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Optimum insulation thicknesses of pipes with respect to different insulation materials, fuels and climate zones in Turkey

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ABSTRACT

This article is about the effects of insulation thickness on the life cycle costs of steel pipes inside the pit (channel, duct) or above-ground structures with different diameters and sensitivity to economic parameters. The heating degree-day and life cycle cost procedures are used for the optimization and sensitivity analyses. For Afyon province in Turkey the fuels are coal, natural gas and fuel-oil. The insulation materials are rock wool, EPS and XPS. The results show that consideration of all the physical and economic conditions appear with the optimum insulation thickness that varies from 5 cm to 16 cm. Both lifetime and unit cost of insulation are sensitive to the insulation thickness. Additionally, the increased discount rate and cost per unit volume of insulation material lowers the optimum insulation thickness. In conclusion, it is expected that this study will provide a guide for engineers, where insulation is used for large diameter pipes.

1. Introduction

Currently, due the effects of limited energy resources, rapid energy consumption and overuse of resources, thermal insulation has gained great interest and importance for many countries. In the industry, there are complicative and costly pipe installation and insulation applications. On the one hand, insulation should reduce energy consumption in buildings, mechanical installations and industrial systems. It also plays an important role in reducing energy loss from the transmission portion of heating and cooling loads in buildings and industrial systems. Insulation appears as one of the most important methods to reach environmental sustainability and energy efficiency in modern cities and systems [1–3].

Large-scale heating systems provide heating and hot water needs for industrial complexes, community housings, neighborhoods in the cities by carrying heat production from one or more energy resources through pipe systems. The important cost components in a district heating system are transmission and distribution pipe configurations, which frequently range from 40% to 60% of the total project cost [4]. The majority of these costs are related to the installation in the pipe system. The use of uninsulated pipes allows reduction in pipe material costs by more than 50% [4]. If insulation material is not used properly the heat losses increase, which lead to the increases in the system capacity (boiler, pipe, pump) by increasing both the initial investment costs and the operation expenses. Increase in the system flow rates or compensation may lead to large pumping costs. It is important to choose the most efficient and appropriate material in the practical application. One way to increase the energy efficiency and cost reduction in such a system is to reduce heat loses from transmission/distribution by more appropriate and efficient district heating design. The most effective way to reduce heat losses is to choose pipe and insulation materials, and then to determine pipe diameter and insulation thickness [5].

The most important difference in insulating pipes, compared to buildings is the temperature levels that are encountered in pipes are much higher than temperature levels in buildings. As a result, good insulation for installations may provide much greater energy saving in comparison to buildings. Depending on the fluid temperature within the pipe, errors in material and thickness choice may cause many problems leding to condensation and freezing. Insulation lowers boiler capacity, numbers of radiators and pipe diameters [6]. In the mechanical installations and industry, especially pipe insulation allows larger heat loss/gain and financial gains. As insulation thickness increases, savings increase and investment costs also increase. Optimum insulation thickness calculations should be completed in the type and thickness determination of the heat insulation material.

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Recent studies of optimization in pipe insulation thickness have increased (e.g. Refs. [7–24]). This is due to the fact that pipes, tanks, depots, air conditioning ducts, valves and fittings in buildings, mechanical installations and industry form a large source of energy consumption. Accordingly, researchers expended efforts in order to reduce the heat losses. At the same time, it may reduce the environmental effects of fuels that are used to produce electricity. Under optimization conditions, insulation thickness is one of the most effective ways to conserve energy. In the previous studies, Ito et al. [7] and Boehm [8] used multipurpose functions and analytical methods to reduce heat loss and insulation amount in pipe systems. Zaki and Al-Turki [9] completed an economic analysis for thermal insulation of double-layer insulated petrol pipelines (nominal pipe sizes of 100–273 mm) by using different insulation materials (rockwool and calcium silicate) with an explicit non-linear function. Sahin [10] numerically modeled variations in insulation thickness to maximize pipe outer surface temperature under extraterrestrial radiation conditions. Another study by Sahin and Kalyon [11] analytically modeled the variation in insulation thickness of pipes under convection and radiation conditions.

Ozturk et al. [12] presented four different thermo-economic methods to optimize pipe diameter and insulation thickness based on heat losses, insulation costs, total costs and exergy efficiency for optimum design in hot water pipe systems. The method that produces the best result is reported to be the one with exergy and cost parameters. Karabay [13] used exergo-economic analysis to determine optimum insulation thickness of hot water distribution pipes (nominal pipe sizes of 100–1000 mm). The effects of mass flow rate, annual operating time, amortization period, and water temperature on the optimum pipe diameter and insulation thickness are also researched by Soponpongpipat et al. [14], who worked to determine the optimum insulation thickness based on the thermo-economic method for double-layer insulation of air conditioning ducts (circular galvanized steel duct of 500 mm). The calculations are completed for insulation material such as rubber and fiber glass based on annual equivalent full load cooling time of the air conditioning system. Bahadori and Vuthaluru [15] estimated optimum insulation thickness with a simple correlation as a function of thermal conduction coefficient of steel pipes and equipment diameter of insulation material at 100 °C, 300 °C, 500 °C and 700 °C. Another study by the same authors [16] helps to calculate a simple correlation for estimation of heat flow through insulation, thermal resistence and insulation thickness for flat and cylindrical surfaces.

Kecebas et al. [17] modified life cycle cost analysis to determine optimum insulation thickness for different pipe diameters in a district heating pipeline network (nominal pipe sizes of 50–200 mm). They calculated the amount of heat carried by fluid within the pipe using the degree-day method. Later, they completed life cycle cost analysis by consideration of the heat loss from the pipe surface. For calculations, as insulation material the rock wool, coal, natural gas, fuel oil and geothermal energy are used as fuel sources. They reported optimum insulation thicknesses between 8.5 cm and 22.8 cm. They also reported that as greater savings from large diameter pipes should be considered separately. Basogul and Kecebas [18] used modified life cycle cost analysis to investigate environmental assessment of insulation pipes in district heating pipelines. They used different fuel types, a variety of insulation materials and nominal pipe diameters for economic and environmental assessment. They reported that the largest optimum insulation thickness, fuel savings and emissions are valid for 200 mm nominal pipe size. Apart from the models used by Ozturk et al. [12] and Karabay [13], Kecebas [19] suggested another method that combines exergy analysis and modifies life cycle cost analysis to determine optimum insulation thickness for pipes. The analysis investigated the effect of combustion parameters such as excess air, stack gas temperature, and combustion chamber temperature on optimum insulation thickness, which reduces waste gases and combustion chamber temperature with increasing fuel entry temperature and decreasing stack. In addition, the optimum insulation thicknesses obtained by exergo-economic analysis are reported as higher than those obtained by energo-economic analysis. Kayfeci [20] used the method recommended by Kecebas et al. [17] for estimation of the optimum insulation thickness in various heating pipe diameters with different insulation materials like EPS, fiberglass, foamboard, rockwool and XPS. The highest energy saving for small diameter pipes is obtained by the fiber glass as insulation material, while for large diameter pipes the EPS yields the highest energy saving. The artificial neural network (ANN) is employed by Kayfeci et al. [21] used to estimate optimum insulation thickness easily for pipe insulation applications. All parameters related to thermal insulation optimization are obtained from insulation markets and then it is determined by a life cycle cost analysis modification. The ANN model can easily and accurately calculate optimum insulation thickness for any pipe diameter. Kaynakli [22] reviewed the previous studies to determine economic optimum insulation thickness for pipes and ducts. They investigated heat transfer equations, optimization procedures and economic analyses methods for cylindrical pipes and ducts by comparison.

More recently, Yildiz and Ersoz [23] determined the optimum insulation thickness for pipe lines in an air conditioning system with VRF using R-410A as cooling fluid both in heating and cooling modes. In heating mode, the optimum insulation thicknesses for high pressure gas and low pressure fluid pipelines are calculated as 1.6 cm–2.0 cm and from 1.1 cm 1.3 cm, respectively. In cooling mode, the thickness varies from 0.7 to 0.8 cm. Another study by the same authors [24] researched to the variation in optimum insulation thickness with wind speed within HVAC ducts. For fuel types such as coal, fuel-oil, LPG and natural gas and insulation materials such as fiberglass and rockwool, life cycle costs are optimized, and they reported that at high wind speeds insulation is necessary.

In the literature, there are many studies on the optimum insulation thickness of pipes and ducts based on the modified life cycle cost analysis that is suggested by Kecebas et al. [17]. These studies researched to the effects of different parameters such as fuel types, insulation materials, pipe diameters, heat degree-days, working fluid, combustion and economic parameters on optimum insulation thickness. However, apart these studies, the current study concentrates on the following points.

(i) Determination of the optimum insulation thickness for large diameter pipes,
(ii) Investigation of the variation in optimum insulation thickness, energy saving and payback period depending on variations in pipe diameters,
(iii) Completion of the sensitivity analysis on the parameters of optimum insulation thickness, energy saving and payback period. This study is expected to provide the most important contribution to thermal insulation thickness analysis in case of for large diameter pipes under optimization conditions and the economic parameters.

2. Material and method

Generally, heat insulation is a precaution taken to prevent heat loss and gains caused by differences in temperature. It is, therefore, installed in buildings, mechanical installations and industries.