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Economic thermal insulation thickness for pipes and ducts: A review study

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ABSTRACT

Energy conservation has become an increasingly important issue for all sectors, particularly in industry. Therefore, the thermal performance of insulation systems and their influence on heat loss/gain in various applications in addition to economic considerations have received increased attention in recent years. In this study, a literature review of papers that addressed the optimum economic thickness of the thermal insulation on a pipe or duct with different geometries used in various industries was carried out. The studies related to determining the critical insulation thickness for different geometries including circular shapes were investigated. The heat transfer equations, the basic results, the optimization procedures and the economic analysis methods used in the studies were presented comparatively. Additionally, a practical application example based on optimizing the insulation thickness on a pipe was performed, and the effective parameters of the optimum thickness were investigated.

Contents

1. Introduction

Thermal insulation systems have been used in practice for many years for different applications and purposes, such as to decrease heat transfer to/from surfaces, to control the process and surface temperatures, to avoid the condensation problem, and to provide a comfortable indoor thermal environment. Increasing concerns regarding energy efficiency, climate change and awareness of the limited energy resources, the use of a proper amount of thermal insulation for buildings and industrial applications has gained popularity. When examining the sectoral distribution of the energy demand, it is seen that considerable portions of the global energy have been consumed in the residential and industrial sectors, accounting for approximately 30% and 40%, respectively, of the total global energy [1–3]. Thermal insulation is primarily used to limit heat loss/gain from/to surfaces under operating conditions at temperatures above or below ambient temperature, i.e., to provide a contribution for energy conservation. Energy conservation is a major concern in many industrial applications. The primary reasons to conserve energy include maximizing the return on investment and minimizing the life cycle cost and the emissions associated with energy consumption.

In addition to economic considerations, attention has focused on improving performance and thermal efficiency of the insulation systems in recent years. The concept of an economic thermal

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Nomenclature

Bi	Biot number ($h\ r_o/k$)
C	cost, US$/kg or US$/m^3
$\dot{C}$	cost rate, US$/s
CRF	capital recovery factor
d	discount rate
D	diameter, m
DP	ratio of down payment to initial investment
$\dot{E}$	exergy rate, kJ/s
h	convective heat transfer coefficient, W/m^{2}K
HDD	heating degree-days
Hu	lower heating value of fuel, kJ/m^3
i	inflation rate
k	thermal conductivity, W/mK
L	pipe length, m
LT	lifetime, years
M_s	ratio of first year miscellaneous costs to initial cost
N	annual operating time, hours
Pr	Prandtl Number
PWF	present worth factor
Q	heat loss rate from pipe, kJ/s
r	radius, m
R	thermal resistance, m^{2}K/W
R_v	ratio of the resale value to initial investment
Ra	Rayleigh number
Re	Reynolds Number
t	wall thickness, m
T	temperature, °C
V	velocity, m/s; volume, m^3
$\dot{W}_p$	pump power, kJ/s
$\dot{Z}$	capital cost rate, US$/s
ϕ	exergy efficiency of pipe segment
x	insulation thickness, m
η	heating system efficiency
σ	Stefan-Boltzmann constant, W/m^{2}K^4
ε	surface emissivity
θ	dimensionless temperature $(T-T_{int})/(T_i-T_o)$

Subscript

1	pipe inside diameter
2	pipe outside diameter
cr	critic
el	electricity
en	energy
f	fluid
i	inside
ins	insulation
int	initial condition
max	maximum
min	minimum
o	outside
opt	optimum
p	pump
s	surface
surr	surrounding
t	total

insulation thickness considers the initial cost of the insulation system plus the ongoing value of the energy savings over the expected service lifetime of the insulation. Numerous studies on thermal insulation systems for different applications, including buildings, cold stores, pipelines, ducts, tanks and other equipment, have been published in the literature. The majority of the studies that are related to optimizing the thermal insulation thickness focus on flat surfaces, such as building walls, rather than cylindrical geometries. The economic insulation thickness for building walls depends on various factors, such as building type, function, wall orientation, construction materials, climatic conditions, insulation properties and cost, energy type and cost and efficiency of the heating or air-conditioning system [4–9]. In these studies, the effect of mass and insulation location on heating and cooling loads were analyzed in buildings with massive exterior envelope components for various wall configurations. Considering the heating and/or cooling loads of buildings, optimization studies on the insulation thickness for the external walls of buildings have been conducted for different climate zones in various countries including Qatar [6], China [9], Maldives [10], Turkey [2,3,10–13], Saudi Arabia [14–16], Malaysia [17], Palestine [18] and Tunisia [19,20]. A suitable amount of thermal insulation in the building envelope can result in a considerable reduction in the heating and cooling energy demands of a building and its associated CO_2 and SO_2 emissions into the atmosphere. In addition to insulation, several investigations have focused on optimizing the building shape to minimize the energy demand and cost [21–23]. All of these studies help to reduce building energy use (annual energy requirements for heating and cooling) and the size of the air-conditioning and heating systems in buildings and to achieve desirable indoor thermal comfort for occupants.

Compared to studies on flat surfaces, there are few studies related to insulation systems on pipes and ducts despite the extensive applications in widely diversified fields. Furthermore, deriving the heat transfer and energy cost equations and taking the derivative of the objective function for cylindrical geometries such as pipes may be considered slightly more difficult. In most studies, optimum insulation thickness computations were performed based mainly on the convective and radiative heat loss from a pipe or duct and other parameters, such as the costs of the insulation material and energy, the heating system efficiency, the lifetime and the current inflation and discount rates. The heat loss from a pipe (or the energy requirement to heat the fluid in a pipe) is the main input required to analyze the optimum insulation thickness. Heat loss occurs by conduction, convection and thermal radiation. Most of the studies considered only convective [24–31] or radiative heat transfer modes [32] while several studies considered both modes [33–36]. Moreover, Kecebas et al. [37] and Basogul and Kecebas [38] used the degree-days (*DD*) for estimating the heating energy requirement.

In this paper, studies related to determining the optimum thermal insulation thickness for pipes and ducts were reviewed first. The optimization procedure was introduced, and the operating conditions and parameters used in these studies were listed. Then, studies determining the optimum insulation thickness on pipes and ducts with various geometries on reducing convective and radiative heat transfer were investigated and presented. After examining the economic analysis methods used to obtain an economic insulation thickness, a simple and practical application for determining the optimum insulation thickness for pipes was conducted.

2. Determining the economic insulation thickness

2.1. Optimization procedure

To minimize the energy and insulation costs in addition to reducing the heat loss to the surroundings, the thickness of the