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Original Research Article

Optimum insulation thickness determination using the environmental and life cycle cost analyses based entransy approach

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ABSTRACT

In this study, optimum insulation thickness is investigated according to the entransy loss. Analyses are carried out using rockwool and glasswool as insulation materials. Two different analyses are applied to the building walls. Firstly, a novel method that combines entransy and environmental analyses is used. The fuel consumption, the CO_2 emission and the environmental impacts of the system related to entransy loss are determined. Secondly, a method that combines entransy and the life cycle cost analyses is applied. The insulation cost, the fuel cost and the total cost are calculated. The optimum insulation thicknesses, which are determined by environmental impact analysis, are 0.15 and 0.064 m for glasswool and rockwool, respectively. The optimum insulation thicknesses depending on life cycle cost analysis are calculated as 0.012 and 0.007 m, respectively for glasswool and rockwool.

Introduction

In Turkey, 34% of the total energy consumption takes place in residential and service buildings [1]. It is one of the major portions when compared to the other sectors such as transportation, industry, and agriculture. The largest portion of the energy demand for residential and service buildings sector is caused by heat losses [2]. Heating and cooling applications make up an important part of energy consumption in buildings. Therefore, insulation is a key method to reduce environmental effects and cost rates that are caused by energy consumption in buildings. Efficient heating and cooling applications can be provided by determining optimum insulation thickness.

Life cycle cost analysis determines the economic savings by using the insulation material and it uses the lifetime of the system and present power factor and minimizes the total cost of system [3]. It is a powerful tool and the most common used method for determining the optimum insulation thickness. On the other hand, the effects of the global warming have reached the sensible levels in the last decade and it is not enough to determine the optimum insulation thickness only with the economic approach. Eco indicator-99 is a method that calculates environmental impact of materials/processes/systems by using the life cycle analysis. In the environmental impact analysis, the optimum insulation thickness is calculated by minimizing total environmental impact of the system.

Until recently, the only evaluation criteria used for the efficient use of energy sources or energy conversion systems were energy and exergy analyses. In addition to these methods [4], presented a new criterion called entransy. Entransy is the heat transfer potential of any substance [5–11]. Similar to exergy, entransy is dissipated too. Entransy analysis might be useful to determine the optimum insulation thickness because it is directly related to the heat transfer rate occurring in the system [12–14]. Entransy presented by Guo et al. [4] is:

$$G = \frac{1}{2}QT \tag{1}$$

Many articles can be found in the literature about determining the optimum insulation thickness [15–27]. However, they use only energy and exergy approaches.

The purpose of this study is to submit a new method using entransy analysis to calculate the optimum insulation thickness. This method is used for building walls for the first time in the literature. Another novelty of this study is to combine entransy analysis environmental impact methods and cost analysis for first time. Analyses are applied for Bilecik, Turkey. Two different insulation

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Nomenclature

b	environmental impact point (mPts/kg)
B	environmental impact rate associated with exergy (mPts)
G	annual entransy (J.K/m^2)
HDD	annual heating degree day (°C.day)
m	annual fuel mass (kg/m^2)
R	heat resistance (Km^2/W)
S	annual net saving of environmental impact (mPts/m^2)
SG	annual net saving of entransy loss (J.K/m^2)
T	temperature (°C or K)
U	heat transfer coefficient (W/m^{2}K)
x	insulation thickness (m)
i	interest rate
g	inflation rate
C	annual entransy cost (\$/m^2)
PWF	present worth factor
N	life time of insulation material (year)
SC	annual entransy cost saving (\$/m^2)
V	volume (m^3)
ΔH	reaction enthalpy (kJ/mol)

Subscripts

o	ambient
CO_2	carbon dioxide
F	fuel
i	indoor
ins	insulation
$Loss$	loss
$nins$	no-insulation
opt	optimum
T	total
ip	inside plaster
op	outside plaster
br	brick
rx	reaction

Greek letters

η	efficiency of the heating system (%)

materials are used and the optimum insulation thicknesses are determined in environmental and economic terms.

Modeling and analysis

The investigated system, which is a composite building wall, is presented in Fig 1. The system consists of parallel layers of different materials. Temperatures of the environment and inside air are assumed to be268.15 K and 296.15 K. Rockwool and glasswool are selected as insulation materials. The heating system operates at 85% efficiency and uses natural gas as fuel. All calculations are conducted for the unit wall area and the annual process. Some properties of the building wall materials are given in Table 1.

The annual heating loss per unit area (J/m^2) from the building wall is calculated from Eq. (2) using heating degree-days [28]:

$$q = 86400.HDD.U \tag{2}$$

where HDD is the heating degree-days (°C day), and U is the heat transfer coefficient (W/m^2 K). The annual entransy loss occurring from the building wall (J.K/m^2) is defined as:

$$G = 86400.HDD.U.(T_i - T_o) \tag{3}$$

where T_i is the indoor temperature and T_o is the ambient temperature (K). Since, natural gas consists more than 90% methane (CH_4), therefore methane can be used in the combustion equation and the combustion process is assumed as complete for easier calculations. Combustion equation can be written as following:

$$CH_4 + 2(O_2 + 3.76N_2) \rightarrow CO_2 + 2H_2O + 7.52N_2 \tag{4}$$

Annual fuel consumption (kg/m^2) depending on the annual entransy loss can be calculated by:

$$m_F = \frac{86400.HDD.U.(T_i - T_o)}{\eta.\Delta H.T_{rx}} \tag{5}$$

where ΔH is reaction enthalpy (kJ/kg) of methane at 298.15 K and 1 bar. T_{rx} is the reaction temperature of the fuel. Using the Eq. (4), CO_2 emission (kg/m^2) can be determined as:

$$m_{CO_2} = 2.75\left(\frac{86400.HDD.U.(T_i - T_o)}{\eta.\Delta H.T_{rx}}\right) \tag{6}$$

Heat transfer coefficients (W/m^2 K) for no-insulation and the insulated wall conditions are given in Eqs. (7) and (8) respectively:

$$U_{nins} = \frac{1}{R_i + R_{ip} + R_{br} + R_{op} + R_0} = \frac{1}{R_{T,nins}} \tag{7}$$

$$U_{ins} = \frac{1}{R_i + R_{ip} + R_{br} + R_{ins} + R_{op} + R_0} = \frac{1}{R_{T,ins}} \tag{8}$$

The total environmental impact function of the system (mPts/m^2) can be defined as follows:

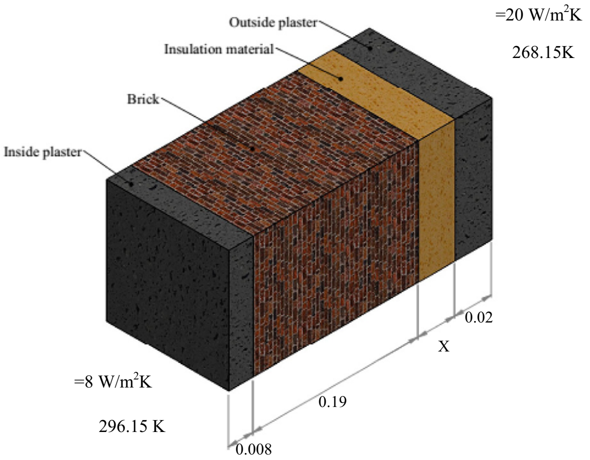

Fig. 1. Investigated building wall system.

Table 1
Some properties of the building wall materials [30,31].

Layer	Thickness (m)	Conductivity (W/mK)
Inside plaster	0.008	0.7
Brick	0.19	0.45
İnsulation materials		
Glasswool	0–0.02	0.032
Rockwool	0–0.02	0.04
Outside plaster	0.02	0.9

$$B_T = b_F m_F + b_{CO_2} m_{CO2} + b_{ins} \rho_{ins} x_{ins} \quad (9)$$

where b_F is the environmental impact of fuel (mPts/kg), b_{CO_2} is the environmental impact of CO_2 (mPts/kg),and b_{ins} is the environmental impact of insulation material (mPts/kg). Also ρ_{ins} is density of the insulation material and x_{ins} is thickness of the insulation material. In this way, the net saving of the environmental impact (mPts/m^2) is obtained from:

$$S = (b_F m_F + b_{CO_2} m_{CO_2})_{nins} - (b_F m_F + b_{CO_2} m_{CO_2} + b_{ins} \rho_{ins} x_{ins})_{ins} \quad (10)$$

The net saving of entransy loss from the building wall (J.K/m) is:

$$SG = G_{nins} - G_{ins} \quad (11)$$

The optimum insulation thickness is obtained by getting the derivative of B_T in respect to x and set equal to zero. B_T will achieve minimum value at the optimum insulation thickness

$$x_{opt} = \frac{\sqrt{-796.9((b_{CO_2}+0.36b_F)T_o-(b_{CO_2}+0.36b_F)T_1)HDD\Delta H k_{ns} \eta T_o \rho_{ins}}}{\sqrt{b_{ins} \Delta H \eta \rho_{ins}}} - k_{ins} R_{T,nins} \quad (12)$$

For the life cycle cost analysis, which is combined with entransy analysis;

The annual fuel cost per unit area is determined as

$$c_F = c_f m_F \quad (13)$$

where c_f is the cost of fuel ($/kg).

The fuel cost over a lifetime is calculated using the present worth factor (PWF), in the life cycle cost. The present power factor depends on the inflation rate, g, and interest rate, i. Interest rate i^*adapted for inflation can be calculated as [29],

$$i^* = \begin{cases} \frac{i-g}{1+g} & ; \quad i > g \\ \frac{g-i}{1+i} & ; \quad i < g \end{cases} \quad (14)$$

and then PWF is defined as follows:

$$PWF = \begin{cases} \frac{1-(1+i^*)^{-N}}{i^*} & ; \quad i \neq g \\ (1+i)^{-1} & ; \quad i = g \end{cases} \quad (15)$$

where N is the lifetime of the insulation material and i^* is the interest rate adjusted for the inflation rate. Finally, the annual fuel cost can be arranged as,

$$C_F = c_f PWF m_F \quad (16)$$

The total cost of the insulation material ($/m^2) can be calculated as,

$$C_{ins} = c_i x_{ins} \quad (17)$$

where c_i is the cost per m^3 of insulation material. The annual total cost ($/m^2) depending on entransy is:

$$C_T = c_f PWF m_F + c_i V_{ins} \quad (18)$$

The annual cost saving per unit surface area of the wall depending on entransy is:

$$SC = C_{T,nins} - C_{T,ins} \quad (19)$$

The optimum insulation thickness is obtained by getting the derivative of SC with respect to r and set equal to zero. SC will receive maximum value at the optimum insulation thickness. Data used in the calculations can be seen in Table 2.

$$x_{opt} = \frac{\sqrt{-289.787 c_f HDD k_{ins} PWF (T_o - T_i)}}{\sqrt{c_i \Delta H \eta}} - k_{ins} R_{T,nins} \quad (20)$$

Table 2
Parameters used in investigation.

Parameter	Unit	Value
Environmental impact point	mPts/kg	
Rockwool [32]		4.2
Glasswool [32]		2.1
Fuel [32]		114
CO_2 [32]		5.45
Mean temperature for heating period [33]	°C	−5
Reaction temperature of methane	°C	25
Heating degree day [34]	°C/days	3492
Boiler efficiency		0.9
Density of insulation material	kg/m^3	
Rockwool [31]		105
Glasswool [31]		45
Reaction enthalpy of the methane [28]	kJ/kmol	802.3
Fuel cost [35]	$/kg	0.53
Inflation rate [36]		8.39
Inflation rate [36]		9.65
Glass wool cost [31]	$/m^3	103
Rock wool cost [31]	$/m^3	132
Life time (N)	year	10

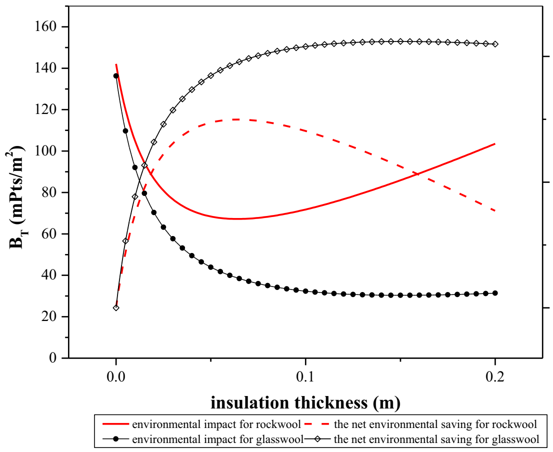

Fig. 2. Changes of the annual environmental impact and the net environmental saving due to the insulation thickness for glasswool and rockwool.

Results and discussion

In the present study, economic and environmental impacts are investigated for wall insulation thickness and results are compared. Analyses are performed due to the entransy loss for Bilecik, Turkey.

Environmental impact analysis depending on the entransy

In Fig. 2, variations of the total environmental effect and the net savings of the environmental effect with insulation thickness for glasswool and rockwool are shown. It can be seen that the environmental impact reduces until the minimum point (the optimum point) and then starts to increase. Similarly, the net saving of the environmental effect increases up to a maximum point (same as the optimum point) and then it tends to reduce. At the optimum point the total environmental effect is the minimum and net savings of the environmental effect is the maximum. From the figure, the optimum insulation thicknesses for glasswool and rockwool are 0.15and 0.064 m, respectively.

Changes of the entransy loss and the net entransy saving due to the insulation thickness for glasswool and rockwool are presented in Fig 3. Figure shows that the entransy loss decreases logarithmically with insulation thickness. On the other hand, the net saving of the entransy loss increases continuously with a logarithmic trend. Also, it has no maximum or minimum point for them. It appears that the decreasing rate of the entransy loss is very dramatic until the

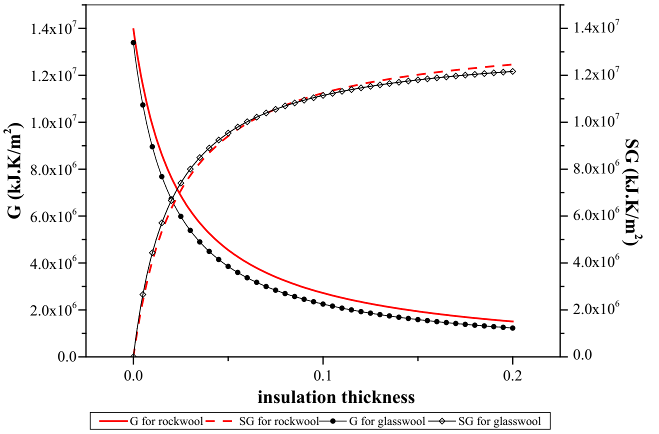

Fig. 3. Changes of the entransy loss and the net entransy saving due to the insulation thickness for glasswool and rockwool.

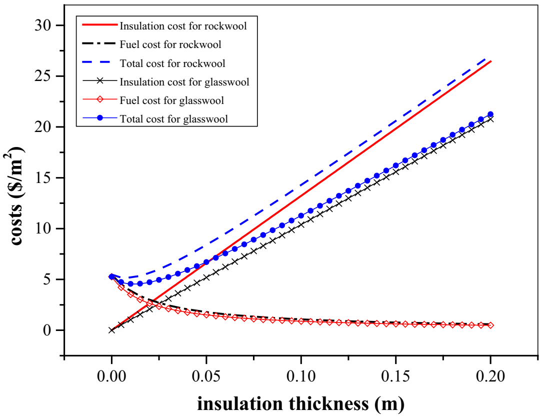

Fig. 5. Variations of the insulation cost, fuel cost and total cost depending on the insulation thickness for glasswool and rockwool.

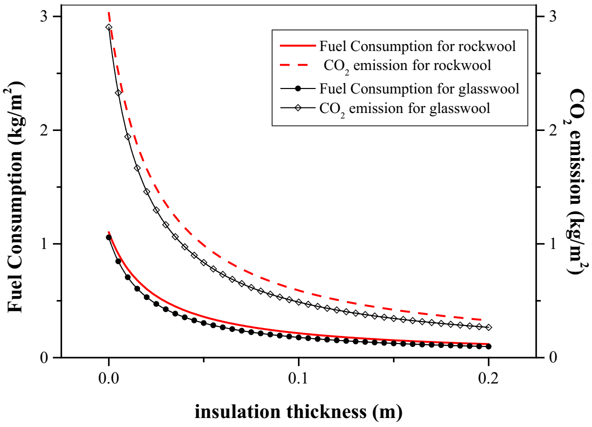

Fig. 4. Changes of the fuel consumption and CO_2 emission due to the insulation thickness for glasswool and rockwool.

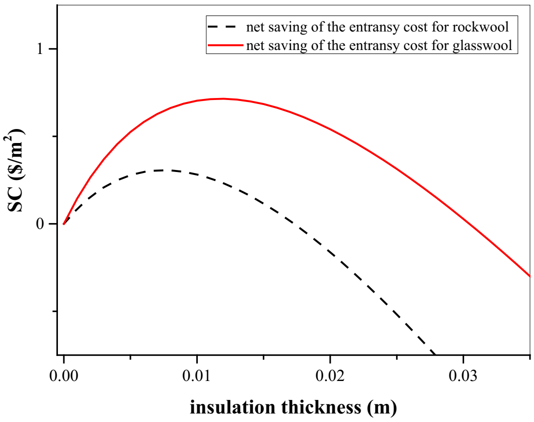

Fig. 6. Variations the net saving of the entransy cost due to the insulation thickness for glasswool and rockwool.

optimum point and then it continues to decreases at insignificant rates. It shows a continuous decrease and has no minimum point. For the glasswool, decreasing of the no-insulation condition until the optimum point is equal to 88% and after the optimum point to 0.2 m, it is equal to 22%. For the rockwool, decreasing of the no-insulation condition until the optimum point is equal to 72.5% and after the optimum point to 0.2 m, is equal to 60%. Similarly, the net entransy loss saving has a higher increasing rate until the optimum point and then the increase continues at insignificant rates. When the rockwool and glasswool are compared, it can be seen that the rockwool has higher values for the entransy loss and the net saving of the entransy loss than glasswool.

In Fig. 4, changes of the fuel consumption and the CO_2 emission according to insulation thickness for the glasswool and rockwool are given. The fuel consumption and the CO_2 emission decrease with insulation thickness for both insulation materials, because the thicker thermal insulation material causes a lower energy requirement. So, lower fuel consumption and CO_2 emissions are obtained. The results show that decreasing the no insulation condition until 0.2 m insulation thickness is 90.8% and 89.2% for the glasswool and rockwool, respectively for the fuel consumption and the CO_2 emission.

Life cycle cost analysis due to entransy

The insulation cost, the fuel cost, and the total cost variations with insulation thickness are shown in Fig 5. Here, the insulation cost increases linearly because of the insulation geometry and the fuel cost decreases with the insulation thickness. According to results, initially fuel cost decreases with larger values and then the decrease continues with smaller values. On the other hand, total insulation thickness decreases until a certain point that achieves minimum values called the optimum point. If the rockwool and glasswool are considered, rockwool has larger cost values than glasswool.

Fig. 6 presents the entransy cost savings with the insulation thickness for glasswool and rockwool. The entransy cost saving increases with insulation thickness until the maximum point. This point is referred to as the economical optimum insulation thickness. After this point, increasing the insulation thickness is not economic. Economical optimum insulation thickness for the glasswool and rockwool are 0.012 and 0.007 m, respectively. These thicknesses are relatively comparing with other studies in the literature. Because, entransy dissipation rate is noteworthily smaller than fuel entransy rate.

Conclusions

In the present study, environmental and economic optimum insulation thicknesses for rockwool and glasswool are determined. Firstly, the entransy loss, the fuel consumption and CO_2 emissions are calculated. Secondly, according to the entransy, the environmental impact of the system and the total cost are determined.

Analyses are performed for Bilecik, Turkey. Some important results obtained from the analysis can be listed as follows:

- The total environmental impact of the system decreases until the optimum point where it achieves its minimum value.
- The optimum insulation thickness for glasswool and rockwool are 0.15 and 0.064 m, respectively.
- Entransy loss decreases with the insulation thickness and it has no minimum point. Similarly, the net entransy saving of the system increases with the insulation thickness and has no maximum point.
- Increasing the insulation thickness decreases the fuel consumption and CO_2 emission. Decreases in fuel consumption and CO_2 emissions are significant up to the optimum thickness.
- The rockwool has more fuel consumption and CO_2 emission values than the glasswool.
- The insulation cost increases linearly and the fuel cost decreases nonlinearly with the insulation thickness. The total entransy cost decreases until the optimum economical thickness and at this point its value is minimum.
- Depending on the insulation thickness, the net saving of the entransy cost increases up to the optimum point. Economical optimum insulation thickness for glasswool and rockwool are 0.012 and 0.007 m, respectively.

As a result, economic and environmental insulation thicknesses are significantly different from each other. Therefore to consider the only economic parameters can be wrong for determining the optimum insulation thickness. On the other hand, environmental analysis has gain importance with the increasing environmental problems.

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