Environmental impact of optimum insulation thickness in buildings

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Abstract: Environmental problems caused by energy usage threaten the world. High CO_2 emission emitted into the atmosphere by combustion of fossil fuels cause global warming. As a result of combustion of fossil fuels used for heating buildings, air pollution occurs. E ffective thermal protection in residential sector playsan important role towards the reduction of energy consumption for space heating. Insulation reduces fuel consumption, undesirable emissions from the burning of fossil fuels, and increases thermal comfort by minimizing heat losses from buildings. In this study, the four different cities of Turkey, Antalya, Istanbul, Eskişehir and Erzurum are selected to determine the optimum insulation thickness of the external wall of buildings. Optimum insulation thicknesses for two different energy sources (coal and natural gas) by using extruded polystyrene as an insulant are calculated and compared to each other. Annual savings in energy consumption and CO_2 emissions have been determined after optimization of insulation thickness. The result proved that when the optimum insulation thickness was used, the energy consumption and the emission of CO_2 decreased.

Keywords: *Environmental impact, Insulation thickness, Energy*

Nomenclature

A_{year}	*Difference of annual total heating cost (\$/m^2 year)*
C_{fuel}	*Cost of the fuel, (\$/m^3, \$/kg)*
$C_{insulation}$	*Cost of the insulant, (\$/m^2)*
$C_{totalinsulation}$	*Total heating cost of the insulated building, (\$/m^2 year)*
C_{total}	*Total heating cost of the insulated building, (\$/m^2 year)*
C_y	*Cost of the insulant (\$/m^3)*
C_{year}	*Annual heating cost for unit surface, (\$/m^2 year)*
DD	*Degree-day value, (^{o}C-days)*
g	*Inflation rate, (%)*
Hu	*Low heat value of the fuel, (J/kg)*
i	*Interest rate, (%)*
k	*Thermal conductivity, (W/mK)*
N	*Lifetime, (year)*
pp	*Pay-back period (year)*
PWF	*Present worth factor*
q	*Annual heat loss, (W/m^2)*
R	*Thermal resistance, (m^{2}K/W)*
R_d	*thermal resistances of the Outdoor, (m^{2}K/W)*
R_i	*thermal resistances of the Indoor, (m^{2}K/W)*
$R_{insulation}$	*Thermal resistance of the insulant, (m^{2}K/W)*
$R_{wall\ total}$	*Thermal resistance of non-insulated wall, (m^{2}K/W)*
T_b	*Base temperature (ºC)*
T_0	*Mean daily temperature (ºC)*
U	*Overall transfer coefficient, (W/m^{2}K)*
x	*Insulation thickness, (m)*
η	*Efficiency of the combustion system*

1. Introduction

In recent years, the amount of the energy consumption is increasing depending on t he development of technology, social and economic life. Although this shows the welfare of the society level, increase in energy consumption has brought environmental problems. One of the most crucial impacts resulting of consumption of variety of energy resources is changing the global climate which is known as the greenhouse effect or the global warming. During the recent years, greenhouse gases concentration has occurred continuous increase in the atmosphere. Turkey has a dynamic economic development besides its rapid population growth and industrial developments. Therefore, energy consumption has dramatically increased. Both the increase in energy need and the environmental problems make it necessary to utilize energy in the most efficient way. In the "climate change report" announced by the UN, it is indicated that global warming has been created in the last 50 years by the human being [1]. Among the order of countries emitting carbon dioxide- the US(5.5 billion tons), Russia(2.8 billion tons) and Japan(1.3) billion tons-, with carbon dioxide emmision of 294 million tons annually, Turkey was annnounced to be 13th. CO_2 emission in Turkey results 42% from industry, 30% from residences, 20% from transportation, 5% from agriculture and 3% from consumption out of the energy. The importance of environmental problems originating from residences will be better understood, when the amount of consumed energy for heating is considered in the portion of total energy. CO_2 emissions produced by the fuels for heating in residences will be reduced by insulating the buildings. When the insulation in optimum thickness is applied to the outer walls of the building, CO_2 emissions will be reduced 30% by status of uninsulated.

Dombaycı et al [1] calculated the optimum insulation thickness for Denizli by using two different insulants and five different fuel types. Dombaycı [2] further calculated the optimum insulation thickness of external walls of buildings in Denizli by using the expanded polystyrene insulant and coal. He determined that with a decrease of 46.6% in fuel consumption. CO_2 and SO_2 emissions dropped by 41.53%.

Çomaklı and Yüksel [3] calculated the optimum insulation thickness for Erzurum which is the coldest cities in the IV. degree-day zone of Turkey in accordance with the TS Standard no 825 on Rules of Heat Insulation in Buildings. He has been determined that CO_2 emissions amount decreased 50%

Ucar A. and Balo F.[4] calculated the optimum insulation thickness of the external wall, energy cost savings over a lifetime of 10 yr, and payback periods for the four different wall types in Elazığ. It is found that when the optimum insulation thickness is used, the amount of fuel consumption and the emissions of CO_2, SO_2, NO_x, and CO are decreased depending on the wall type.

For this purpose in this study, the optimum insulation thicknesses of external walls were calculated by using two different fuel types (coal and natural gas) for heating and expanded polystrene as the insulation material in buildings at selected cities of Turkey in four degree-day zones such as Antalya, Istanbul, Eskişehir and Erzurum, respectively. Annual savings in energy consumption and CO_2 emissions have been determined after optimization of insulation thickness.

2. Methology

Turkey is divided into four climatic zones depending on average temperature degree days of heating. Table 1 shows the degree-day values with reference to an equilibrium temperature of 18^{o}C in provinces within the four degree-day zones of Turkey as per the TS Standard no 825 on Rules of Heat Insulation in Buildings [5].

Table 1 Degree-day values with reference to an equilibrium temperature of 18°C [6]

Region	Provinces	Degree-day value
I	Antalya	1083
II	Istanbul	1865
III	Eskişehir	3049
IV	Erzurum	4827

2.1. The Heat Loss Calculation For External Walls

Heat losses in buildings generally occur through external walls, windows, roof, floors and air infiltration. In this study, the optimum insulation thickness has been calculated in consideration of heat losses only occurring in the external walls.

The external wall of a building is an externally-insulated wall composed of a 2 cm internal plaster. 13 c m bricks, insulant and a 3 cm external plaster. Physical characteristics of constituents of the wall are given in Table 2. In calculations, only the heat losses occurring in external walls were considered to calculate the optimum insulation thickness.

Table 2 Physical properties of the materials of external wall

Constituent	Thickness(m)	k (W/mK)	R (m^2K/W)
Internal Plaster(Lime-based)	0.02	0.87	0.02
Bricks	0.13	0.45	0.28
External plaster(cement-based)	0.03	1.4	0.02
R_i			0.14
R_o			0.04
$R_{wall\ total}$			0.50

In the study, extruded polystyrene (k=0.032 W/mK) was used as an insulation material. The price of insulation material is 158 $/m3.

The heat loss per unit area of external wall is

$$q = U \cdot (T_b - T_0) \tag{1}$$

The annual heat loss in unit area,q, can be determined using the degree days,DD asoccurring in unit surface is calculated by using U and the degree-day value [6].

$$q_{year} = 86400 \cdot DD \cdot U \tag{2}$$

The annual energy requirement can be calculated by dividing the annual heat loss to the efficiency of the heating system η:

$$E_{year} = \frac{86400 \cdot DD.U}{\cdot \eta} \tag{3}$$

where U is the overall heat transfer coefficient for a typical wall that includes a layer of insulation is given by

$$U = \frac{1}{R_i + R_{wall} + R_{insulation} + R_o} \tag{4}$$

R_i and R_o are the the inside and outside air film thermal resistances respectively and R_{wall} is the total thermal resistance of wall layers without insulation. $R_{insulation}$ is the thermal resistance of the insulant and calculated as follows:

$$R_{insulation} = \frac{x}{k} \tag{5}$$

Total resistance of the non-insulated wall layer $R_{wall.\ total}$ is

$$R_{wall,total} = R_i + R_{wall} + R_o \tag{6}$$

As a result, the annual heating load is then given by

$$E_{year} = \frac{86400 \cdot DD}{\left(R_{wall,total} + R_{insulation}\right) \cdot \eta} \tag{7}$$

Annual energy cost for unit surface C_{year} is calculated with the following equation:

$$C_{year} = \frac{86400 \cdot DD \cdot C_{fuel}}{\left(R_{wall,total} + R_{insulation}\right) \cdot Hu \cdot \eta} \tag{8}$$

The price and lower heating values of fuels and efficiencies of heating systems used in these calculations are given in Table 3.

Table 3 The parameters used in calculations

Parameter Natural gas	Value	Parameter Coal	Value
Chemical formula	CH_4	Chemical formula	$C_{7.078}\ H_{5.149}\ O_{0.517}\ S_{0.01}\ N_{0.086}$
Hu (J/kg)	$34{,}526.10^6$	Hu (J/kg)	$29{,}295.10^6$
η	0,93	η	0,65
C_{fuel} ($/m^3)	0,72	C_{fuel} ($/kg)	0,2216
Interest rate (i)		%7	
Inflation rate (g)		%10	
Life cycle (N)		10 years	
Present Worth Factor (PWF)		11.67	

The life cycle cost analysis method was used in calculating the optimum insulation thickness. Annual energy cost was calculated based upon t he present worth factor and the lifetime determined [1]. The interest rate adapted for inflation rate r is given by if

$$i > g \rightarrow r = \frac{i-g}{1+g}$$

$$i < g \rightarrow r = \frac{g+i}{1+i} \tag{9}$$

The present worth factor is calculated based upon the inflation and interest rates as follows:

$$PWF = \frac{(1+r)^N - 1}{r \cdot (1+r)^N} \tag{10}$$

Insulation cost is calculated as follows:

$$C_{insulation} = C_y \cdot x \tag{11}$$

Ultimately, the total heating cost of an insulated building as per the life cycle cost analysis is calculated as follows:

$$C_{insulation,\,total} = C_{year} \cdot PWF + C_y \cdot x \tag{12}$$

Energy savings ($\$/m^2$) obtained dring the life time of insulation material can be calculated as follows:

$$A_{year} = C_{total} - C_{t\,ins} \tag{13}$$

where, C_{total} and C_{tins} are the total heating costs of the building when insulation is not and is applied, respectively.

Pay-back period

$$pp = \frac{C_{total}}{A_{year}} \tag{14}$$

the fuel consumption per year as follows:

$$M_F = \frac{86400.DD}{(R_{wall,\,total} + R_{insulation})\eta \cdot Hu} \; (Kg/year) \tag{15}$$

2.2. Calculation Of Annual Combustion Gases Amount

Building lose heat through the wall and insulation reduces this heat loss giving increased comfort conditions and fuel consumption reduced. The general chemical formula of combustion for fuel is given by

$$C_xH_yO_zS_pN_q + \alpha A(O_2 + 3.76N_2) \rightarrow xCO_2 + \left(\frac{y}{2}\right)H_2O + p.SO_2 + B.O_2 + D.N_2 \tag{16}$$

The constants A, B and D calculated from the oxygen balance formulas given in (17), (18)and (19) respectively:

$$A = a + \left(\frac{b}{4}\right) + e - \left(\frac{d}{2}\right) \tag{17}$$

$$B = (\alpha - 1) + \left(a + \frac{b}{4} + e - \frac{d}{2}\right) \tag{18}$$

$$D = 3.76\alpha\left(a + \frac{b}{4} + e - \frac{d}{2}\right) + \frac{f}{2} \tag{19}$$

Total emission of CO_2 products resulting from the burning 1 kg of fuel can be calculated by

$$M_{CO_2} = \frac{x.CO_2}{\dot{M}} = kg\ CO_2 / kg\ fuel \quad (20)$$

$\dot{M}$ is the weight of mol for fuel which can be calculated using,

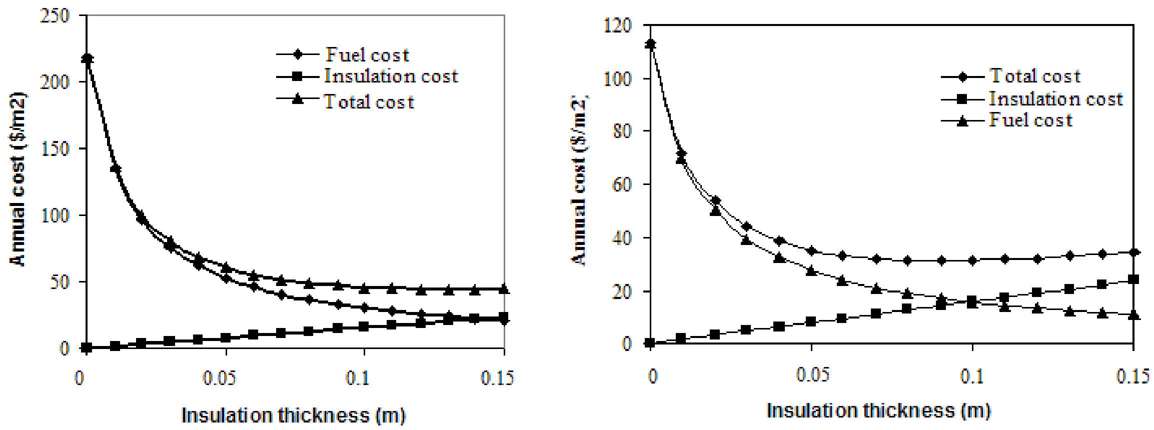
$$\dot{M} = 12x + y + 16z + 32q + 14p\ kg / kmol \quad (21)$$

2.3. Results

In this study, the optimum thickness of insulation with heating load for four different walls used for the buildings in turkey is determined. The effect of insulation thickness on total cost, fuel cost and investment cost for Antalya, Istanbul, Eskişehir and Erzurum province has been calculated. Optimum insulation thickness, pay-back period and energy saved over a period of 10 years calculated for two different fuel types are shown in Table 4. The effect of insulation thickness on the total cost over the lifetime of 10 year in Erzurum,which is the coldest city in Turkey, is given in Figure 1a-b. As shown in the figure 1, while the optimum insulation thickness for Erzurum with extruded polystyrene used for the insulation of the external wall within a natural-gas fuelled heating system is 14 cm, it is 9 cm when coal used as a fuel.

Table 4. Optimum insulation thickness, pay-back period and energy saving for different fuel types

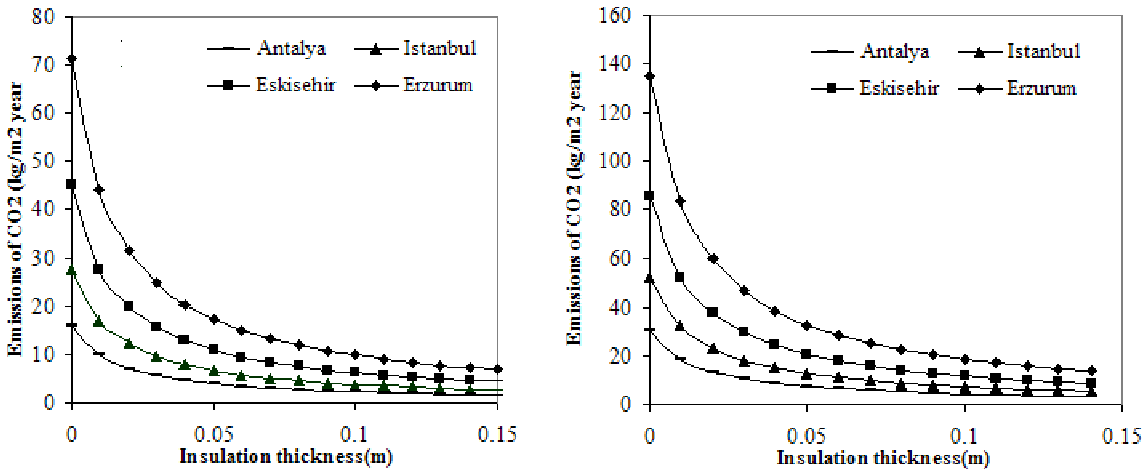
	Insulant	**Extruded polystyrene**		
City	**Fuel type**	**Thicknes s (m)**	**Pay-back period (year)**	**Energy Saving (10 years) ($/m^2)**
Antalya	Coal	0.03	2.14	11.84
	Natural gas	0.05	1.67	29.22
Istanbul	Coal	0.05	1.73	25.28
	Natural gas	0.08	1.46	57.69
Eskişehir	Coal	0.07	1.51	47.22
	Natural gas	0.09	1.3 4	102.93
Erzurum	Coal	0.09	1.38	82.03
	Natural gas	0.14	1.26	173.5



(a) (b)

Fig. 1 Effect of insulation thickness on total cost for Erzurum a) natural gas b) Coal

The variations of the emissions of CO_2 versus insulation thickness for a 1m^2 external wall of a building for four different cities of Turkey are shown in Figure 2 a by using natural gas and 2.b by using coal respectively.



(a) (b)

Fig. 2 Emissions of CO_2 versus insulation thickness a)For natural gas b) For Coal

As shown in the figure 2, CO_2 emission release from coal is greater than the natural gas when the coal is fired in Erzurum, located in the 4th climate region.The use of low- quality coal will increase the air pollution in particular. CO_2 emissions produced by the fuels for heating in residences will be reduced by using insulate the buildings. As shown the figures 2a, if we apply 14 cm insulation, which was found to be the optimum when natural gas is burned, the emission rates of fuel 7 kg/m^2. If insulation was not applied, CO_2 emission rate would be 71 kg /m^2. Similary, if we apply 9 cm insulation, which was found to be the optimum when coal (Figure 2b) is burned, the emission rates of fuel 20 kg/m^2. If insulation was not applied, CO_2 emission rate would be 135 kg /m^2.

Conclusion

As energy sources of our country are limited and foreign-dependent, conservation and efficient use of energy particularly in housing sector where energy is intensively consumed, and heat losses are much gain more significance day by day. In this study, optimum insulation thickness for external walls with two different fuels in four climatic zones of

Turkey have been calculated. The life cycle cost analysis method has been used in the calculations. Though variable by the fuel used selected, pay-back period of insulations applied to buildings are usually too short. Investments in insulation shortly pay off and contribute to diminishing the dependency of our country in terms of fuel sources. At the present, where fuel and energy costs drastically increase, this situation becomes vitally important. It is found that when the optimum insulation thickness is used, the amount of fuel consumption and the emissions of CO_2 decreased depending on the fuel. The highest values of the CO_2 emission rates is reached for coal. The results indicate that the optimum insulation thicknesses show significant variation due to fuel and climatic conditions.

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