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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:

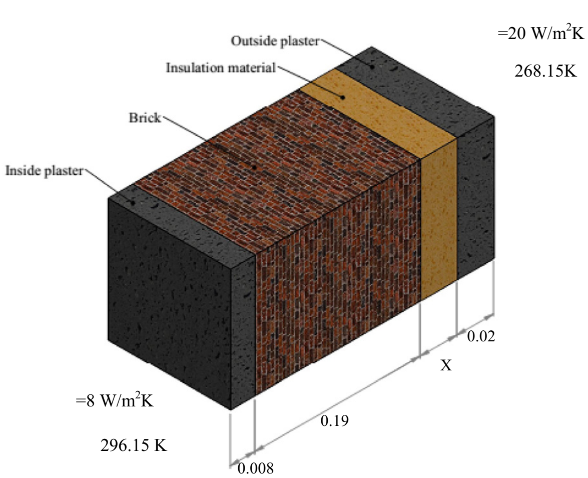

Fig. 1. Investigated building wall system.

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

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:

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