A STUDY ON DETERMINATION OF OPTIMUM THERMAL INSULATION THICKNESS USING LIFE CYCLE COST ANALYSIS

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Abstract - In this paper, a systematic approach for optimization of thermal insulation thickness used in external walls was developed. The optimization model was based on the life cycle cost analysis using present worth method. The heat losses and the heating energy requirement of a prototype building were calculated by using degree-days utilizing long-term meteorological temperature data. The total cost, including heating cost, insulation material cost and installation of insulation cost, was calculated, and the cost curves were obtained for different fuel types to determine the optimum insulation thicknesses. The results show that the optimum thermal insulation thickness varied between 4.2 and 10.3 cm depending on fuel types. Moreover, the optimum insulation thickness varied more dramatically between 1.6 and 18.5 cm with different degree-days.

Keywords - Life Cycle Cost; Optimum Thermal Insulation Thickness; Energy Savings.

I. INTRODUCTION

Energy conservation is an integral part of energy policies. This is particularly important for Turkey because it imports most of its energy and its share of imports continues to increase each year. Due to the very limited indigenous energy resources, Turkey has to import nearly 55-60% of the energy from abroad to meet her needs [1-3]. Because a considerable portion of the total energy consumption is used in the residential sector (approx. 32%), and space heating has the highest value (more than 40%) among the residential energy consumption sources [3-5]. It is clear from the data given above that effective thermal protection in residential sector has an important role towards reducing the energy consumption for space heating.

In the literature, there are many studies on the estimation of energy requirement, energy conservation of building, the degree-time concept and its applications [4-16]. Kaynakli [6] reviewed the studies related to the optimum thermal insulation thickness for building walls. The optimum thicknesses of five insulation materials (expanded polystyrene, extruded polystyrene, foamed polyurethane, perlite and foamed polyvinyl chloride) were calculated on the basis of heating and cooling *DD*s by Yu et al. [7] for a typical residential wall in China. Papakostas and Kyriakis [10] present heating and cooling degree hours for two cities in Greece. Hasan [12] optimizes the insulation thickness for walls based on the life-cycle cost analysis using the present worth method. The transmission load is estimated using the degree-days concept. He found that savings up to 21$/m^2 of wall area are possible for rock wool and polystyrene insulation, and determined the payback periods of 1-1.7 years for rock wool and 1.3-2.3 years for polystyrene insulation depending on the type of wall structure. Expanded polystyrene was found to be the most profitable insulation material for Tunisia in the study of Daouas et al. [13]. That study concluded that the optimum thickness of insulation is 5.7 cm, which leads to energy savings of 58% with a payback period of 3.11 years.

In this study, firstly, the heating degree-days (*DD*s) were calculated for a prototype building using long-term data (from 1991 to 2006) obtained from the regular meteorological temperature measurements for Bursa. After the calculation of the heating energy requirement and fuel consumption, the cost analysis based on the life cycle cost was carried out to optimize the insulation thickness used external walls of the prototype building. The optimum insulation thickness was obtained for Bursa and also for certain cities in Turkey. The amount of savings and the savings rate were computed for five fuel types; natural gas, coal, fuel-oil, liquefied petroleum gas (LPG), and electricity. Moreover, the variation of optimum insulation thickness with *DD* was also investigated.

II. MATHEMATICAL MODEL

Degree-day

The total number of degree-days for a heating season can be calculated as

$$DD = \sum_{days} \left(T_b - T_o\right)^+ \qquad (1)$$

The plus sign above the parenthesis indicates that only positive values are to be counted. In this study, the base temperature for heating is assumed as 18ºC [16].

Heat loss calculations

Heat losses occur in buildings mainly from external walls, ceiling, windows, basement and by infiltration. In this study, dimensions of the considered prototype building are taken from the study of Durmayaz et al. [9]. Namely, the outside dimensions, width x depth x height, of the prototype apartment building are considered as 20 x 11 x 14 m. The roof, outside walls

and floor areas follow 220 m^2, 868 m^2, 220 m^2, and the total volume of the building is V=3080 m^3. The physical and thermal properties for the examined building, the parameters used in the calculations and their corresponding values are given in Table 1.

Table 1. Values of parameters used in the calculations

Parameter		Value
Outside wall		
2 cm	internal plaster	k = 0.87 W/mK
13.5 cm	hollow brick	k = 0.45 W/mK
x cm	insulation (polystyrene)	k = 0.034 W/mK
8.5 cm	hollow brick	k = 0.45 W/mK
2 cm	external plaster	k = 0.87 W/mK
	inside heat transfer coefficient	h_i = 8.29 W/m²K
	outside heat transfer coefficient	h_o = 34.0 W/m²K
		U =1/(R_{ins}+0.685) W/m²K
Insulation on external wall (polystyrene)		
conductivity		k = 0.035 W/mK
material cost		C_{ins} = 85 $/m³
installation cost		C_{ad} = 3.73 $/m²
Financial parameters		
inflation rate, i		8.5%
interest rate, g		13%
lifetime, LT		10
present worth factor, PWF		8.05 (by eq. 9)
Fuels		see Table 2

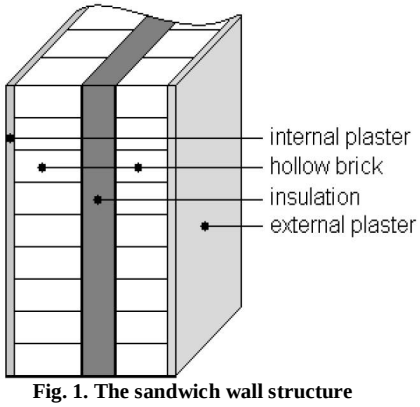


Fig. 1. The sandwich wall structure

The sandwich wall consists of an insulation layer in the middle of the two brick layers and two plaster layers on the inside and outside surfaces, as illustrated in Fig. 1. In this study, polystyrene was chosen for the insulation of the outside walls, and the thermal conductivity of polystyrene is also given in Table 1 [14-17].

The total heat transfer coefficient (L) of the prototype building can be calculated as

$$L = \sum_{1}^{M} UA + I\left(\rho c_p\right)_{air} V / 3600 \qquad (2)$$

where M represents the zones where the heat losses take place (*i.e.* outside walls, windows, ceiling, and basement). I is the seasonal average air exchange rates per hour due to the ventilation and infiltration. $(\rho c_p)_{air}$ is the volumetric thermal capacity of air, and it is taken as 1200 J/m^3K [18]. Hence the term of L is rewritten as

$$L = U_{o,w}\left(868 - A_{wd}\right) + U_{wd} A_{wd} + U_{bm} A_{bm} + U_c A_c + I V / 3 \qquad (3)$$

The overall heat transfer coefficient of the outside wall ($U_{o,w}$) that includes a layer of insulation is given by

$$U_{o,w} = \frac{1}{1/h_i + R_w + x_{ins}/k_{ins} + 1/h_o} \qquad (4)$$

where recommended design values for heat transfer coefficients on the inner and outer surfaces of a building are h_i = 8.29 W/m^2K and h_o = 34.0 W/m^2K [19].

In terms of degree-days, the seasonal heating energy requirements and the fuel consumption (m_f) can be calculated as

$$Q = 86400 L\, DD \qquad (6)$$

$$m_f = \frac{86400 L\, DD}{\eta\ \mathrm{LHV}} \qquad (7)$$

where η is the heating-system efficiency and LHV is lower heating value of the fuel (see Table 2).

Table 2. Prices (C_f) and lower heating values (LHV) of fuels and efficiencies of heating systems (η)[11,20]

Fuel	Price		LHV		η (%)
Natural gas	0.259	$/m³	34.526 x 10^6	J/m³	93
Coal	0.199	$/kg	29.295 x 10^6	J/kg	65
Fuel-oil	0.737	$/kg	40.594 x 10^6	J/kg	80
LPG	1.244	$/kg	46.453 x 10^6	J/kg	90
Electricity	0.091	$/kWh	3.599 x 10^6	J/kWh	99

Economic analysis

In this study, the Life Cycle Cost (LCC) analysis was used to calculate the total cost of heating over the lifetime of the building. The LCC includes not only the initial investment costs but also the continuing costs of heating and cooling the building through its lifetime. If the thickness of insulation increases, the cost of the insulation material increases, while the heating load and consequently energy cost decrease. The cost of the extra thickness of insulation should then be balanced against the reduced cost of heating. The optimum insulation thickness is the thickness at which the total cost is a minimum. The total cost per unit area of wall is [14]:

$$C_t = C_{t,ins} + C_{t,ad} + C_{h,pv} = C_{ins} x_{ins} A_{o,w} + C_{ad} A_{o,w} + C_h PWF \qquad (8)$$

Assuming an inflation rate in energy cost i, an interest rate g and an expected lifetime of building LT (years), the present worth factor (PWF) is calculated as [21]:

In case $g \neq i$,

$$PWF = \left(\frac{1+i}{g-i}\right)\left[1 - \left(\frac{1+i}{1+g}\right)^{LT}\right] \qquad (9)$$

LT is the expected lifetime, which is taken to be 10 years [22,23]. The total cost of heating the insulated building in present dollars can be rewritten as follows

$$C_t = C_{ins} x_{ins} A_{o,w} + C_{ad} A_{o,w} + \frac{86400 L\, DD\, C_f}{\eta\, \mathrm{LHV}} PWF \quad (11)$$

The optimum insulation thickness is obtained by minimizing eq. (11). The derivative of C_t equation with respect to x is taken and set equal to zero from which the optimum insulation thickness (x_{opt}) is obtained as

$$x_{opt} = \left(\frac{86400\, DD\, C_f\, PWF\, k_{ins}}{\eta\, LHV\, C_{ins}} \right)^{1/2} - R_{t,w} k_{ins} \quad (12)$$

III. RESULTS AND DISCUSSION

In the calculations, *U*-factor for single glass, the glazing area of the total outside wall area (GAP) and *I* values have been assumed as 5.96 W/m^{2}K, 20% (173.6m^2) and 0.5, respectively [9]. The ambient temperature (dry bulb) data during 16 years (from 1991 to 2006) have been used to determine the heating degree-days. Variation of the daily mean outdoor air temperature for Bursa city is seen in Fig. 1. This figure is used for determination of the start and end of the heating season. Variation of the daily degree-day values based on T_b=18ºC are shown in Fig. 2. Owing to the fact that the outside temperatures are low, the degree-day values are high at the beginning and end days of year. As there is no need for heating between the 137th and 275th days of year, the degree-days are equal to zero. The total number of heating degree-days is estimated *DD*=1900.7 for the heating season in Bursa by aid of eq. (1) and Fig. 2.

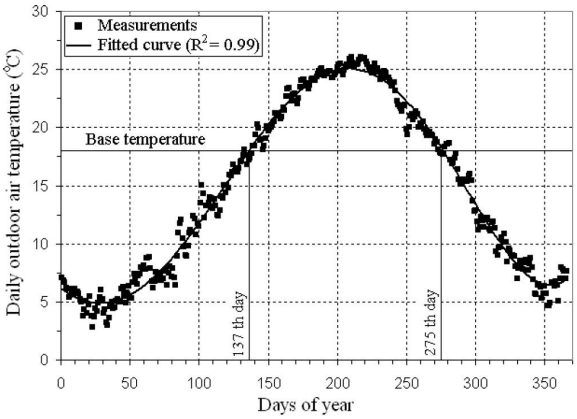


Fig. 1. Variation of the daily mean outdoor air temperature

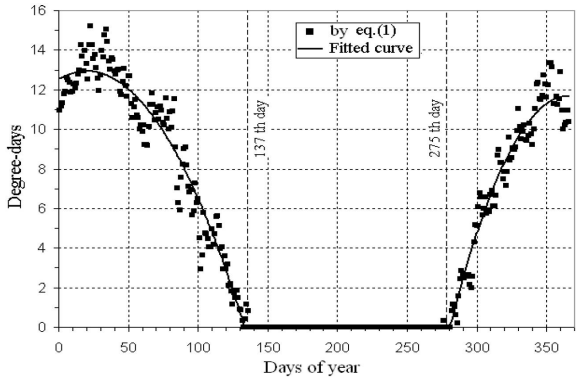


Fig. 2. Variation of the degree-days

With the insulation thickness increases, the heat losses and the heating cost decreases, but the initial investment cost of insulation increases, as seen in Fig. 3. The cost of heating ($C_{h,pv}$) decreases by diminishing increments with the increase in thickness of insulation, whereas the sum of the material ($C_{t,ins}$) and installation ($C_{t,ad}$) costs of insulation increase linearly. The insulation thickness at the minimum of total cost curve is taken as the optimum insulation thickness. Variation of the total heating cost with insulation thickness is given in Fig. 4 for different fuel types. The highest heating energy cost occurs for LPG usage, on the other hand, the lowest cost is found for the natural gas usage. The cost ratio of between the mentioned two fuels, LPG and natural gas, is approximately more than 3.5 times. Whereas the optimum insulation thickness is 4.2 cm for natural gas, it is 10.3 cm for LPG.

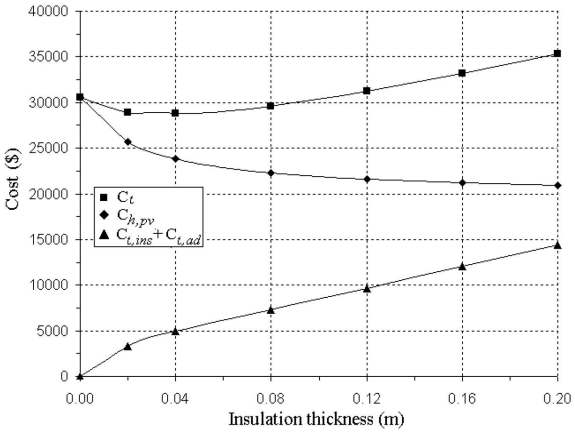


Fig. 3. Variation of the costs with insulation thickness (for natural gas)

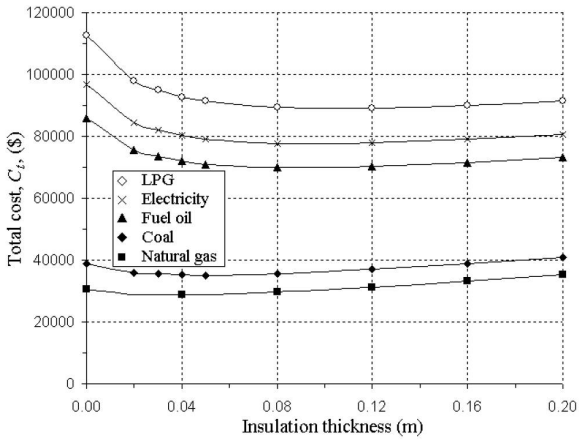


Fig. 4. Variation of the total heating cost (*Ct*) with insulation thickness for various fuel types

The effect of conductive heat transfer coefficient of insulation on the optimum insulation thickness is shown in Fig. 5 for different fuel types. The optimum insulation thickness increases by diminishing increments with the increase in thermal conductivity of insulation material. So, if heat transmission of insulation material increases, the required insulation thickness also increases.

The *DD* values in Turkey vary between 690 and 5137 for T_b=18ºC and the ratio of these two values is 7.4. The ratio of the highest to the lowest *DD* values is 2.07 in Austria, 1.70 in France and only 1.23 in Germany [24,25]. Because of the high ratio in Turkey, insulation thickness varies significantly from one region to another. The variation of the optimum insulation thickness with *DD* is shown in Fig. 6. It is clearly seen from the figure that the insulation thickness take higher values for more severe climate conditions and also for higher fuel costs.

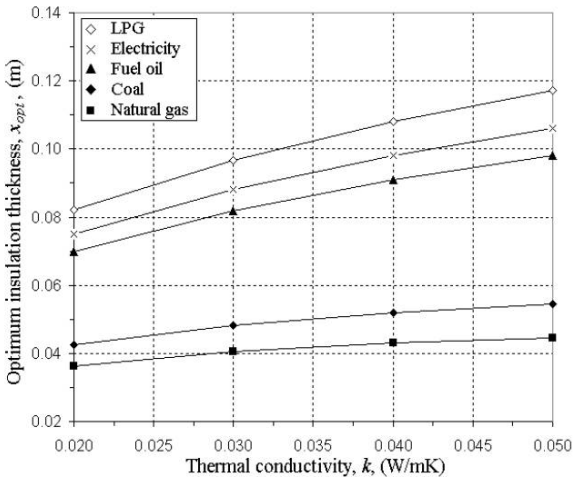


Fig. 5. Variation of the optimum insulation thickness with conductivity of insulation material

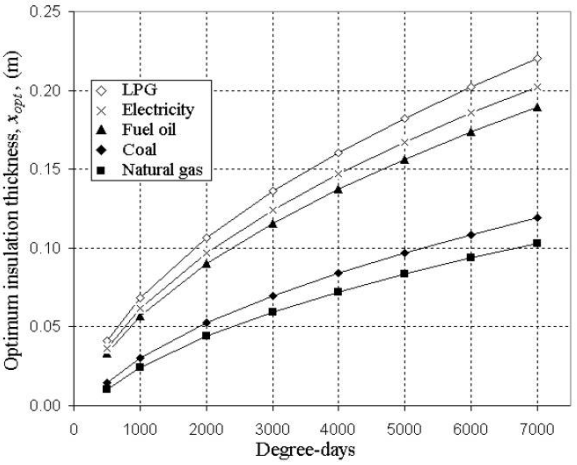


Fig. 6. Variation of the optimum insulation thickness with *DD*

CONCLUSION

In this study, the length of the heating period and the values of degree-days for province of Bursa were calculated by using the long-term meteorological air temperature measurements. Then, the optimization of insulation thickness used on external walls of buildings is developed. The results show that the heating season for Bursa is average 228 days which contains approximately 62% of year. The optimum insulation thickness varied between 4.2 and 10.3 cm depending on the fuel types. Optimum insulation thickness is a concept related with the thermal resistance of a wall, and it doesn't depend on the architectural properties of building such as air leakage and glazing area although the amount of savings, the savings rate and the payback periods are connected with these factors. Moreover, the optimum insulation thicknesses considerably varied with *DD*s.

Nomenclature

A	area, m^2
C	cost, $
c_p	specific heat, $Jm^{-3}K^{-1}$
DD	total number of degree-days
GAP	glazing area percentage
h	convective heat transfer coefficient, $Wm^{-2}K^{-1}$
i	inflation rate
I	air exchange rates per hour, h^{-1}
g	interest rate
k	thermal conductivity, $Wm^{-1}K^{-1}$
L	total heat transfer coefficient, $W K^{-1}$
LCC	life cycle cost
LHV	heating value of fuel, Jkg^{-1}, Jm^{-3}, $J kWh^{-1}$ depending on the fuel type
LT	lifetime, year
m	fuel consumption, m^3
PWF	present worth factor
Q	annual energy requirement, J
R	thermal resistance, m^2KW^{-1}
T	temperature, ºC
U	overall heat transfer coefficient, $Wm^{-2}K^{-1}$
V	volume, m^3
x	insulation thickness, m

Greek letter

η	heating system efficiency
ρ	density, $kg\ m^{-3}$

Subscripts

ad	additional
b	base
bm	basement
c	ceiling
f	fuel
h	heating
i	indoor, inside
ins	insulation
o	outdoor, outside
opt	optimum
pv	present value
t	total
w	wall
wd	window

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