DETERMINATION OF OPTIMUM INSULATION THICKNESS FOR BUILDING EXTERNAL WALLS WITH DIFFERENT INSULATION MATERIALS USING ENVIRONMENTAL IMPACT ASSESSMENT

by

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Original scientific paper
https://doi.org/10.2298/TSCI180903010D

The aim of this study is to determine the optimum heat insulation thickness for the glasswool and rockwool insulation material. Since natural gas is mostly used for heating in Turkey, it has been selected as fuel for the calculation. In order to calculate the optimum thickness of the insulation, the number of the degree-day and total environmental factor have been used. For the optimum insulation thickness, the decrease in exergy loss, CO_2 emission and the fuel consumption were 75%, 73%, and 71% for the glasswool, respectively. On the other hand, for the rockwool, they were 35%, 18%, and 43%, respectively. Optimum thickness was calculated as 0.40 m for glasswool, and 0.18 for the rockwool.

Key words: *insulation, optimum insulation thickness, life cycle, exergy loss, environmental impact*

Introduction

Energy is vitally important and energy demand increases with the increase in world population, industrialization, needs, and changing the lifestyle [1]. In EU-27, residential sector (housing and commercial) account for more than 40% of the final energy consumption [2]. Today, environmental problems, global warming, and energy crisis force the nations to decrease the energy consumption in every sector especially the residential sector [3]. Turkey imports about 85% of its total energy consumption and foreign energy dependency of the country is growing. Turkey's rate of dependence on imported energy was increased to 75.9% in 2016. Primary energy demand and energy imports increased 268%, respectively, from 1990 to 2016. However, for the same period, energy production in Turkey increased only 21% [4]. In order to decrease the foreign-dependency on energy, the energy production can be increased by diversifying the existing energy resources. However, using energy efficiently such as raising energy awareness, optimizing room and water temperatures and lighting control is one of the most effective solutions to reduce the energy consumption and foreign-dependency on energy [5]. On the other hand, insulation is one of the most effective methods in decreasing the energy consumption [6]. The external wall and roof of the houses is an interface between the indoor and outdoor of the house. For an effective insulation, the outdoor environmental conditions and indoor thermal comfort should be the consideration. If a proper insulation material is selected

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and optimum insulation thickness is applied, energy consumption can be minimized [7]. It is well known that efficient thermal insulation reduces the energy consumption and fluctuations of temperature in buildings for the comfort. Yuan *et al.* [8] studied for optimize the combination of surface reflectivity and the insulation thickness of exterior walls for energy savings in regions of Japan. Kurekci [9] determined the optimum insulation thicknesses required in Turkey's 81 provincial centers. In another paper, Liu *et al.* [10] presented a coupled heat and moisture transfer model which considers the effect of the moisture transfer on heat transfer to calculate the cooling and heating transmission load. Wati *et al.* [11] optimized the thicknesses of insulation layers in external walls of continuously used building in a tropical region according to shade level. Nematchoua *et al.* [12] presented the study about a literature review on the thermal insulation applications to external walls of buildings, and a case was investigated in a tropical wet and hot climate. Axaopoulos *et al.* [13] determined the optimum insulation thickness for external walls of different orientation of a piggery building accounting for both the heating and the cooling period. Ozel [14] has calculated the optimum insulation thickness according to cooling requirements of buildings in a hot climate by using a computer program developed in MATLAB. Kaynakli [15] presented a literature review in his study which, was carried out the optimum thickness of thermal insulation material in a building envelope and its effect on energy consumption by using the optimization procedures and the economic analysis methods. The study which was carried out by Ozel [16] for a south-facing wall and the climatic conditions of a city in Turkey, showed that the optimum insulation thicknesses vary between 2 cm and 8.2 cm, the energy savings vary between 2.78 $/m^2 and 102.16 $/m^2 and the payback periods vary 1.32-10.33 years depending on five different structure materials and two different insulation materials which were XPS and EPS. Daouas [17], determined that the wall orientation had a small effect on optimum insulation thickness, but a more significant effect an energy savings and also economic parameters had a noticeable effect on optimum insulation and energy savings. Mahlia and Iqbal [18], found that by introducing optimal thickness of different insulation materials and by having air gaps of 2, 4, and 6, energy consumption and emissions could be reduced by 65-77 % in comparison to a wall without insulation or air gaps. Daouas *et al.* [19] determined an optimum insulation thickness is under steady periodic conditions in Tunisia. Thermal insulation of buildings is very important in minimizing the energy usage and reducing emission. Environmental impact of optimum insulation thickness has been investigated for a city in Turkey by Dombayci [20]. Sanea *et al.* [21] investigated the effect of the average electricity tariff on the optimum insulation thickness in building walls by using a dynamic heat-transfer model and an economic model based on the present-worth method. Some results were obtained by Al- Khawaja [22] for a typical house in Qatar which is an example of hot area. The wall mate insulation was found to have the best performance for houses in Qatar. The energy saving was maintained by reducing the energy consumption in buildings. For this reason, the energy savings could be obtained by using proper insulation material in external walls and roof of buildings. Life-cycle cost analysis (LCA) method, taking inflation and interest rates into account, is mostly used in order to calculate the optimum thickness [23]. Hasan [24] has calculated the optimum insulation thickness using LCA method for rockwool and polystyrene insulation material in Palestine. The LCA method was also examined by Comakli and Yuksel [25] to calculate the optimum insulation thickness for styrofoam insulation material in Kars, Erzurum, and Erzincan, which are the coldest cities of Turkey. In these studies, the energy balance principle has been considered to determine the optimum insulation thickness for the external wall of the houses. The life cycle assessment method was also used to calculate the optimum insulation thickness. This method includes the environmental impact of thermal insulation thickness in buildings. There are several studies used this method to calculate the optimum insulation thickness. Kecebas [26] was used exergetic life-cycle cost (LCC) assessment method to calculate the optimum thickness of rockwool insulation material for the heat system distribution pipes by using the fuel of coal, natural gas and fuel-oil in the city of Afyonkarahisar in Turkey. Pargana *et al.* [27] compared the insulation materials using the life-cycle assessment method and the European standards on the environmental assessment of the buildings. Schlanbusch *et al.* [28] suggested new approaches for designing hollow silica nanospheres for the application of insulation with life-cycle assessment integration. Gao *et al.* [29] investigated the environmental impacts of these materials with the method of life-cycle assessment by synthesizing the nanoinsulation materials. Turkey is divided into four climatic regions, and Denizli locates at the third climate zone. In this region, heating season is about five months. Heating degree days (HDD) of Denizli is 2055 [6]. In this study, the optimum insulation thickness was calculated for unit external wall surface of the house in Denizli. Environmental impact assessment method in the exergy perspective was used with two different insulation materials (rockwool and glasswool) in order to calculate the optimum insulation thickness for external walls. These two materials are the most widely used insulation material for exterior wall insulation in Turkey. Therefore, these two materials are dedicated to the handling. In the literature, there is very limited study investigates environmental impact assessment method in the exergy perspective calculating the optimum insulation thickness.

Material and methods

In order to determine the annual natural gas consumption, the heat transfer rate from the indoor to the outdoor through the unit external wall surface of the houses in Denizli by using degree-day method was calculated. Steady-state exergy analysis has been conducted for unit wall surface and entropy production and exergy destruction have been calculated depending on the heat loss. The amounts of fuel and CO_2 emission have been calculated using the annual energy consumption for the unit wall surface. The heat transfer through the external wall of houses causes to the exergy loss during the heating period. In steady-state, the heat loss occurs through external walls, roof, window, air infiltration and ventilation. Air infiltration and ventilation have no effect on the calculation of the external wall insulation. Optimum insulation thickness value has been calculated by equating the derivative to zero according to the insulation thickness of the function from the total environmental impact function for an insulated wall system. The structures of investigated external wall construction shown in fig. 1. The wall is an example of a sandwich wall which comprises a combination of 2 cm interior plastering, 8.5 cm horizontally hollow bricks, insulation material, 8.5 cm horizontally hollow bricks and 3 cm external plastering. In the study, rockwool and glasswool insulation materials have been applied. Table 1 shows the parameters used in the external wall. The heat transfer through the external wall of

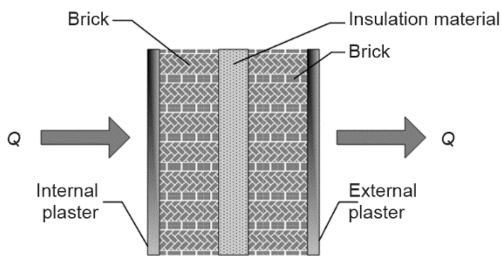

Figure 1. External walls with insulation

Table 1. Parameters used of energy demand calculations [6]

Parameter	Value
HDD	2055
R_{wt}	0.592 m^{2}K/W
η	0.93

houses causes to the exergy loss during the heating period. In steady-state, the heat loss occurs through external walls, roof, window, air infiltration, and ventilation. Air infiltration and ventilation have no effect on the calculation of the external wall insulation [23]. Typically, natural gas consists of over 90% CH_4 and small amounts of ethane and other hydrocarbons. For that reason, only CH_4 can be used in combustion equations. Atmospheric air consist of approximately 21% O_2 and 79% of *other gasses* is mostly N_2, so air can be assumed to be composed of 21% O_2 and 79% N_2 by volume. It is well known that in air every mole of O_2 is accompanied by 3.76 moles of N_2. The N_2 is considered inert and the reaction equation can be written as follow if n mole fuel is consumed for annual unit surface energy need [30].

$$n\mathrm{CH_4} + 2n(\mathrm{O_2} + 3.76\mathrm{N_2}) \rightarrow n\mathrm{CO_2} + 2n\mathrm{H_2O} + 7.52n\mathrm{N_2} \tag{1}$$

For the fuel, air and waste gasses, exergy balance equation together with the chemical exergy of the fuel by assuming the steady state can be written as following equation [31]. Table 2 shows the parameters used in equation:

$$\begin{gathered} n[\bar{h}_{\mathrm{CH_4}} + 2\bar{h}_{\mathrm{O_2}} + 7.52\bar{h}_{\mathrm{N_2}} - \bar{h}_{\mathrm{CO_2}} - 2\bar{h}_{\mathrm{H_2O}} - 7.527\bar{h}_{\mathrm{N_2}} - \\ -T_0(\bar{s}_{\mathrm{CH_4}} + 2\bar{s}_{\mathrm{O_2}} + 7.52\bar{s}_{\mathrm{N_2}} - \bar{s}_{\mathrm{CO_2}} - 2\bar{s}_{\mathrm{H_2O}} - 7.527\bar{s}_{\mathrm{N_2}})] - E_{xQ,loss} - E_{x,d} = 0 \end{gathered} \tag{2}$$

Table 2. Molar enthalpy and entropy parameters used in calculations

$\bar{h}$ (molar enthalpy) [kJkmol^{-1}]		$\bar{s}$ (molar entropy) [kJkmol^{-1}K^{-1}]	
CH_4	14598	CH_4	107.08
O_2	8682	O_2	205.03
N_2	8669	N_2	191.50
CO_2	9364	CO	213.68
H_2O	9904	H_2O	188.72

As seen in tab. 2, $\bar{h}$ and $\bar{s}$ are the molar enthalpy and entropy of reactant and products, respectively, $E_{x,d}$ is the exergy destruction, occurring due to the heat lost from the unit wall surface. It has been considered that the fuel and air enter to the combustion system in environment reference conditions (T_0 = 25 °C, P_0 = 1 atm) and waste gasses exit from the chimney at 150 °C (T_{stack}). It has been presented that the effects on the results of energy and exergy analyses of variations in dead-state properties are insignificant [32]. Exergy destruction may be identified by calculating the entropy production, occurring by the second law analysis of the combustion equation [33]:

$$S_{\mathrm{CH_4}} + S_{\mathrm{air}} - S_{\mathrm{stack}} - S_{Q,\mathrm{loss}} + S_{\mathrm{production}} = 0 \tag{3}$$

Entropy and exergy destruction due to the heat loss can be calculated:

$$S_{Q,\mathrm{loss}} = \frac{8.64\ \mathrm{HDD}}{\left(R_{\mathrm{wt}}\ \dfrac{x}{k}\right)T_{\mathrm{b}}} \tag{4}$$

$$E_{x,d} = T_0 S_{\mathrm{production}} \tag{5}$$

The boundary temperature, T_b, had been taken as 328 K (55 °C). As a result, mole number of the fuel for the annual energy consumption can be calculated substituting the values calculated previously into the eq. (10). Then, the fuel and CO_2 masses can be calculated from following equations:

$$m_{CH_4} = nM_{CH_4} \tag{6}$$

$$m_{CO_2} = nM_{CO_2} \tag{7}$$

where M_{CH_4} and M_{CO_2} are methane and CO_2 molecular masses, respectively. Fuel and CO_2 masses can be determined for the insulation material of the glasswool by:

$$m_{CH_4,\text{glasswool}} = \frac{0.13}{0.0189 + x} \tag{8}$$

$$m_{CO_2,\text{glasswool}} = \frac{0.355}{0.0189 + x} \tag{9}$$

In rockwool use following equation can be obtained:

$$m_{CH_4,\text{rockwool}} = \frac{0.150}{0.0236 + x} \tag{10}$$

$$m_{CO_2,\text{rockwool}} = \frac{0.416}{0.0189 + x} \tag{11}$$

In this study, the amount of environmental impact, B_T, has been calculated by using the environmental impact assessment method. Total environmental impact function for the insulated external wall [mPtsm^{-2} per year) [26, 30] can be written:

$$B_T = b_f m_f + b_{CO_2} m_{CO_2} + b_{ins}\rho_{ins} x \tag{12}$$

and the total environmental impact savings obtained:

$$S = (b_f m_f + b_{CO_2} m_{CO_2})_{nins} - (b_f m_f + b_{CO_2} m_{CO_2} + b_{ins}\rho_{ins} x)_{ins} \tag{13}$$

where b_f [mPtskg^{-1}] is the environmental impact of the fuel, b_{ins} [mPtskg^{-1}] – the environmental impact of the insulation material, b_{CO_2} [mPtskg^{-1}] – the environmental impact of the CO_2, and x – the thickness of the insulation material. Table 3 shows the calculations parameters.

Optimum insulation thickness is obtained by the derivation of B_T to x is determined and equalized to zero and the optimum insulation thickness for glasswool and rockwool are obtained:

$$x_{opt,\text{glasswool}} = \sqrt{\frac{0.13 b_f + 0.355 b_{CO_2}}{b_{ins}\rho_{ins}}} - 0.0189 \tag{14}$$

$$x_{\mathrm{opt,rockwool}} = \sqrt{\frac{0.150 b_{\mathrm{f}} + 0.416 b_{\mathrm{CO_2}}}{b_{\mathrm{ins}} \rho_{\mathrm{ins}}}} - 0.0236 \tag{14}$$

Table 3. Parameters used in calculations of optimum thickness [30]

Parameter	Unit	Value
Environmental impact point	[mPtskg^{-1}]	
Rockwool		4.2
Glasswool		2.1
Fuel		114
CO_2		5.45
Density of insulation material	[kgm^{-3}]	
Rockwool		105
Glasswool		45
Conductivity of insulation material	[WmK^{-1}]	
Glasswool		0.032
Rockwool		0.040

Results and discussion

Figures 2 and 3 show the variation of total environmental impact depending on the insulation thickness for glasswool and rockwool, respectively. As shown in the figures, the total environmental impact decreases to a minimum value and then increases. The insulation thickness value at the minimum point of the total environmental impact is the optimum insulation thickness. However, the environmental impacts of the insulation materials increase linearly. On the other hand, environmental impact of fuel decrease logarithmically. Optimum insulation thickness value is 0.4 m and 0.18 m for glasswool and rockwool, respectively. Figures 4-6 show the annual exergy loss from the unit external wall surface, annual CO_2 emission, and annual fuel consumption, respectively, for glasswool and rockwool depending on the insulation thickness. As can be seen from the figures, these values decrease logarithmically. The decrease

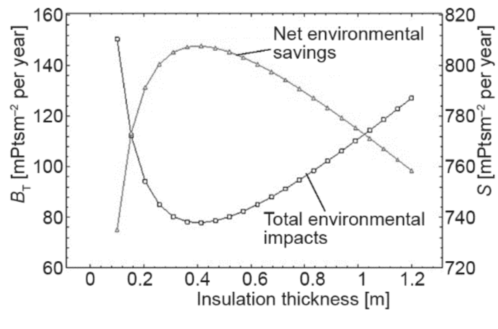

Figure 2. The total environmental and the net saving of total environmental *vs.* glasswool insulation thickness

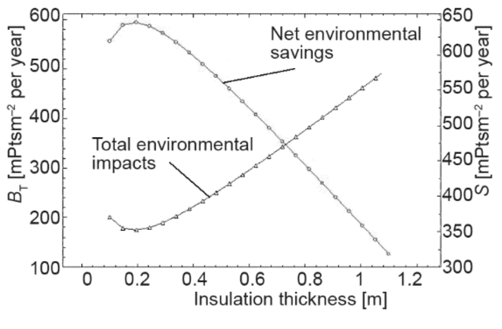

Figure 3. The total environmental impacts and the net environmental savings *vs.* rockwool insulation thickness

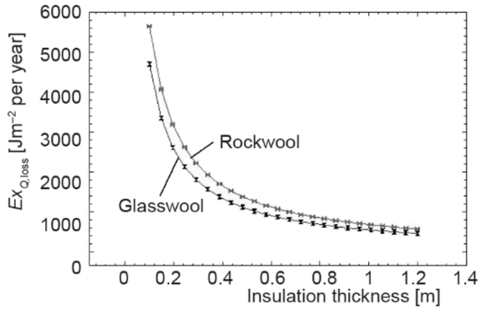

Figure 4. The exergy of heat loss *vs.* glasswool and rockwool insulation thicknesses

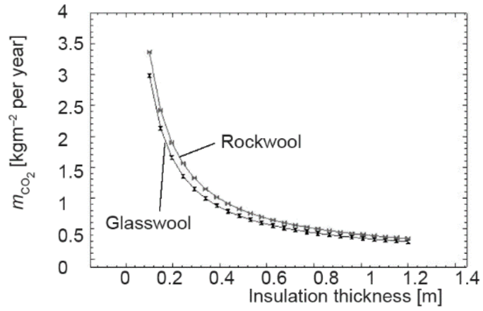

Figure 5. The emission of CO_2 *vs.* glasswool and rockwool insulation thicknesses

in exergy loss is 75% for the glasswool and 35% for the rockwool; and decrease in CO_2 emission is 73% for glasswool and 18% for rockwool and decrease in fuel consumption is 71% for glasswool and 43% for rockwool at optimum insulation thickness.

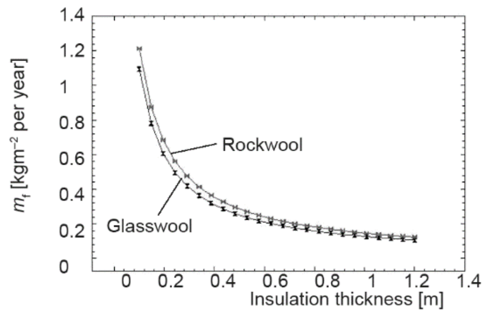

Figure 6. The consumption of fuel *vs.* glasswool and rockwool insulation thicknesses

Conclusions

In this study, environmental impact assessment method has been used to calculate the optimum insulation thickness for the different insulation material used on the external wall of a house located in the city of Denizli, Turkey. Natural gas has been selected as the fuel and glasswool and rockwool was selected as the insulation materials.

The environmental impact of the boiler system, CO_2 emission, fuel consumption, total environmental saving, and exergy loss have been calculated depending on the optimum insulation thickness. The followings may be concluded from this study.

- Total environmental impact decreases to the minimum value which is called as the optimum insulation thickness.
- The optimum insulation thickness at the external wall was calculated as 0.40 m and 0.18 m for glasswool and rockwool, respectively.
- The fuel consumption and CO_2 emissions are significantly decreased at the optimum insulation thickness. While the environmental impacts of insulation materials increase in a linear way with the insulation thickness, the total environmental impact and environmental impact of the fuel decrease logarithmically (non-linear).
- Exergy loss, the annual fuel consumption and CO_2 emissions were calculated higher for rockwool if it is compared with glasswool material.
- The net total environmental saving for glasswool and rockwool were 810 and 640 mPts/m^2 per year, respectively.

In this study, the variation of total environmental impact, B_T, value was taken into consideration when calculating optimum insulation thickness. In some other studies, insulation thickness was calculated using present worth factor and total heating cost, C_T. Because the environmental impact factor is taken into account in our calculations, this approach is more accurate, although the optimum thickness is slightly larger than the practical value. In future studies, optimum thickness values to be calculated considering all these factors are expected to be the most appropriate value for practical use.

Nomenclature

B – total environmental impact, [mPtsm^{-2} per year]
b – environmental impact point, [mPtskg^{-1}]
E_x – annual unit surface exergy, [kJm^{-2} per year]
$E_{xQ,\mathrm{loss}}$ – exergy loss with heat
$\bar{h}$ – molar enthalpy, [kJkmol^{-1}]
k – thermal conductivity, [Wm^{-1}K^{-1}]
m – mass, [kgm^{-2}]
n – number of kmoles, [kmol]
q – heat transfer, [kJm^{-}]
R – thermal resistance, [m^{2}K/W^{-1}]
$\mathrm{R_u}$ – universal gas constant, [kJkmol^{-1}K^{-1}]
S – total environmental impact savings, [mPtsm^{-2} per year]
$\bar{s}$ – molar entropy, [kJkmol^{-1}K^{-1}]
T – temperature, [K]
x – insulation thickness, [m]

Greek symbols

η – efficiency
ρ – density [kgm^{-3}]

Subscripts

b – boundary
d – destruction
f – fuel
i – inner
ins – insulation
o – outer, environmental state
T – total
wt – total without insulation

Abbreviation

HDD – heating degree days, [°C days]

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Paper submitted: September 3, 2018
Paper revised: December 4, 2018
Paper accepted: December 10, 2018