 - \left(\frac{1+i}{1+g}\right)^{LT}\right] \quad (\text{if } g \neq i) \quad (7)$$

LT is assumed to be 20 years in this study. The total cost for heating can be expressed as follow,

$$C_{total} = C_{t,ins} + \frac{86400HDDC_fPWF}{(R_{t,w} + x/k)Hu\eta} \quad (8)$$

The optimum insulation thickness for heating season is obtained by minimizing Eq. (8). The derivative of the C_{total} equation with respect to insulation thickness is taken and set equal to zero from which the optimum insulation thickness (x_{opt}) for heating degree-day can be obtained as follow,

$$x_{opt} = 293.94\left(\frac{HDDC_fkPWF}{HuC_{ins}\eta}\right)^{1/2} - kR_{t,w} \quad (9)$$

While the PWF coefficient is used for life-cycle cost analysis, the *LT* value is used for simple payback method.

The saving amount (*SA*) obtained by isolation can be calculated as follow for the insulation thickness of *x*,

$$SA = C_{H(x=0)} - C_{H(x)} - C_{t,ins(x=0)} \quad (10)$$

III. RESULTS AND DISCUSSION

The structure of external wall considered in this study consists of 0.02 m inner plaster (k=0.87 W/mK), 0.135 m horizontal hollow brick (k=0.45 W/mK), 0.03 m external plaster (k=0.87 W/mK) and insulation material (k=0.034 W/mK). Various parameters related to this study are given in Table I.

TABLE I. The parameters used in the calculations [10,11]

Parameter	**Value**
Wall structure	
0.02 m Internal plaster	k=0.87 W/mK
0.135 m Hollow brick	k=0.45 W/mK
x m Insulation material	k=0.034 W/mK
0.03 m External plaster	k=0.87 W/mK
Inside heat transfer coefficient	h_i=8.3 W/m^{2}K
Outside heat transfer coefficient	h_o=34 W/m^{2}K
	$R_{t,w}$=0.507 m^{2}K/W
	U=1.971 W/m^{2}K
Fuel (Natural gas)	
Lower heating value (Hu)	34.526 x 10^6 J/m^3
Price (C_f)	0.332 USD/m^3
Efficiency of heating system (η)	0.93
Insulation material (XPS)	
Thermal conductivity (k)	0.034 W/mK
Material cost (C_{ins})	160 USD/m^3
Installation cost (C_{inst})	8.5 USD/m^2
Density (ρ)	ρ>30 kg/m^3
Financial parameters	
Inflation rate (i)	%18
Interest rate (g)	%22
Lifetime (LT)	20
Present worth factor (PWF)	14.355 (with Eq. 7)

In the calculation of the optimum insulation thickness, firstly the HDD values should be determined by using the daily average temperature values of the region to be examined. The variation of the temperature data of the outdoor air for the Bursa province is shown in Fig. 1.

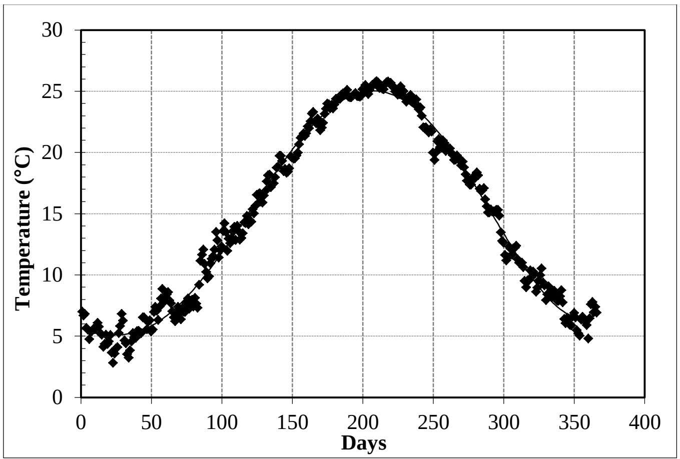

Fig. 1. Variation of the outdoor air temperature

The variation of the HDD values calculated for Bursa province is shown in Fig. 2. When Fig. 2 is examined, it is seen that HDD values increase in the first and last days of the year. The reason for this situation is that the amount of energy required for heating is higher due to the low outside temperature at these days of the year. The total HDD value for Bursa province was determined as 1954.9.

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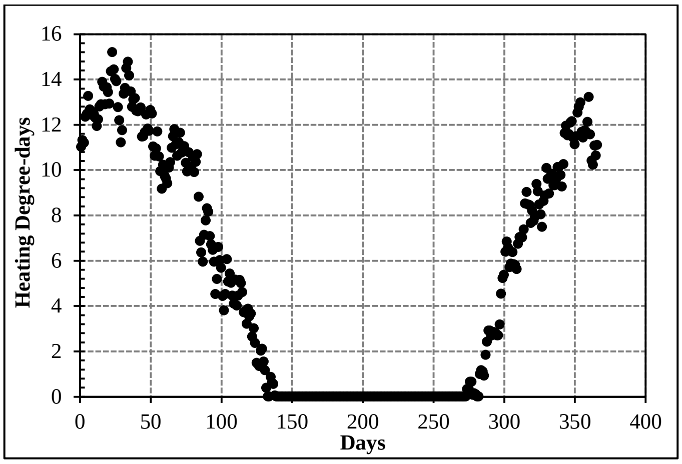

Fig. 2. Variation of the heating degree-days for the Bursa province

The variation of the energy, insulation and total costs with the insulation thickness is given in Fig. 3 and Fig.4. As the insulation thickness applied to the wall increases, the total thermal resistance (R_t) increases and the heat loss from the wall decreases. With the reduction of heat loss, the annual fuel cost (C_H) decreases as seen in Fig. 3 and Fig. 4. However, the insulation cost ($C_{t,ins}$) increases as the insulation thickness increases. Considering these two costs, the total cost (C_{total}) decreases first and then increases depending on the increased insulation thickness. The reason for this situation is that energy cost loses its effectiveness in total cost. The insulation thickness where the total cost is minimum is determined as the optimum insulation thickness.

In Fig.3, without considering inflation and interest rates, the optimum insulation thickness (x_{opt}) obtained by simple payback method was determined as 0.0689 m. At the optimum insulation thickness, the payback period was calculated as 7.09 years.

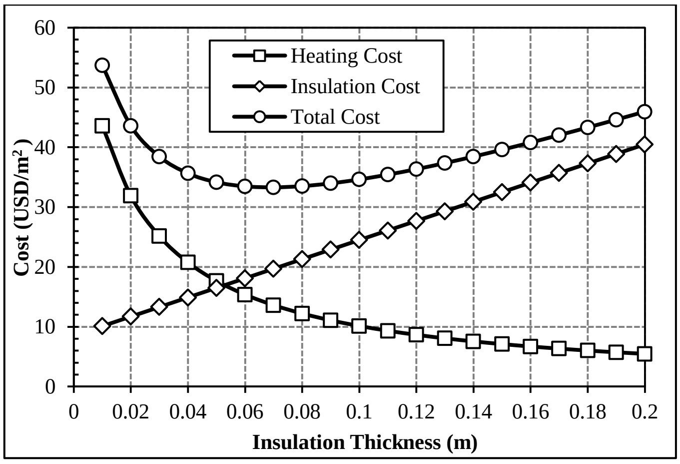

Fig. 3. Variation of cost depending on insulation thickness for simple payback method

In Fig. 4, when inflation and interest rates are taken into consideration, optimum insulation thickness (x_{opt}) obtained by life-cycle cost analysis method is calculated as 0.0558 m. At the optimum insulation thickness, the payback period was calculated as 9.23 years.

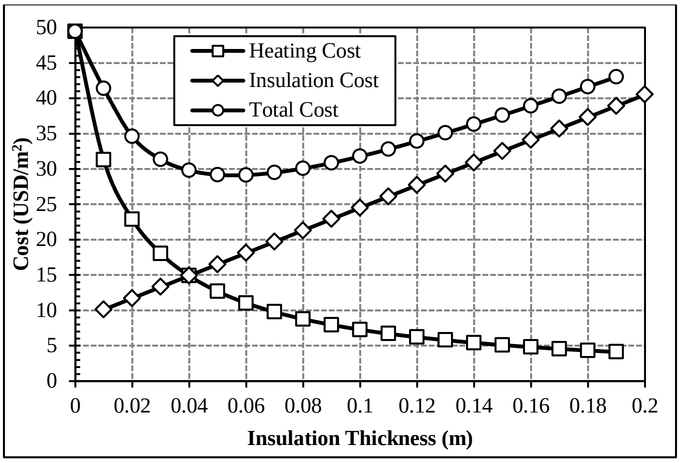

Fig. 4. Variation of cost depending on insulation thickness for life-cycle cost analysis

The variation of the saving amount obtained with the applied insulation thickness is given in Fig. 5 for the simple payback method and life-cycle cost analysis. In Fig. 5, the insulation thicknesses corresponding to the peak points of the curves show the optimum insulation thickness for the cost approach used. The saving amount provided at the optimum insulation thickness was calculated as 35.58 USD/m^2 for the simple payback method while 20.35 USD/m^2 for the life-cycle cost analysis.

In general, the simple payback method does not take the inflation and interest rates into account, therefore the saving amount obtained is greater. However, the results obtained with the life-cycle cost analysis are more reliable and realistic since this analysis is based on financial parameters.

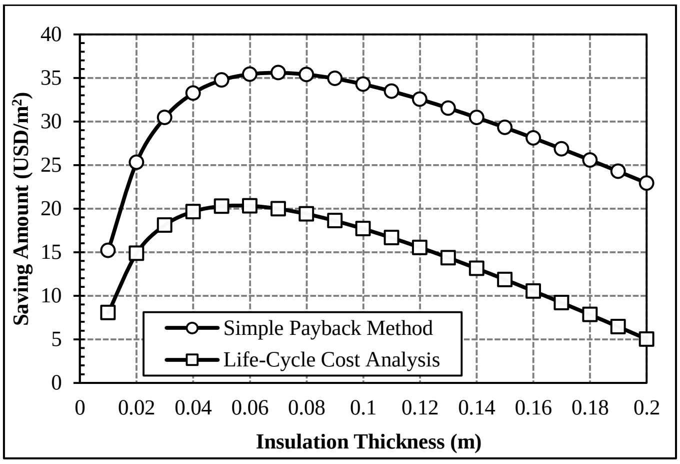

Fig 5. Variation of saving amount depending on the optimum insulation thickness for the sample payback method and life-cycle cost analysis

IV. CONCLUSION

The optimum insulation thickness was determined for the sample city in Turkey by using the heating degree-day method. In addition, the simple payback method and life cost analysis were used to calculate the payback periods and the energy savings. The results obtained are:

- The optimum insulation thickness was calculated as 0.0689 m for the sample Payback method and the payback period was determined as 7.09 years for this cost approach.
- In similarly, using the life-cycle cost analysis, the optimum insulation thickness was obtained as 0.0558 m and the payback period was calculated as 9.23 years.
- At the applied optimum insulation thickness, the saving amount was obtained between 20.35 USD/m^2 and 35.58 USD/m^2 based on the different cost approaches.

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