A New Point of View for Insulation Calculations

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***Abstract*-The main aim of this study is to provide a new perspective for general insulation calculations. Some important points previously ignored in other studies were considered in this study. A new approach was proposed to obtain precise and realistic results. Four important recommendations regarding determination of the degree-hours values, effect of concrete columns on external wall, type of credit, consideration of labor and auxiliary equipment costs exist for the proposed approach. Optimum insulation thicknesses, energy savings and payback period calculations were conducted for different fuels, degree-hours values and type of credit for insulation.**

Keywords: Optimum Insulation Thickness; Life-Cycle Cost; Energy Saving, Payback Period, Degree-Hours

I INTRODUCTION

Many Industrial applications of insulation, such as district heating systems [1], pipe lines [2], thermal storage systems [3], etc. are drawing strong interest within the recent years not only to attenuate the environmental impact of energy consumption but also to cope with the high costs of energy. Meanwhile, the heating and cooling load decreases as the insulation thickness increases in buildings. Because of the drop in heat losses or gains, the total cost of energy for heating or cooling decreases. This reduction in the annual total cost peaks at the optimum insulation thickness. At thicknesses beyond this optimum level, the total cost begins to rise again. Numerous parameters influence the optimum insulation thickness, and they could be summarized as the following: a) the total degree-hours value depending on the chosen base temperature, b) the specific cost of unit energy, c) the building structure, d) life time of the building and the insulation material, e) the current inflation and discount rates, and f) the chosen insulation material's thermal properties and cost.

Many scientists [4-8] studied the optimum insulation thickness by mainly focusing on the regional characteristics and utilized the heat source and wall structure in their analyses. Ucar [4] found optimization of insulation thickness for the four different climatic regions in Turkey. Mahlia and Iqbal [5] analyzed the cost benefits and emission reductions for building walls in Maldives. Ucar et al. [6] applied three different methods for determination of optimum insulation thickness in external walls. Özkan and Onan [7] analyzed the optimum insulation thickness for different glazing areas in various climatic regions in Turkey. Sisman et al. [8] found the optimum insulation thicknesses for Turkey's different degree-day regions by considering external walls and roof (ceiling). It is difficult to identify a universal insulation thickness for all buildings in any region because of the independent effects of differing building structures, types of heating fuel used, chosen insulation materials, desired indoor temperatures, heated/cooled time periods, external heat gains, etc. As a result of all these factors, the optimum insulation thickness should be calculated separately for each individual building. Researchers generally determine the optimum insulation thickness utilizing degree-day parameter for the purpose of calculating the energy requirement in full time heated or cooled buildings.

Dombaycı [9] determined the degree-days maps of Turkey for various base temperatures. Büyükalaca et al. [10] analaysed the heating and cooling degree-days for Turkey for variable-base temperatures. Satman and Yalcinkaya [11] and Sen and Kadıoglu [12] analyzed the heating and cooling degree-hours for different region of Turkey. El-Shaarawi and Al-Masri [13] calculated the heating-degree days for Saudi Arabia. Coskun [14] and Oktay et al. [15] proposed a new technique to determine the hourly degree-hours for each month and applied it to Turkey. Sarak and Satman [16] and Duryamaz et. al. [17] utilized degree-hour and degree-day data for calculating the residential heating energy requirement.

In the literature, only the cost of insulation material is taken into consideration for calculating the optimum thickness. The total cost of insulation material varies with the chosen insulation thickness for a given area. Meanwhile, in practice, a fixed cost is present for applying insulation onto a particular area. The fixed cost can be expressed in terms of the labor and auxiliary equipment costs. The fixed cost per square meter of wall area is determined in US$ depending on the cost of particular insulation material (US$/$m^3$) in Turkey. For this reason, a new calculation procedure was proposed in this study. Results showed that relatively low insulation (0-3 cm) thicknesses may have a negative impact on total annual savings contrary to the general perception.

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II 2. ENERGY REQUIREMENT

The heat transfer coefficient (U) for a typical wall is given by the equation below:

$$U = \frac{1}{R_i + R_w + R_{ins} + R_o} = \frac{1}{R_{wl} + R_{ins}}, \quad (1)$$

where R_i and R_o are the inner and outer air-film thermal resistances, respectively. R_{wl} is the total thermal resistance of the wall layers without insulation. The thermal resistance of the insulation layer R_{ins} is given by Eq. (2)

$$R_{ins} = \frac{x}{k}, \quad (2)$$

where x and k are the thickness and thermal conductivity of the insulation, respectively. The overall heat transfer coefficient of a sample wall can be calculated by using Eq. (3) below:

$$UA_{wl} = \frac{A_{wl}}{R_{wl} + R_{ins}} = \frac{A_{wl}}{R_{wl} + \left[\frac{x}{k}\right]_{ins}}, \quad (3)$$

The Total heat loss from external wall can be found by multiplying heating degree-hour value (HDH) by the total heat transfer coefficient.

$$Q_{loss} = \left[\frac{A_{wl}}{R_{wl} + \left[\frac{x_1}{k_1}\right]_{ins}}\right] \cdot HDH, \quad (4)$$

$$HDH = \sum (T_{ref} - T_{amb})^+, \quad (5)$$

where T_{ref} and T_{amb} refer to indoor reference and actual ambient temperatures, respectively. Coskun et al. [8-10] proposed the concept of outdoor temperature distribution. They applied this approach to many cities in Turkey. They investigated monthly outdoor temperatures in five cities in Turkey. We applied the proposed approach to the determination of hourly temperature distribution trends in this study.

III ENERGY COSTS

The annual heating energy cost ($C_{heating}$) can be found by multiplying the specific energy cost of the fuel ($SECF$) stated in units of $\$/kWh$ by the total heating requirement in units of kWh.

$$C_{heating} = SECF \cdot Q_{loss} \quad (6)$$

The specific energy cost of fuel can be calculated by the equation below:

$$SECF = \frac{UCF}{H \cdot \eta}. \quad (7)$$

Here, UCF is the unit cost of fuel in either $\$/kg$ (solid fuels) or $\$/m^3$ (gaseous fuels). H is the heating value (lower or higher) of fuel in kWh/kg or kWh/m^3.

IV ECONOMICAL ANALYSES

In the literature, only the insulation material cost is taken into consideration for the purposes of calculating the optimum insulation thickness. Total cost of insulation material varies with the insulation thickness for the particular application area. Meanwhile, in practice, a certain level of fixed cost is associated with applying insulation to a chosen area, which could be attributed to the labor costs and auxiliary equipment costs. The latter cost factor stands for the costs associated with the fixing equipment for insulation material, covering or painting, the outer plaster, etc. Fixed costs are stated in terms of US$ per square meter unlike the variable cost of insulation material (US$/m3) in Turkey. Thus, a new calculation formula is generated and given in Eq. (10) to express the total insulation cost ($C_{Total,\,ins}$) in US$.

$$C_{Total,\,ins} = (C_i \cdot x + C_w)\cdot(A_{wl}), \tag{8}$$

where, $C_{i,n}$ is the insulation material cost in walls in US$/m^3. C_w indicates the fixed dollar costs (labor and auxiliary equipment) per an area of 1 square meter **(**US$/m^2**)**. Auxiliary equipment means insulation fixing materials, painting or wall covering materials. The thermal conductivity and unit cost parameters of expanded polystyrene are given in Table 1 for exemplary purposes.

The annual insulation cost effect (C_{ins}) can be found in $US\$/yr$ by dividing the total insulation cost to the expected lifetime of insulation material (N).

$$C_{ins} = \frac{C_{Total,\,ins}}{N} = \frac{(C_i \cdot x + C_w)\cdot(A_{wl})}{N} \tag{9}$$

The annual net cost saving (S_{Total}) can be formulated as

$$S_{Total}(x) = \left[\frac{A_{wl}}{R_{wl}} - \frac{A_{wl}}{R_{wl} + \left[\frac{x}{k}\right]_{ins}}\right]\cdot\frac{HDH \cdot SECF}{1000} - \left[\frac{(C_i \cdot x + C_w)\cdot(A_{wl})}{N}\right]. \tag{10}$$

The payback period of insulation cost, N_P is calculated by

$$N_P = \frac{C_{Total,\,ins}}{S_{Total}}. \tag{11}$$

A sample calculation is therefore conducted to present the calculation procedure. Assumption for calculation can be given as below form.

V RESULTS

It is known that applying insulation to building facades reduces the fuel consumption and hence CO2 emissions. In general, calculations (including only the insulation material costs) show that annual savings tend to take negative values at only high insulation thicknesses that are not normally applied in practice. Annual savings cannot take negative values for relatively small insulation thicknesses such as 0-3 cm in the general calculation procedures. This approach reveals that annual savings might not be achieved for relatively small insulation thicknesses in actual conditions with respect to economical perspective. Effect of seven input parameters, namely heating degree-hours, lifetime of insulation material, specific energy cost of fuel, thermal resistance of the wall, insulation material cost in walls, fixed dollar costs and thermal conductivity of the thermal insulation material, on annual cost savings, saving starting and finishing insulation thickness. In the calculations, both insulation material cost and fixed costs were considered. Total thermal resistance of the exterior wall (R_w) is given in Table 2 for three walls composition. Wall-I (W-I), Wall-II (W-II) and Wall-III (W-III) have total thermal resistance of 0.612, 0.337 and 0.667 m2 K/W. Concrete columns on external wall take into account in the calculation of wall total thermal resistance. One of the unique features of this study is the consideration given to concrete columns in the external wall in heat loss calculations.

TABLE 1 WALL STRUCTURES AND THERMAL CHARACTERISTIC

Wall types	Materials	Thickness (m)	Thermal conductivity (W/mK)	Total thermal resistance (m^2 k/w)
Wall-I	Stone	0.70	1.70	0.612
	Plaster	0.03	0.87	
Wall-II	Ext. plaster	0.03	0.87	0.337
	Concrete	0.20	2.10	
	Int. plaster	0.03	0.72	
Wall-III	Ext. plaster	0.02	0.87	0.667

	Hollow brick	0.20	0.45
	Int. plaster	0.03	0.87

Three cities from different countries were analyzed for three wall types in this study. Ankara, London and New York were chosen for investigation. Optimum insulation thickness values were calculated and are given in Table 1. The assumptions for calculation are as below.

- Life time of the insulation material was taken as 10 years.
- Indoor reference temperature was accepted as 20 °C. Heating degree day values for three cities were taken from [10, 18] and converted into degree-hours for calculation.
- Natural gas heated system was considered for calculation

TABLE 2. OPTIMUM INSULATION THICKNESS VALUES FOR DIFFERENT COUNTRIES AND WALL TYPES

City/ Country	Wall type	R_{wt} m^2 K/W	C_i \$/m^3	C_w \$/m^2	HDH °C-hours	$SECF$ US\$/kWh	OIT cm
Ankara, Turkey	W-I	0.612	85	8.0	81800	0.041	10.2
	W-II	0.337					11.4
	W-III	0.667					10.0
London, England	W-I	0.612	75	14.0	59500	0.057	11.3
	W-II	0.337					12.5
	W-III	0.667					11.2
New York, USA	W-I	0.612	110	18.0	70400	0.055	10.1
	W-II	0.337					10.9
	W-III	0.667					10.0

As can be seen in Table 2, optimum insulation thickness value increases with the increases in heating degree-hours, lifetime of insulation material and specific energy cost of fuel. Insulation material finance type has an effect on annual saving and payback period. Payback period increases for bank loan utilization for insulation. A sample calculation was therefore conducted to present the effect of bank loan on payback period. Calculation was conducted for Ankara, Turkey. Results are given in Table 3. The insulation payback period decreases from 3.93 years to 1.44 years for the sample wall when the labor and auxiliary equipment costs are ignored (Table 4).

TABLE 3. VARIATION OF PAYBACK PERIOD FOR DIFFERENT CREDIT MATURITIES.

	Payback period (year)		
	Insulation only	Insulation + auxiliary equipment	Insulation + labor + auxiliary equipment
Cash	1.44	2.25	3.93
2 year credit	1.57	2.60	4.89
4 year credit	1.72	3.01	6.08

Effect of total heating degree-hour on the payback period can be seen in Fig. 1. Payback period of insulation increases with the increase of the heating degree-hours. The effect of total heating degree-hour on the annual cost saving was calculated and is given in Fig. 2. In order to determine the level of savings for external wall insulations, the insulation thickness should be chosen between 2.5 cm and 14.5 cm for 25000 °C-hours. If insulation thickness rises above or below this interval for external wall, annual savings cannot be attained. Saving varies depending on the wall composition, which should be considered in calculations.

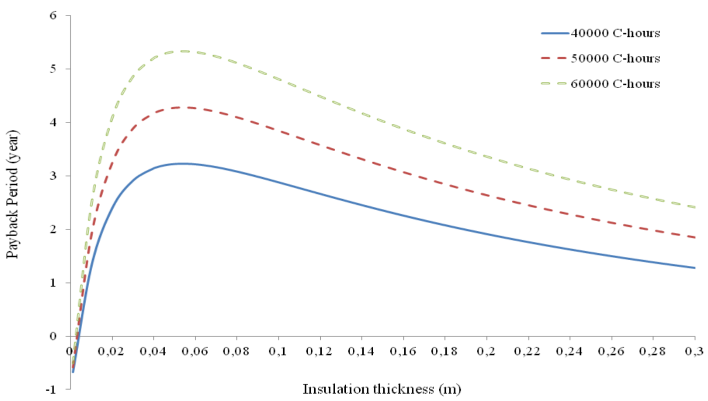

Fig. 1 Variation of payback period with total degree-hour value

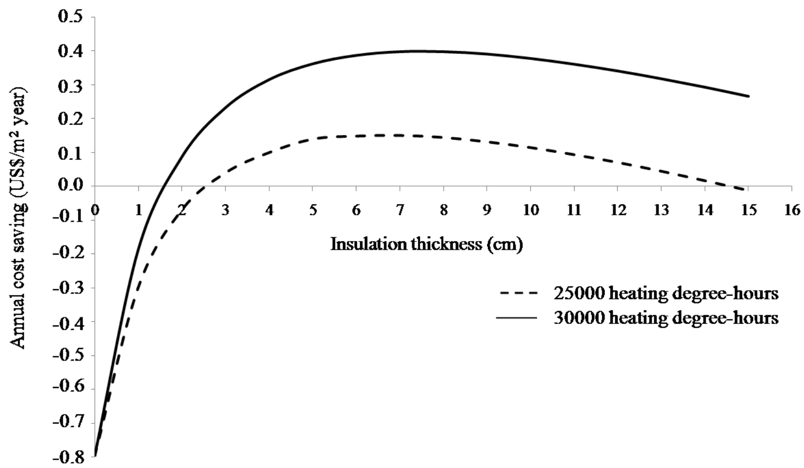

Fig. 2. Variation of annual cost saving with total degree-hour value

Effect of utilized fuel on annual cost saving was investigated for model building's exterior wall in Ankara (W-III). The behavioral trends of annual savings demonstrated by the five different fuel were investigated and are given in Fig. 3. It was determined that the natural gas accomplishes higher annual savings than other fuels. A sample calculation was conducted to present the insulation thickness on total cost and annual saving for natural gas (Fig. 4).

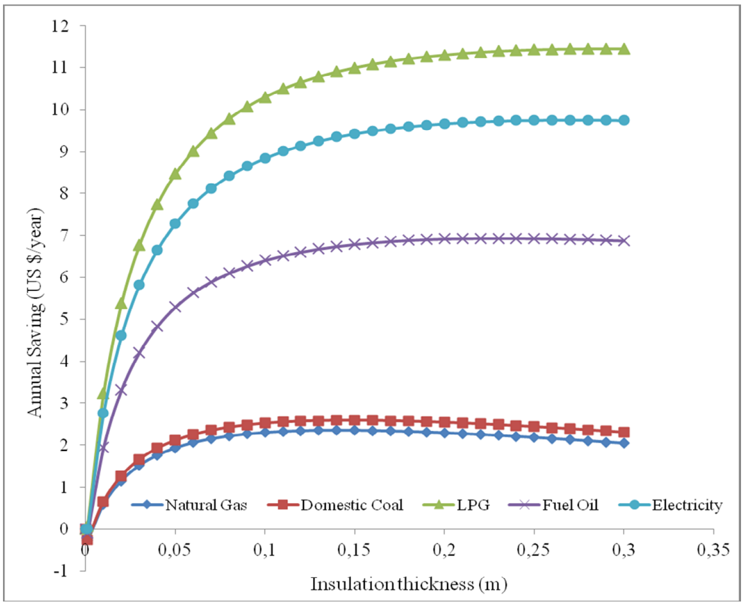

Fig. 3. Variation of annual cost saving with different fuels

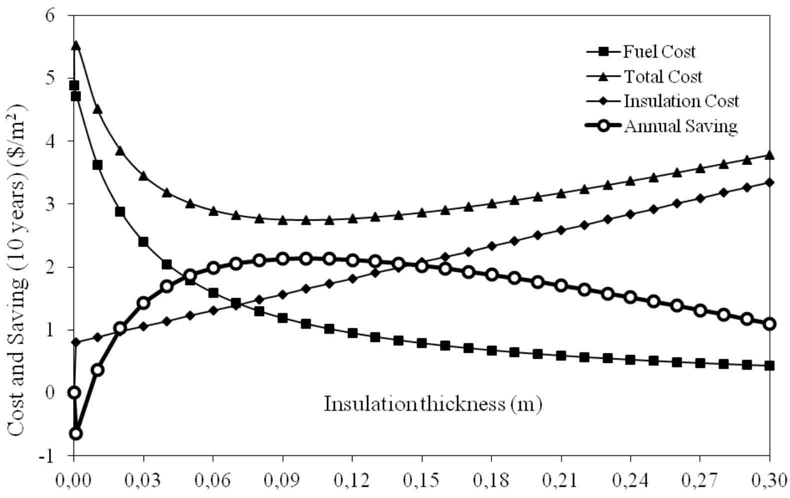

Fig. 4. Variation of cost and saving with insulation thickness

VI CONCLUSIONS

The costs of labor and auxiliary equipment usage were incorporated into the total insulation cost in this approach. The newly developed approach very closely approximates practical applications. Results showed that annual savings can become negative for relatively small insulation thicknesses depending on the wall composition, heating energy requirements, etc. This approach revealed that annual savings might not be achieved for relatively small insulation thicknesses in actual conditions with respect to economical perspective. The main conclusions drawn from the present study are given as follows:

- Research results showed that the annual savings can become negative for relatively small insulation thicknesses depending on the wall composition, heating or cooling energy requirements, etc. This approach revealed that the annual savings might not be achieved for relatively small insulation thicknesses under actual conditions with respect to an economical perspective.
- Costs of labor and auxiliary equipment utilization should be incorporated into the total insulation cost.
- Effect of the financed source, cash or bank credit should be considered to determine the optimum insulation thickness.

NOMENCLATURE

A	area (m^2)
C_w	fixed costs (labor and auxiliary equipment) **(**US\$/m^2**)**
C_i	insulation material cost (US\$/m^3)
$C_{Total,ins}$	total insulation cost (US\$)
$C_{heating}$	annual heating energy cost ($\$/yr$)
H	heating value (kWh/kg or kWh/m^3)
HDH	heating degree-hour (℃-hours)
k	thermal conductivity (W/ m^2 K)
N	Lifetime of insulation material (years)
N_P	payback period of insulation cost (years)
R	thermal resistance (m^2 K/W)
S_{Total}	annual net cost savings ($US\$/yr$)
$SECF$	specific energy cost of the fuel ($\$/kWh$)
$SSIT$	saving starting insulation thickness (m)
$SFIT$	saving finishing insulation thickness (m)
T	temperature (℃)
UCF	unit cost of fuel ($\$/kg$ or $\$/m^3$)
x	insulation thickness (m)
Greek letter	
ρ	density (kg/m^3)
η	Energy efficiency (-)
Subscripts	
amb	ambient
in	inner
ins	insulation
o	outside
ref	reference
wl	wall layers

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