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Determination of Proper Insulation Thickness for Building Walls Regarding Economic Consideration

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Abstract— *Determining the thickness of the thermal insulation to be applied to building walls is economically important as well as energy saving. In this study, the thermal insulation thicknesses for building walls were determined based on the cooling and heating energy requirements. Life cycle cost analysis considering a certain lifetime period was used to determine the proper insulation thickness. The most suitable insulation thickness calculations in terms of economy were performed for a sample city which has heating and cooling loads. The sol-air temperatures were calculated taking into account the solar radiation falling on vertical surfaces (such as external walls), and then they were used to determine the degree-day (DD) values. As a result, the variation of insulation thicknesses with the heating, cooling and annual energy requirements of buildings based on the seasonal or annual energy requirements were presented comparatively. The economic insulation thickness was found to be 4.7 cm.*

Keywords— *Insulation thickness, heating and cooling energy requirements, lifetime.*

I. INTRODUCTION

Thermal insulation for external walls is one of the most important applications to reduce energy consumption in buildings by preventing heat gain/loss through the building envelope. However, determining the most suitable thermal insulation thickness regarding economic parameters is also an important issue. There are many studies on this subject in the literature. Bolatturk [1] and Aytac and Aksoy [2] calculated the optimum insulation thicknesses for different degree day (*DD*) zones in Turkey considering heating energy requirement of buildings. Comakli and Yuksel [3] determined the optimum insulation thicknesses for only three cities located in fourth climatic region in Turkey. They found that the optimum insulation thicknesses for each city are 10.4, 10.7 and 8.5 cm respectively when coal is used for heating. Ucar and Balo [4] carried out to optimize the insulation thickness on the basis of heating and cooling degree-days (*HDD*s and *CDD*s). Kaynakli [5] investigated the residential heating energy requirements and optimum insulation thickness on a prototype building in a sample city (Bursa) in Turkey. Daouas [6] focused on the economic parameters affecting the optimum insulation thickness. In that study, the most economical insulation thickness was 10.1 cm and energy savings was 71.33% for a life-cycle cost analysis over a building lifetime of 30 years. Canbolat et al. [7] investigated the effect of condensation factor on determination of insulation thickness. They calculated the required minimum insulation thickness for the insulation applications taking into considering the condensation factor. They found that the minimum insulation thickness required to prevent condensation has been increased by increasing the indoor temperature, indoor relative humidity and outdoor ambient temperature.

In this study, the proper insulation thicknesses have been calculated taking into account the space-heating and cooling loads. The solar-air temperature considering the incident solar radiation on a wall has been used in the calculation of heating and cooling transmission loads. The most suitable insulation thickness calculations in terms of economy have been performed for Istanbul which is the biggest province in Turkey considering the population.

II. MATHEMATICAL MODEL

A. Solar-Air Temperature

The sol-air temperature is a concept relating to the outside air temperature and the solar radiative flux. For opaque surfaces (wall, roof), the effect of solar radiation is conveniently accounted for by considering the outside temperature to be higher by an amount equivalent to the effect of solar radiation [8,9].

$$T_{sol-air} = T_o + \frac{a_s \dot{q}_s}{h_o} - \frac{es\left(T_o^4 - T_{surr}^4\right)}{h_o} \qquad (1)$$

where T_o is the outside air temperature, α_s the solar absorptivity of the surface, h_o is the outer surface heat transfer coefficient, q_s is the solar radiation incident on the surface, ε is the emissivity of the surface, σ is the Stefan-Boltzman constant, and T_{surr} is sky and surrounding surface temperature. In this equation, the second term indicates the solar heat gain effect on the opaque surface while the last term represents the correction to the radiation heat transfer between surface and environment if T_{surr} is different from T_o.

In this study, as an example, Istanbul province is chosen to determine the most suitable thickness of insulation in terms of economic consideration. The degree-day region and certain features of the city is given in Table I.

B. Annual Heating and Cooling Energy Requirements

Heat loss/gain through a wall, the properties of which are given in Table II, is respectively

$$q = U\left(T_b - T_{sol-air}\right) \qquad q = U\left(T_{sol-air} - T_b\right) \qquad (2)$$

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TABLE I. The certain data for selected cities in each degree-day zone.

City	Degree-day zone	Longitude	Latitude	Altitude (m)	Winter outdoor design temp. (°C)	Summer outdoor design temp. (°C)
Istanbul	II	29.05	40.58	39	-3	33

TABLE II. The parameters used in the calculations.

Parameter		Value
Wall structure		
3 cm	external plaster	k = 0.87 W/mK
x cm	Insulation material	k = 0.030 W/mK
20 cm	hollow brick	k = 0.45 W/mK
2 cm	internal plaster	k = 0.87 W/mK
	inside heat transfer coefficient	h_i = 8.29 W/m^{2}K
	outside heat transfer coefficient	h_o = 34.0 W/m^{2}K (for winter)
		h_o = 22.7 W/m^{2}K (for summer)
		U =1/(R_{ins}+0.652) W/m^{2}K (for winter)
		U =1/(R_{ins}+0.667) W/m^{2}K (for summer)
Natural gas (in heating)		
Price, C_f		0.367 USD/m^3
Lower heating value, Hu		34.526 x 10^6 J/m^3
Efficiency of heating system, η		0.93
Electricity (in cooling)		
Price, C_e		0.118 USD/kWh
COP		2.5

In terms of degree-days, the annual heating and cooling energy requirement per unit area because of the heat loss and gains from the wall can be expressed as follows

$$q_{A,H} = 86400\ HDD\ U / h \tag{3}$$

$$q_{A,C} = 86400\ CDD\ U / COP \tag{4}$$

where η is the efficiency of the heating system and COP is the coefficient of performance of the cooling system. The overall heat transfer coefficient of a typical external wall that includes a layer of insulation is given by

$$U = \frac{1}{1/h_i + R_w + x/k + 1/h_o} = \frac{1}{R_{t,w} + x/k} \tag{5}$$

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, x and k are the thickness and thermal conductivity of insulation material, respectively.

C. Energy Costs and Optimum İnsulation Thickness

As the thickness of insulation increases, the cost of insulation applied increases, but the heating/cooling load decreases. The optimum insulation thickness is the thickness at which the total cost (i.e. energy and insulation costs) is a minimum. The cost of insulation is a function of its thickness, which is given by

$$C_{t,ins} = C_{ins} x \tag{6}$$

where C_{ins} is the cost of insulation material per unit volume. Assuming an inflation rate (i), an interest rate (g) and an expected lifetime, the present worth factor (PWF) is calculated as [10-12]

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

LT is assumed to be 10 years [11,12]. The total cost for heating can be expressed as

$$C_{t,H} = C_{ins} x + \frac{86400 HDD\ C_f PWF}{\left(R_{t,w} + x/k\right) Huh} \tag{8}$$

where Hu is lower heating value of the fuel, C_f is the cost of fuel (natural gas). The certain values related to natural gas are also given in Table II.

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

$$x_{opt,H} = \left(\frac{86400\ HDD\ C_f\ PWF\ k}{\eta\ Hu\ C_{ins}}\right)^{1/2} - R_{t,w} k \tag{9}$$

Above equations are valid for only heating season. The annual total cost (heating and cooling) and the optimum insulation thickness considering the annual total cost are given by

$$C_{t,A} = C_{ins} x + \frac{86400 HDD\ C_f PWF}{\left(R_{t,w} + x/k\right) Huh} + \frac{86400 CDD\ C_e PWF}{\left(R_{t,w} + x/k\right) COP} \tag{10}$$

The optimum insulation thickness for total energy requirements (heating and cooling) is obtained by minimizing Eq. (10), and is given by,

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$$x_{opt,A} = \left(\frac{86400\,PWF \left(\frac{C_f HDD}{\eta\, Hu} + \frac{C_e CDD}{COP} \right) k}{C_{ins}} \right)^{1/2} - R_{t,w} k \quad (11)$$

From an economic point of view, both the heating and cooling energy requirements should be considered together when calculating the optimum insulation thickness.

III. RESULTS AND DISCUSSION

The *HDD* and *CDD* values considering and not considering solar load for Istanbul which is located in the second climatic zone in Turkey are given in Table III. When calculating the first values (i.e. with asterisk) for degree-days in this table, the solar load is not considered.

Table III clearly indicates that the solar radiation has a significant effect on both the heating and cooling loads.

TABLE III. The *HDD* and *CDD* values.

Zone	City	*HDD**	*HDD*	*CDD**	*CDD*
II	Istanbul	1908.0	1371.5	145.6	523.6

* The degree days were calculated without taking into account of sol-air temperature

The variation of daily average air temperature during year is shown in Fig. 1. As it can be seen, the air temperatures are higher in summer months as expected. Considering the air temperatures, heating and cooling degree-day variations with months is shown in Fig. 2 for the base temperatures of 18ºC and 24ºC respectively. In relatively warmer months, *CDD* has higher values than *HDD* values. In relatively colder months (winter season), the heating energy requirement (i.e. *HDD*) takes great values.

The total degree-days for Istanbul are calculated as *HDD*=1371.5 and *CDD*=523.6. These values have considered the solar radiations.

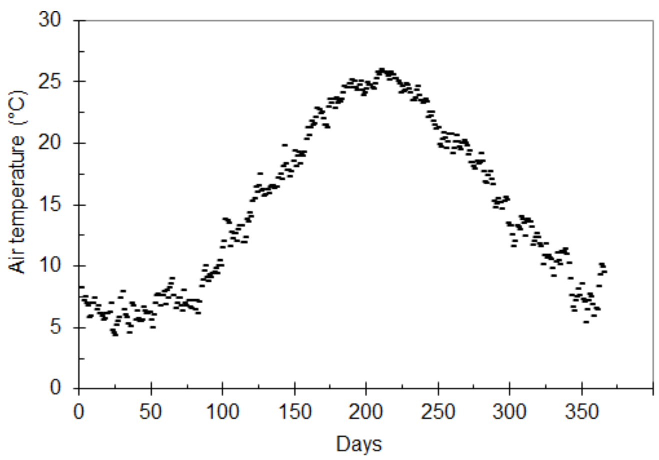

Fig. 1. Variation of outside air temperature.

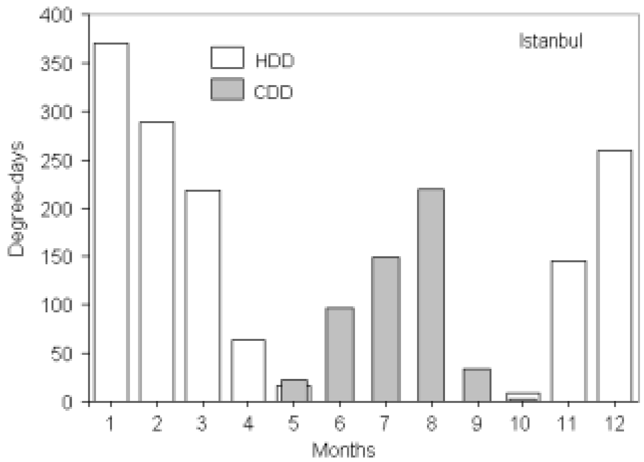

Fig. 2. Variation of monthly degree-days.

The effect of insulation thickness on the annual heating and cooling energy requirements per square meter of wall is shown in Fig. 3(a). The variation of cost curves with insulation thickness, and the determination of proper insulation thicknesses according to different approaches (heating total cost, cooling total cost or annual total cost) is shown in Fig. 3(b). The heating and cooling energy costs decreases whereas the insulation cost increase linearly with increase in the thickness of insulation.

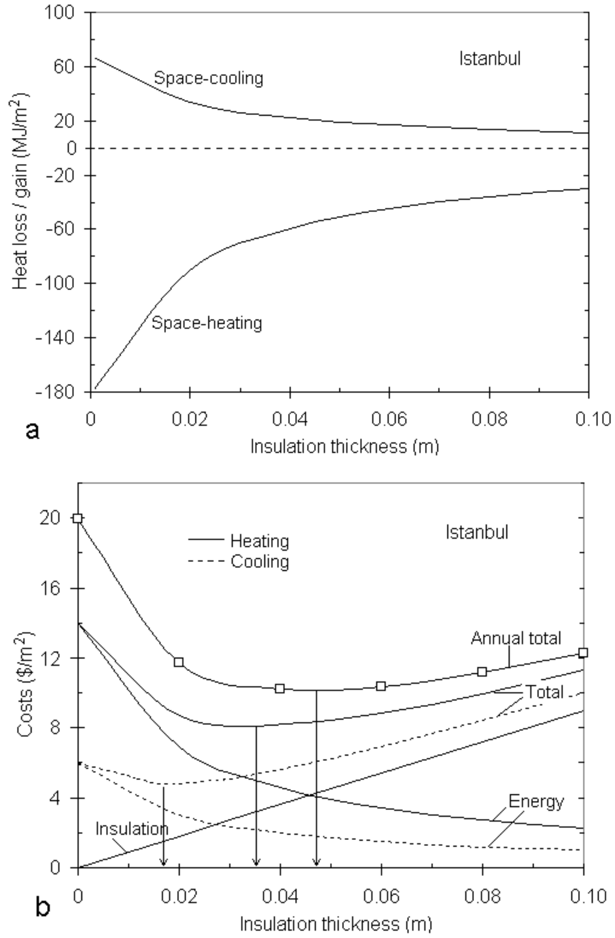

Fig. 3 (a) Annual heating or cooling transmission loads and (b) heating and cooling costs variations with insulation thickness.

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On the other hand, both the seasonal (heating and cooling) total costs and the annual total cost decreases in the beginning, and then increases slowly due to the insulation material cost. The insulation thickness minimizing the total cost is taken as the proper insulation thickness. The optimum insulation thicknesses are obtained 1.7 cm for cooling, 3.6 cm for heating and 4.7 cm for both (annual energy requirement). The insulation thickness at which the savings is maximum value gives the most suitable thickness of insulation. Choosing a thickness value apart from the optimum one will increase the total cost. When similar calculations are performed for cold or hot cities, the results given in Fig. 4 are obtained. It is seen that insulation is not required for the city having high *CDD* in cooling season ($x_{opt,C}$ =0 cm). Because, there is not an economic insulation thickness since the insulation does not payback the its initial investment cost during lifetime (*LT*=10 years). On the other hand, for heating season the optimum insulation thickness is quite high as 7.5 cm because of high *HDD* value. The variation of optimum insulation thicknesses with degree-days is shown in Fig. 5. The optimum insulation thicknesses increases (but not linearly) with increasing *DD* values because of the fact that high *DD* value means the high energy requirement (heating or cooling).

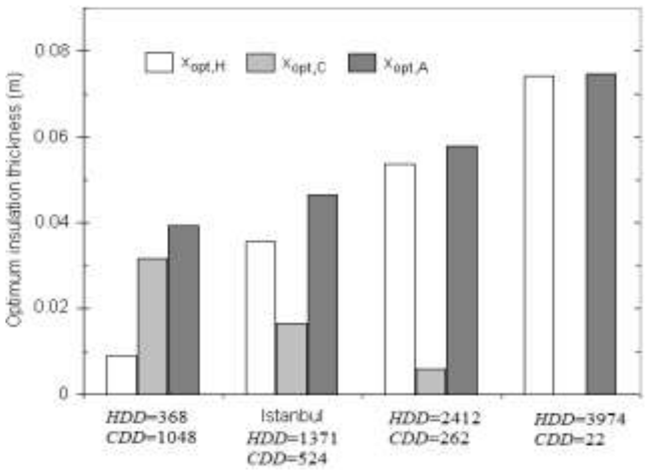

Fig. 4. The optimum insulation thicknesses considering heating, cooling and annual energy requirements.

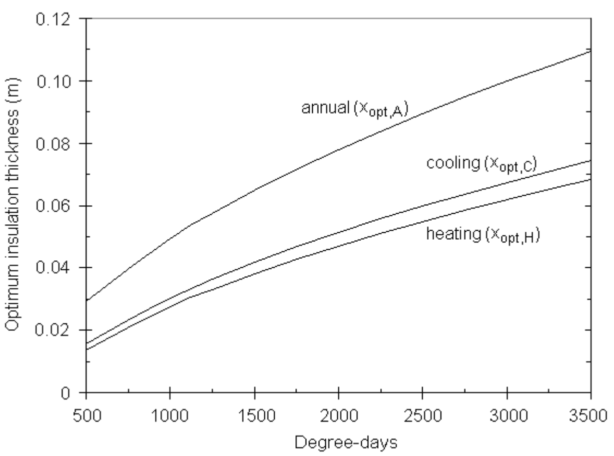

Fig. 5. Variation of optimum insulation thicknesses with degree-days.

IV. CONCLUSION

The thickness of thermal insulation applied to the external walls of buildings was optimized based on the heating and cooling degree-days. The solar-air temperature which considers the incident solar radiation on a wall was used in the calculation of heating and cooling transmission loads.

Incoming solar radiation on the wall decreases the heating load a little while it increases the cooling load more. The proper insulation thickness was found as 4.7 cm for considering annual energy requirements. Moreover, as the *DD*s increases, the economic insulation thickness also increases. For example, for HDD=3974, the most suitable thickness of insulation in terms of economic is found 7.5 cm.

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