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Determination of optimum insulation thickness in pipe for exergetic life cycle assessment

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ABSTRACT

The energy saving and the environmental impacts' reduction in the world building sector have gained great importance. Therefore, great efforts have been invested to create energy-saving green buildings. To do so, one of the many things to be done is the insulation of cylindrical pipes, canals and tanks. In the current study, the main focus is on the determination of the optimum insulation thickness of the pipes with varying diameters when different fuels are used. Therefore, through a new method combining exergy analysis and life cycle assessment, optimum insulation thickness of the pipes, total exergetic environmental impact, net saving and payback period were calculated. The effects of the insulation thickness on environmental and combustion parameters were analyzed in a detailed manner. The results revealed that optimum insulation thickness was affected by the temperature of the fuel when it enters into the combustion chamber, the temperature of the stack gas and the temperature of the combustion chamber. Under these optimum effects, the optimum insulation thickness of a 100 mm pipe was determined to be 55.7 cm, 57.2 cm and 59.3 cm for coal, natural gas and fuel–oil, respectively with the ratios of 76.32%, 81.84% and 84.04% net savings in the exergetic environmental impact. As the environmental impacts of the fuels and their products are bigger than those of the insulation material, the values of the optimum insulation thickness of the method used this study was found greater. Moreover, in the pipes with greater diameters, through the use of optimum insulation thickness, very high net savings and low payback periods were to be obtained.

1. Introduction

Thermal insulation processes have been used for many purposes such as reduction of heat transfer to/through surfaces, controlling temperature of operation and surface, prevention of perspiration, condensation and melting problems, provision of thermal comfort conditions, food protection and medical insulation for many years. Energy efficiency, climate changes, increasing interest in limited energy resources of the world and industrial applications have made the utilization of thermal insulation quite popular [1]. Energy consumption in buildings and industrial applications can be detracted by using insulation materials. Even in enough insulated buildings and industrial applications, energy consumption may be lessened by insulating cylindrical pipes, canals and tanks. The heating and cooling, chemical and industrial processing plants include complex and expensive pipe, canal and tank constructions. For instance, in district heating applications, the cost related to distribution pipelines constitutes nearly 40–60% of the total cost [2]. Therefore, it is of great importance to select the least expensive material for application. Uninsulated pipes, canals and tanks are a stable source of waste energy. Through the optimum insulation of pipes, canals and tanks, a decrease can be achieved in the emission along the insulation as well as further energy saving.

Technological developments enable us to produce better insulation materials and fuels having greater energy efficiency and lower environmental impacts. The energy-related and environmental impacts of insulation materials and fuels can be divided into two categories [3]: (i) direct effects based on embodied energy of insulation materials and fuels, (ii) indirect effects resulting from the reduction of energy consumption by using the insulation and fuel.

Due to the progress toward the production of insulation materials with low or zero embodied energy, carbon emission caused by these materials is minimized. Thus, precautions taken to control and reduce all the environmental impacts of production cycle of insulation should merit priority. Increase investment in insulation materials with zero embodied energy encourages the usage of positive solutions as a result of the increased insulation thickness in all the systems (as building, pipe, duct, storage, etc.) over the world. In

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Nomenclature

A	total surface area of pipe (m^2)
A_i	inside surface area of pipe (m^2)
A_o	outside surface area of last layer of pipe (m^2)
A'_o	outside surface area of nth layer of pipe (m^2)
b	environmental impact point (Pts/kg)
b_f	environmental impact point of fuel (Pts/kg)
b_{ins}	environmental impact point of insulation material (Pts/kg)
b_{CO_2}	environmental impact point of stack gases (Pts/kg)
$\dot{B}$	total environmental impacts (Pts/m yr)
d	density (kg/m^3)
D	diameter (m)
E_A	total annual energy requirement for heating (kW)
$\dot{E}x_F$	exergy of fuel (W/m yr)
$\dot{E}x_{loss,Q}$	exergy losses due to heat transfer (W/m yr)
$\dot{E}x_{loss,S}$	exergy losses due to stack gases (W/m yr)
h	enthalpy (kJ/kmol, kJ/kg)
h_i	convection heat transfer coefficient for inside of pipe (W/m^2 K)
h_o	convection heat transfer coefficient for outside of pipe (W/m^2 K)
k	the thermal conductivity (W/m K)
k_i	the thermal conductivity of fluid in the inside of pipe (W/m K)
k_{ins}	the thermal conductivity of insulation material (W/m K)
k_{pipe}	the thermal conductivity of pipe (W/m K)
L	unit length of pipe (m)
m_f	annual fuel consumption (kg/m yr, m^3/m yr, J/m yr)
m_{CO_2}	amount of annual stack gas (m^3/m yr)
M	weight of molecule (kg/mol)
n	mole (kmol)
P	payback period of exergetic environmental impacts (yr/m)
Pr	Prandtl number
Q_A	the annual heat loss (W/m yr)
Q_F	the fuel energy (W)
Re	Reynould number
r_{ins}	the thermal conductivity of pipe (W/m K)
R_p	total internal resistance of pipe (K/W)
$R_{p,ins}$	internal resistance of insulated pipe (K/W)
$R_{p,un\text{-}ins}$	internal resistance of un-insulated pipe (K/W)
r_0, r_1, r_2	radius (m)
s	entropy (kJ/kmol K, kJ/kg K)
S	net saving of exergetic environmental impacts (Pts/m yr)
T_{cc}	the temperature of combustion chamber (K)
T_{ms}	the mean outside surface temperature of pipe (K)
T_{rt}	the heating circuit return temperature (K)
T_o	design temperature of outside air (K)
U	overall heat transfer coefficient (W/m^2 K)
U_{ins}	overall heat transfer coefficient of insulated pipe (W/m^2 K)
$U_{un\text{-}ins}$	overall heat transfer coefficient of un-insulated pipe (W/m^2 K)
V	the volume of insulation material (m^3)
V_{air}	air velocity in the outside of pipe (m/s)
W	work (W/m)
y	mole fraction
ΔU	difference between overall heat transfer coefficients of un-insulated and insulated pipes (W/m^2 K)
–	molar values

Greek symbols

δ_{ins}	optimum insulation thickness (m)
λ	excess air coefficient
η_s	the efficiency of the heating system (%)
ρ_{ins}	density of insulation material (kg/m^3)

Abbreviations

ASTM	american society for testing and materials
HDD	heating degree-days
ISO	international organization for standardization
LCA	life cycle assessment
LCC	life cycle cost

this way, the positive contribution of such materials to the life cycle environment impact is increasing. In the literature, there are various definitions of embodied energy related to the "direct" environmental impacts for buildings (e.g., [3–10]). Many studies focus on the evaluation of environmental impacts when optimum thickness is used in buildings (e.g., [11–17] for buildings and [18] for pipes); however, optimum thickness relies on life cycle cost analysis rather than environmental impact analysis. The above-mentioned studies used one dimensional heat conductivity equation in multi layer walls/pipes to calculate the thermal transmission loads with different insulation materials and fuels. In this way, some correlations and fuel combustion formulas were employed to predict energy saving and emission prevention.

When the current state of the evaluation methods is examined, it is seen that there are important uncertainties and variability in the prediction of both direct and indirect environmental impacts of insulation materials and fuels used in buildings. Moreover, under the category of direct impacts, it should be considered that the other factors are not included in embodied energy. The main focus of the evaluation procedure in the current study is the determination of all the factors contributing to the total energy and environmental impacts of insulation product and more importantly, the presentation of a method of standard setting so that insulated pipes with differing diameters having not been reported in the literature and different fuel types can be compared. In addition to this, this method proposes a calculation technique to predict optimum insulation thickness by using direct and indirect environmental impacts related to low operation energy in cylindrical pipes, canals and tanks resulting from the use of insulation materials and fuels.

Today, the world has to face serious environmental and energy problems, and great efforts have been invested to reduce primary energy consumption and environmental impacts (CO_2 emission). Some authors combine savings in energy consumption or greenhouse emissions. In most of the scientific research, optimum thickness is calculated from economical perspective. In addition to this, while many articles employ the life cycle cost (LCC) analysis from energetic perspective, there is very little research including the life cycle assessment (LCA) of insulation materials [6,19]. For instance, Papadopoulos and Giama [20] administered the LCA analysis to two insulation materials being rockwool and XPS. They focused on the embodied energy of these materials during the production of them. Dylewski and Adamczyk [16] analyzed economic and environmental aspects of the thermal insulation of the building external walls of a building by reducing the negative effects of a building on the environment. Barrau et al. [21] investigated ener-