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Modelling the optimum distribution of insulation material

M. Kemal Sevindir, Hakan Demir*, Özden Ağra, Ş. Özgür Atayılmaz, İsmail Teke

Yıldız Technical University Mechanical Engineering Department, 34349, Besiktas, Istanbul, Turkey

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ABSTRACT

The optimum insulation thickness is determined according to investment and operation and maintenance costs using various economic analysis techniques. Calculation of thickness distribution according to maximum temperature differences may give undesired results if the temperature differences varies during time. Thus, the variation of temperature differences should be taken into account by optimizing the distribution of insulation material according to total amount of heat transfer. Also, neighboring volumes are kept at constant temperatures by means of cooling and heating by refrigerators and heat pumps. Therefore, total energy cost for both sides of the wall (heated/cooled one side and cooled/heated at the other side) should be considered. In this study, a general solution of the optimum distribution of thermal insulation material for a given investment cost or material volume is provided for the volumes confined with environments at different temperatures considering the total amount of heat transfer and total energy cost. Also a case study is given to explain the usage of the new method.

1. Introduction

Energy requirement for heating and cooling applications due to either thermal comfort or special climate requirements for industrial applications is large portion of total energy consumption. Insulation materials the used to reduce the heat transfer through the walls of the volumes to reduce energy consumption. There are plenty of works on determining the optimum insulation thickness using thermo-economical models. Christensen [1] and Dimitriyev [2] studied on refrigerators and freezers and recommended that the insulation thickness should be between 100 and 150 mm for PU foam. Lee et al. [3] proposed a methodology to optimize insulation thickness for reducing energy consumption for a given interior volume. Yoon et al. [4] developed of an optimization strategy for insulation thickness of a domestic refrigerator-freezer. Söylemez and Ünsal [5], studied on determination of optimum insulation thickness for refrigeration applications. Daouas et al. [6] determined the insulation thickness for steady periodic conditions using Complex Finite Fourier Transform for two different types of insulation materials and two typical wall types. Kaynakli [7] conducted a parametrical study based on life-cycle cost analysis to determine optimum thermal insulation thickness for external walls. Energy required for heating or cooling has been calculated according to number of degree-days. Ozel and Pihtili [8] studied 12 different wall configurations with different configurations of insulation layers to determine optimum distribution and location of insulation material in a wall. Al-Sanea and Zedan [9] also studied insulation layer distribution and thickness for same thermal mass.

Ekici et al. [10] studied optimum insulation thicknesses for different types of wall materials, fuels and climate zones. Axaopoulos et al. [11] included the effects of wall orientation considering speed and direction of wind. Ozel [12] also included the effects of wall orientation by taking into account of the variation of solar radiation according to direction for steady periodic conditions.

Yu et al. [13] studied optimum insulation thickness based on life cycle cost analysis and solar-air degree-hours for residential roof with different surface colors. Li and Chow [14] analyzed methods for protecting water pipes in cold regions by using thermal insulation material and heating cable.

Al-Sanea et al. [15] studied to compute the yearly cooling and heating transmission loads under steady periodic conditions through a typical building wall which has different insulation thickness. Bahadori and Vuthaluru [16] developed a simple method to estimate the thermal insulation thickness which is required to

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* Corresponding author.
E-mail address: hdemir@yildiz.edu.tr (H. Demir).

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arrive at a desired heat flow rate or surface temperature for flat surfaces, ducts and pipes. Daouas [17] calculated optimum insulation thickness, energy saving and payback period for a typical wall structure based on both cooling and heating loads. Dongmei et al. [18] studied the effects of external wall insulation thickness on annual cooling and heating energy usage under different climates. Hasan [19] prepared general charts for selecting the optimum insulation thickness as a function of degree days and wall thermal resistance for Palestine. Barrau et al. [20] studied the impact of the optimization criteria on optimum insulation thickness calculations for the building's envelope. Asan [21] examined the effects of insulation thickness and location on time lag. Kayfeci et al. [22] analyzed the optimum insulation thickness on the external walls for cooling applications using the degree-hours and the annual equivalent full load cooling-hours methods. Kayfeci et al. [23] also predicted the insulation thickness and the life cycle costs (LCCs) for pipe insulation applications employing the artificial neural networks (ANNs).

Kaynaklı [24] carried out a literature review on the optimum economic thickness of the thermal insulation for a pipe or duct with different geometries which are used in various industries. Wong et al. [25] analyzed the heat transfer characteristics of an insulated tank taking into account the inner side thermal resistance and wall conduction. Usta and Ileri [26] determined the economic optimum values of the design parameters of refrigeration systems using a specifically developed computer program to show the importance of economic optimization of large capacity or industrial refrigeration systems. Wong and Chou [27] investigated the relation for the critical and the neutral thickness and the heat transfer characteristics of an insulated regular polyhedron using a new regular polygon top solid wedge thermal resistance (RPSWT) model obtained from a solid angle concept. Sofrata and Salmeen [28] developed a consistent and general mathematical model written in Fortran 77 to select the best insulation thickness. These studies would be inadequate and requires tedious iterations to achieve a satisfactory solution.

Recently, Demir et al. [29] proposed a new analytical method to determine optimum distribution of insulation material for a given insulation volume or investment cost under steady state conditions. Using this model, optimum distribution of insulation material can be calculated using the equations or obtained from the figures given.

Although there are plenty of works on optimum insulation thickness, there are few ([1–3] and [29]) deals with the optimum distribution of insulation material for a given volume. Models calculating the optimum insulation thickness does not take into account the volume occupied by the insulation material and therefore these models not suitable for calculating the insulation thicknesses for the walls of a comparatively small volumes such as refrigerators and refrigerated trucks or cold storages whose walls are in contact with the environments at different temperatures. Since the optimum insulation thickness is determined based on economical parameters and for the volumes whose walls in touch with the same environment, it is almost impossible to find an analytical solution without dealing with lots of iterations for optimum distribution of insulation material in cases such as cold storage applications and refrigerators and therefore requires a specialized computer software.

In this study, optimum distribution of insulation material is investigated for the confined volumes such as cold storage, freezer, refrigerated truck etc. Neighboring volumes can be cooled or heated by refrigerators and heat pumps instead of exposed to ambient air. Therefore, total energy cost for both sides of the wall are considered. It is shown that optimum distribution of insulation material easily achieved by the proposed model.

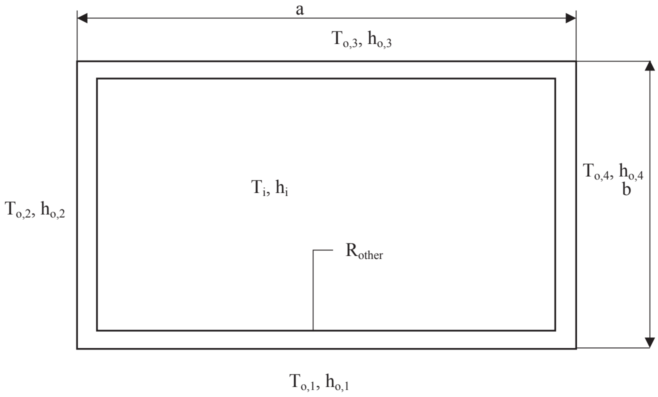

Fig. 1. Confined volume in contact with different environments.

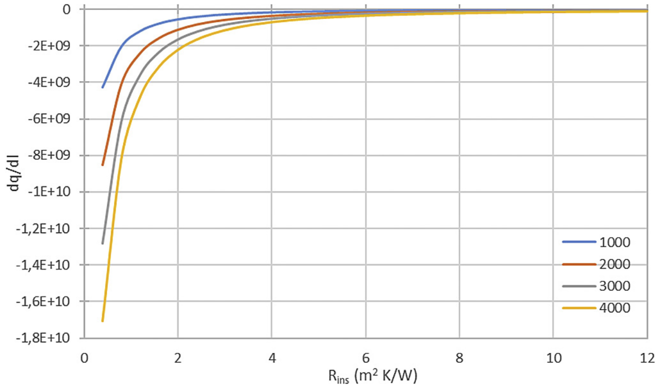

Fig. 2. Variation of dq/dl as a function of insulation resistance and degree days.

2. General solution

Assuming the volume has a finite number of walls having different thermal resistances which in contact with different environments at different temperatures (Fig. 1). Amount of heat transfer per unit area according to degree days through ith wall which consists of different layers is expressed as,

$$q_i = \frac{86400DD_i}{\frac{1}{h_{in,i}} + \frac{1}{h_{out,i}} + \sum_{j=1}^{n}\frac{l_{j,i}}{k_{j,i}} + \frac{l_{ins,i}}{k_{ins}}} \tag{1}$$

Also the derivative of q_i with respect to l_{ins} is of the form,

$$\frac{dq_i}{dl} = 86400DD_i\left[-\frac{\frac{1}{k_{ins}}}{\left(\frac{1}{h_{in,i}} + \frac{1}{h_{out,i}} + \sum_{j=1}^{n}\frac{l_{j,i}}{k_{j,i}} + \frac{l_{ins,i}}{k_{ins}}\right)^2}\right] \tag{2}$$

Eq. (2) represents the variation of amount of heat transfer per unit area as a function of insulation thickness and degree days for a given wall. Fig. 2 shows the variation of dq_i/dl as a function of insulation resistance and degree days when the thermal resistance of the wall is 0.5 m^2 K/W except insulation material.

As seen in Fig. 2, dq/dl is sensitive to temperature difference for insulation resistances below 6 m^2 K/W in a range of 1 °C–50 °C. For a specific volume consists of adiabatic surfaces except for two walls