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Economical and Environmental Effects of Thermal Insulation Thickness in Four Different Climatic Regions of Turkey

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Abstract: In the countries which supply big amount of their energy needs by import like Turkey using the energy economically is important. Thermal insulation technologies in buildings are the main method for using energy economically. However, choosing the thickness of the insulation material redundant causes high insulation costs. For this reason, an optimum point provides the highest gain in insulation applications is the subject. In this study, for Antalya, Manisa, Ankara and Sivas in the four climate regions in Turkey and optimum insulation thickness, energy saving and payback period in using two different insulation materials (extruded polystrene and rock wool) and five different kinds of fuel (coal, natural gas, fuel-oil, LPG, electricity) were calculated. In addition to this, an analysis of insulation thickness of the harmful emissions of the gas like CO_2 and SO_2 was made. The results of the study showed that the optimum insulation thickness vary between 0.016 and 0.145 m, energy savings vary between 1.79 $/m² and 103.44 $/m² and the payback period vary between 1.268 years and 6.022 years depending on the city and type of fuel. Environmental impacts of high used coal fuels were observed during the combustion, and emissions of CO_2 and SO_2 revealed decreases between 67%-75%.

Keywords- Optimum insulation thickness, Energy saving, Environmental impact.

1. Introduction

In Turkey, 80% of the energy consumed in households is utilized for heating and cooling purposes. It is very high amount for some countries which import nearly all of consumed energy like Turkey. Environmental problems are increasing day by day. Although some efforts are being made for declining of fossil-fuel resources, studies focusing on energy reduction as well as the use of renewable energy resources, high costs and groundwork difficulties make these enterprises slow down. The biggest environmental problem caused by using of various energy sources is the global climate changing known as greenhouse gas emission or the global warming. The combustion gases such as CO_2 and water vapor in the atmosphere transmit the bulk of the solar radiation but absorb the infrared radiation emitted by the surface of earth. Energy-related activities contribute both directly and indirectly to the generation of CO_2 and other potential greenhouse gases. CO_2 emissions from fossil-fuel combustion are estimated to account for half of the radiative balance dynamics caused by the greenhouse gases [1,2].

From this point, using the energy sources economically is the very economic and environmental method. Thermal insulation is the first of the methods for decreasing the energy declines. Reduction of the energy consumption to the minimum values for the buildings is compulsory according to national regulates. For this reason, Turkey's needs were thought, and "laws of heating insulation in buildings" is consumption. The insulation cost in suitably insulated buildings pays itself so many times during life of the building. Exhaust gas emission made by energy consuming and fossil fuels indicated in 1999 (TS 825). According to the TS825, four regions which have different degree and day were indicated, and these regions were showed in the Fig. 1.

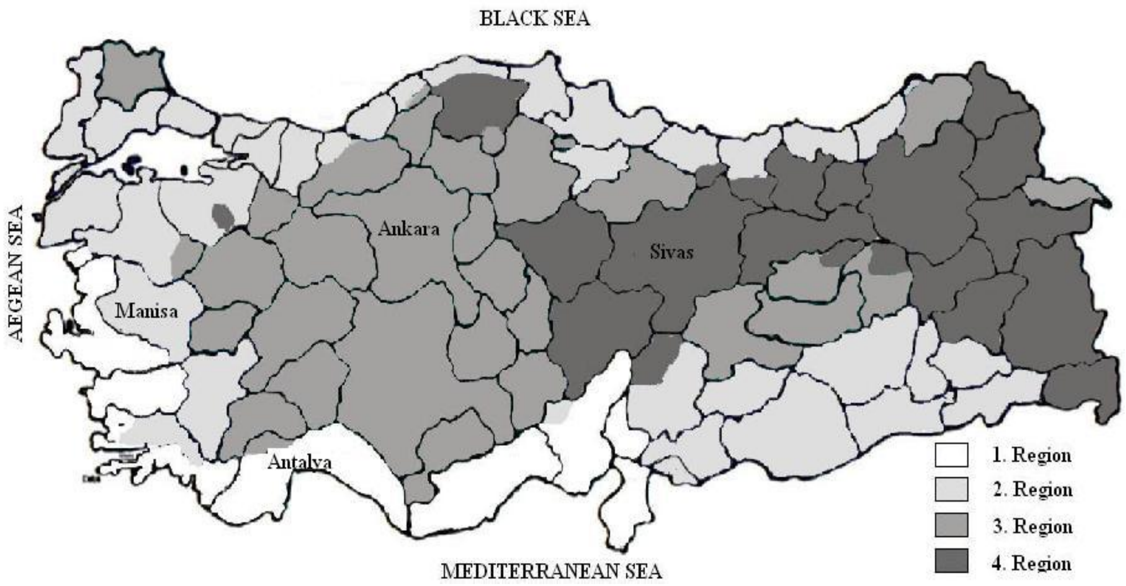

Fig. 1. Climate zones of Turkey according to TSE 825

The most important parameter determining the needs of heating is the climate conditions. For 15°C base temperature and 20°C indoor temperature, *DD* values are less than 1500 and for the forth region it is more than 4500 [3]. For selected cities degree days for a base temperature of 20 °C and mean daily temperatures are given Table 1.

Table 1. Degree days for a base temperature of 20 °C and mean daily temperatures [4].

City	Degree days (°C days)	Main mainly temperatures (°C)
Antalya	1481	+3
Manisa	1947	-3
Ankara	3214	-12
Sivas	4061	-18

In literature there are different studies for determination of optimum insulation thickness. Hasan [5] used life-cycle method in determination of the optimum insulation thickness. The results showed energy saving as 21$/m^2 for polystyrene and rock wool. At the end of the study, the payback period is determined as 1-1.7 year for rock wool and 1.3-2.3 years for polystyrene. Daouas [6] researched the effects of different wall sides on costs for both heating and cooling in Tunisian in his study. The study showed that the most economic result was for the south wall. In this case, optimum insulation thickness, energy saving and payback period are respectively 10.1cm, 71.33 %

and 3.29 years. Uçar and Balo [7] researched the economic side for determining the optimum insulation thickness for four different climate regions of Turkey in their study. At the end of the study, they determined that the optimum insulation thickness varies between 1.06 and 7.64 cm, energy saving varies between 19$/m^2 and 47$/m^2, and the payback period varies between 1.8 and 3.7 years. Çomaklı and Yüksel [8] evaluated environmental effects of the heating insulation for the coldest region of Turkey. They determined that when optimum insulation thickness is used in the external wall of the buildings, CO_2 emissions are decreased 50 %. Dombaycı et al. [9], in his studies, used different fuels and insulation materials. At the end of the study, It is indicated that when the coal is used as fuel, and expanded polystyrene is used as a insulation material, they determined that life cycle saving for optimal insulation thickness is 14.09$/m^2, and payback period is 1.43 year. Yu et al. [10] in their studies compared the different insulation materials in order to determine the optimum insulation thickness in cities in the winter and summer regions in China. The results showed that the payback periods changed between 1.9–4.7 years according to the different climate regions and life cycle savings 39 $/m^2-54.8 $/m^2.

In buildings heat is lost by 40% of external wall, 30% window, 17% door and ventilation, 7% of roof and 6% floor. The insulation materials that are commonly used have standard sizes, so one must choose between the available sizes [11]. In this study, for Antalya, Manisa, Ankara and Sivas in the four climate regions in Turkey and optimum insulation thickness, energy saving and payback period in using two different insulation materials (extruded polystyrene and rock wool) and five different kinds of fuel (coal, natural gas, fuel oil, LPG, electricity) were calculated. In the study, not only the economic analysis for determination of the optimal insulation thickness but also the environmental analyses were made. The coal, natural gas, fuel-oil and LPG exhaled like CO_2 and SO_2 emission amount were calculated. In study the environmental effects of electricity were not evaluated.

2. The Structure of External Wall

In Turkey, the external wall insulation applications are generally made by the sandwiches wall type. The structure of external wall is made by 2 cm internal plaster, 8.5 cm horizontal hollow brick, insulation material, 8.5 cm horizontal hollow brick and 3 cm external plaster. The structure of the external wall in calculations is indicated in Fig. 2.

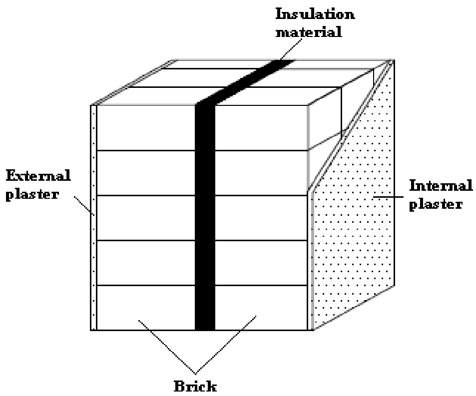

Fig. 2. Structure of sandwich wall

3. Heating Load for External Wall

Heat loss in buildings is because of the surface of external wall, windows, ceiling and air infiltration. In the study, heating loss is observed only on the external wall surface.

Heat loss on the external wall can be calculated by using the Equation below.

$$q = U.(T_b - T_o). \tag{1}$$

the U is the heat-transfer coefficient.

Annual heating loss can be calculated according to value of the degree day.

$$q_A = 86400DDU \quad (2)$$

Energy need for heating can be calculated by using the equation 3.

$$E_A = \frac{86400DDU}{\eta} \quad (3)$$

The overall heat transfer coefficient U for a typical wall as given by

$$U = \frac{1}{R_i + R_W + R_{ins} + R_o} \quad (4)$$

R_i and R_0 mentioned above are the inside and outside air film thermal resistances, respectively. R_W is total thermal resistance of the composite sandwich wall materials without the insulation, and R_{ins} is the thermal resistance of the insulation layer, which are respectively

$$R_{ins} = \frac{x}{k} \quad (5)$$

x and k are the thickness and thermal conductivity of the insulation, respectively. If R_{tw} is the sum of R_i R_w and R_o, then

$$U = \frac{1}{R_{tw} + R_{ins}} \quad (6)$$

$$R_{tw} = R_w + \frac{x}{k} \quad (7)$$

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

$$E_A = \frac{86400DD}{(R_{tw} + x/k)\eta} \quad (8)$$

and the annual fuel consumption is

$$m_F = \frac{86400DD}{(R_{tw} + x/k)LHV\eta} \quad (9)$$

LHV is lower heating value of the fuel given usually in J/kg, J/m^3 or J/kWh depending on the fuel type.

4. Optimization of Insulation Thickness

The life Cycle Cost Analysis is used in this study. It determines the cost analysis of a system. Total heating cost is indicated together with life cycle (*N*) and presents worth factor (*PWF*). *PWF* can be calculated by using inflation range g and bank rate i. For the calculation of PWF, value of N was considered as 10 years. Inflation and the interest rates are calculated as 5 % and 4 % [12]. For calculation of the PWF value, the equation can be used below.

If $i > g$ then,

$$r = \frac{i - g}{1 + g} \quad (10)$$

If $i < g$ then,

$$r = \frac{g - i}{1 + i} \quad (11)$$

and

$$PWF = \frac{(1 + r)^N - 1}{r(1 + r)^N} \quad (12)$$

If $i = g$ then,

$$PWF = \frac{N}{1 + i} \quad (13)$$

The annual energy cost used for heating the unit of area is calculated by the equation below.

$$C_A = \frac{86400.DD.C_f}{(R_{tw} + x/k).H_U.\eta} \quad (14)$$

C_f in \$/kg is the cost of the fuel, and H_u in J/kg is its heating value. The prices and lower heating values of fuels and efficiencies of heating systems used in these calculations are given in Table 2.

Table 2. Properties of fuels and heating systems.

Fuel	Price	H_u	η	Chemical formula
Coal	0.2265 \$/kg	29.295 x 10^6 J/kg	0.65	$C_{5.85}H_{5.26}O_{1.13}S_{0.008}N_{0.077}$
Natural gas	0.4794 \$/m^3	34.526 x 10^6 J/m^3	0.93	$C_{1.05}\,H_4O_{0.034}N_{0.022}$
Fuel-oil	1.3245 \$/kg	40.594 x 10^6 J/kg	0.80	$C_{7.3125}H_{10.407}O_{0.04}S_{0.026}N_{0.02}$
LPG	1.5695 \$/kg	46.453 x 10^6 J/kg	0.90	$C_{3.7}\,H_{4.1}$
Electricity	0.1875 \$/kWh	3.599 x 10^6 J/kWh	0.99	

The cost of insulation is given by

$$C_{ins} = C_i.x \qquad (15)$$

C_i is the cost of insulation material in \$/m^3 , and x is the insulation thickness in m.

As a result, the total heating cost of the insulated building is given by

$$C_t = C_A.PWF + C_i.x \qquad (16)$$

The optimum insulation-thickness, which makes the total cost a minimum, is calculated as

$$X_{OP} = 293{,}94.\left(\frac{DD.C_f.PWF.k}{H_U.C_i.\eta_f}\right)^{1/2} - k.R_{WT} \qquad (17)$$

From Eq. (17), it can be seen that the optimum insulation-thickness depends on parameters such as the price of fuel, price of the insulation material, properties of the wall and insulation material and the PWF. The parameters being used for indicating the insulation thickness, payback periods, energy savings are given in Table 3.

Pay-back period (PP*)* is calculated by the following equation for *PP* [11].

$$\frac{C_{ins}}{A_s} = \frac{(1+r)^{PP}-1}{r(1+r)^{PP}} \qquad (18)$$

C_{ins}/A_s is the simple payback period and this value does not take interest rate into account. A_s is the amount of the annual savings obtained by insulation.

Table 3. The parameters used in calculations

Parameter	Value
Degree-days (°C days)	See Table 1
Fuel	See Table 2
Insulation	
Extruded polystyrene	
Conductivity, *k*	0.031 W/mK
Cost, C_i	90\$/m^3
Rock wool	
Conductivity, *k*	0.039 W/mK
Cost, C_i	165\$/m^3
External walls	
Interior plaster	
Conductivity, *k*	0.872 W/mK
Brick	
Conductivity, *k*	0.45 W/mK
External plaster	
Conductivity, *k*	0.872 W/mK
R_{tw}	0.59 m²K/W
Lifetime, *N*	10

5. Calculation of Combustion Processes

In buildings, increasing the insulation thickness reduces heat loss. This situation causes to bring down the fuel consumption and air pollution. The general chemical Formula of combustion for fuel is given in [2]

$$C_xH_zO_wS_yN_t + \alpha A(O_2 + 3{,}76N_2) \rightarrow$$
$$xCO_2 + \frac{z}{2}H_2O + ySO_2 + (\alpha - 1)AO_2 + BN_2 \qquad (19)$$

The constants A and B are calculated from the oxygen balance formulas given in (20) and (21), respectively:

$$A = \left(x + \frac{z}{4} + y - \frac{w}{2}\right) \qquad (20)$$

$$B = 3{,}76\alpha\left(x + \frac{z}{4} + y + \frac{w}{2}\right) + \frac{t}{2} \qquad (21)$$

In (19), NO_x and CO emissions are neglected. The emission rate of combustion products resulting from the burning 1 kg of fuel can be calculated by [5,11]

$$M_{CO_2} = \frac{x.CO_2}{M} \equiv kg\ CO_2 / kg\ \ fuel \qquad (22)$$

$$M_{SO_2} = \frac{y.SO_2}{M} \equiv kg\ SO_2 /\ kg\ \ fuel \qquad (23)$$

The total emission of CO_2 and SO_2 could be calculated if the right hand side the above expressions by m_F which is total burned fuel within *DD*. The equations of emission are given in

$$M_{CO_2} = \frac{44x}{M} m_f \qquad (24)$$

$$M_{SO_2} = \frac{64y}{M} m_f \qquad (25)$$

M is the weight of mol for fuel which can be calculated using

$$M = 12x + z + 16w + 32y + 14t \qquad (26)$$

6. Results and Discussion

There are two parameters affecting the total heating cost of insulated buildings. These are the costs of insulation material and fuel. The heating loss is decreased because of reduces the insulation of the buildings. As a result, energy need for heating unit of an area is decreased, and the total cost is decreased. However, increasing of the insulation thickness more than adequate reduces the insulation cost. In this case, the total cost starts to rise because of the high insulation cost. This point which the total cost is minimum is found voice in optimum insulation thickness value.

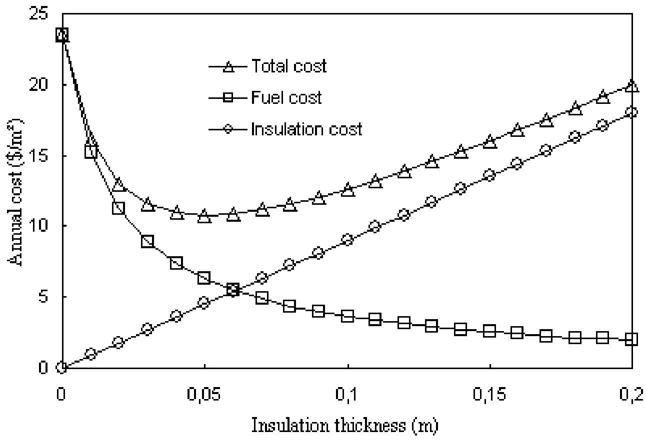

Fig. 3. Effect of insulation thickness on the total cost for the city of Ankara (DD–3214°C-days)

In Fig. 3 the effect of insulation thickness on the total cost for Ankara is observed. By the raising of the insulation thickness, the total cost is decreased to the optimum point. However, spending the total cost rises because of the high insulation cost for the external wall of the building. Annual energy saving from the unit of an area according to the fuel used is directly proportionate to the fuel cost and PWF value. A rising in the fuel cost will rise the energy saving. For this reason, if having high cost fuels such as fuel-oil, LPG and electricity are used, the energy saving of them will be much more than coal and natural gas which have low cost. The effect of insulation thickness on energy saving for different fuels used in the studying is indicated at Fig. 4.

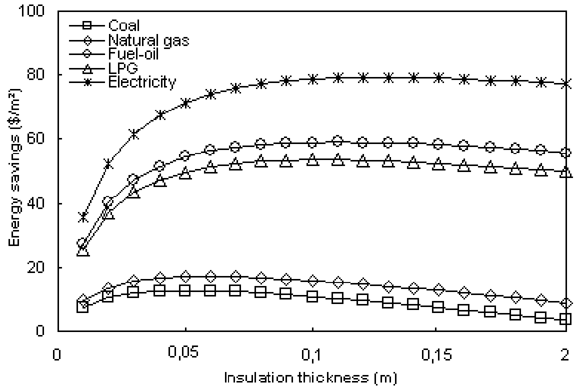

Fig. 4. Effect of insulation thickness on energy saving for different fuel types in city of Ankara (extruded polystyrene insulation material)

Optimum insulation thickness which is calculated according to the different insulation thickness, payback periods and the energy savings are indicated in the Table 4. The basic parameters which affect the calculated values are the type of degree-day of the region and fuel, insulation material. Optimum insulation thickness is getting rise in the regions which have high degree and day value. For example when using the extruded polystrene as the insulation material and coal as fuel in Sivas, optimum insulation thickness is 0.059m, in Antalya having warmer climate this value is 0.029 m. Payback period is a period in which insulation cost pays itself. This period is very short in the regions that have high degree day values. The reason is that the annual energy saving is much more because of the insulation in the cold regions. When the table is analyzed, it is understood that the optimum insulation thickness is between 0.016 and 0.145m, the energy saving is between 1.79 $/m² and 103.44 $/m², and the payback period is between 1.268 years and 6.022 years.

Table 4. Optimum insulation thickness energy savings, and payback periods, calculated according to different fuels and insulation material types

Insulation material		Fuels	City			
Extruded polystrene	Optimum insulation thickness (m)		Antalya	Manisa	Ankara	Sivas
		Coal	0.029	0.035	0.051	0.059
		Natural gas	0.034	0.042	0059	0.069
		LPG	0.065	0.077	0.104	0.12
		Fuel-oil	0.069	0.081	0.11	0.125
		Electricity	0.08	0.095	0.127	0.145
	Energy savings ($/m²)					
		Coal	4.02	6.187	12.68	17.32
		Natural gas	5.77	8.65	17.17	23.11
		LPG	20.78	29.32	53.61	70.41
		Fuel-oil	23.1	32.47	59.09	77.44
		Electricity	31.74	44.19	79.32	103.44
	Pay-back period (years)					
		Coal	2.688	2.297	1,855	1.711
		Natural gas	2.354	2.062	1.714	1.603
		LPG	1.642	1.529	1,381	1.329
		Fuel-oil	1.605	1.501	1.361	1.312
		Electricity	1.507	1.423	1.308	1.268
Rock Wool	Optimum insulation thickness (m)					
		Coal	0.016	0.022	0.034	0.041
		Natural gas	0.021	0.027	0.041	0.049
		LPG	0.046	0.056	0.079	0.091
		Fuel-oil	0.049	0.059	0.083	0.096
		Electricity	0.059	0.071	0.097	0.113
	Energy savings ($/m²)					
		Coal	1.79	3.31	8.38	12.22
		Natural gas	3.01	5.17	12.1	17.24
		LPG	15.16	22.56	44.21	59.68
		Fuel-oil	17.14	25.33	49.32	66.17
		Electricity	24.68	35.78	67.91	90.35
	Pay-back period (years)					
		Coal	6.022	4.283	2.791	2.424
		Natural gas	4.506	3.445	2.433	2.158

LPG	2.251	1.988	1.671	1.568
Fuel-oil	2.162	1.924	1.631	1.536
Electricity	1.938	1.757	1.528	1.452

Preventing the loss of thermal energy in buildings can be achieved by keeping the heat inside. There are some ways to do this, one of which is the thermal insulation [2].

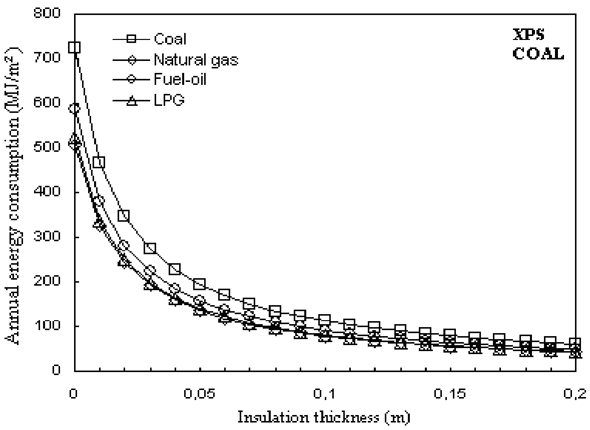

Fig. 5. Annual energy consumption according to insulation thickness in Ankara city

In Fig. 5 annual energy consumption is decreased depending on the insulation thickness which is observed. At the end of this, CO_2 and SO_2 emissions at the burning are declined. For 1 m² external wall CO_2 and SO_2 emissions were calculated by using parameters and Eq. in Table 3 (24)-(25) During the use of different fuels, alteration of CO_2 and SO_2 emissions for 1m^2 external wall were indicated in the Fig. 5 and 6. By raising the insulation thickness, the annual heating loss of the external wall is decreased. As a result of this, annual energy consumption and emission are decreased too.

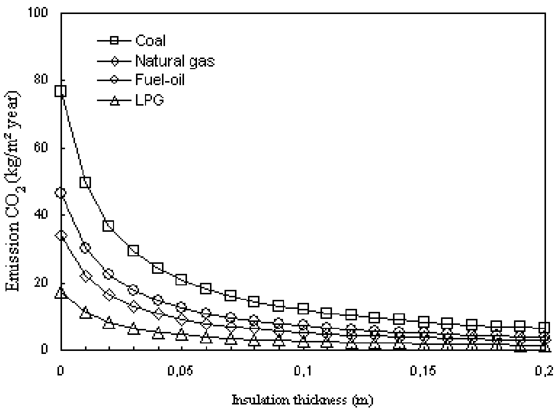

Fig. 6. Emission CO_2 versus insulation thickness in Ankara city (extruded polystyrene insulation material)

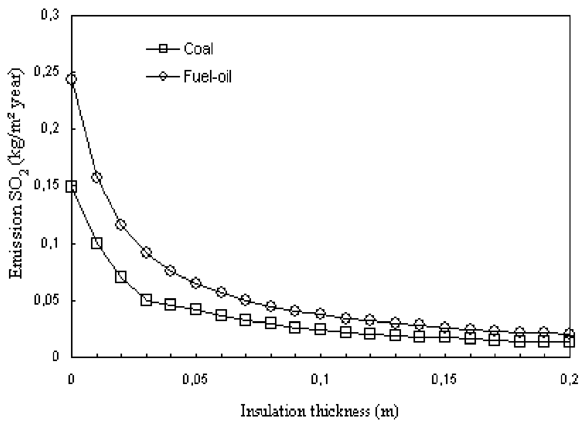

Fig. 7. Emission SO_2 versus insulation thickness in Ankara city (extruded polystyrene insulation material)

CO_2 and SO_2 amounts which were calculated for different insulation materials and cities in using coal as fuel are indicated in the Table 5. It is possible to decrease of CO_2 and SO_2 emissions in big amounts by implementations of insulation especially in the cold regions. For example, when declined polystyrene is used as insulation material and coal is used as fuel in Ankara, optimum insulation thickness, CO_2 and SO_2 emissions are declined respectively (0.051 m), 67% and 73%.

7. Conclusion

In this study, five different fuel types and two different insulation materials for Manisa, Antalya, Ankara, Sivas, they are from the four different climate regions in Turkey, and the environmental and economical effects of insulation applications in insulation material using for these cities are analyzed. The result of the study shows that optimum insulation thickness is between 0.016 and 0.145 m, energy saving is between 1.79 \$/m² and 103.44 \$/m² and the payback period is between 1.268 year and 6.022 year. The highest energy saving is handled as103.44 when the extruded polystrene is used as insulation material and electricity as fuel $/m^2 in Sivas which is the one of the coldest city of Turkey. During the use of optimum insulation, CO_2 emission for coal decreases according to the insulation material between 41.03% and 76.33% in contrast SO_2 emissions decreases between 41.66% and 75.26%.

Table 5. Annual CO_2 and SO_2 emissions when coal is used as fuel.

Insulation material	City	Emission CO_2 (kg/ m² year)		Emission SO_2 (kg/ m² year)	
Extruded polystyrene		Without insulation	After insulation	Without insulation	After insulation
	Antalya	35.431	8.906	0.072	0.018
	Manisa	46.58	15.98	0.95	0.032
	Ankara	76.89	25.94	0.158	0.042
	Sivas	97.15	22.99	0.19	0.047
Rock wool		Without insulation	After insulation	Without insulation	After insulation
	Antalya	35.431	20.89	0.072	0.042
	Manisa	46.58	23.81	0.95	0.048
	Ankara	76.89	33.34	0.158	0.068
	Sivas	97.15	34.92	0.19	0.071

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Nomenclature

C	Cost [\$/kg, \$/m^3, \$/kWh]
DD	Degree-days [°C-days]
E_A	Annual heating energy [Jm^{-2}yıl^{-1}]
g	Inflation rate [%]
h	Convection heat transfer coefficient [W/m^{2}K]
i	Interest rate [%]
k	Thermal conductivity [W/mK]
LCCA	Life-cycle cost analysis
LHV	lower heating value of the fuel [J/kg, J/m^3, J/kWh]
m_f	Annual fuel consumption [kg m^{-2} year^{-1}, m^3 m^{-2} year^{-1}, kWh m^{-2} year^{-1}]
PP	Payback period [years]
PWF	Present worth factor
q	Heat loss [MJ m^{-2} year^{-1}]
r	Interest rate adjusted for inflation
R	Thermal resistance [m^{2}K W^{-1}]
T_b	Base temperature [°C]
T_0	Mean daily temperature [°C]
U	Overall heat transfer coefficient [W/m^{-2} K^{-1}]
ins	Insulation

Greek letter

η	Efficiency of space heating system

Subscripts

A	Annual
f	Fuel
i	Inside
t	Total
t_w	Total wall excluding insulation material
X	Insulation thickness [m]