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Cost analysis for optimum thicknesses and environmental impacts of different insulation materials

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ABSTRACT

In this study, the optimum thickness of thermal insulation used to reduce heat gain and losses in buildings is investigated under dynamic thermal conditions by using the climatic conditions of Elazığ, Turkey. Numerical method based on an implicit finite difference procedure which has been previously validated is used to determine yearly cooling and heating transmission loads, yearly averaged time lag and decrement factor under steady periodic conditions. These loads are used as inputs to an economic model for the determination of the optimum insulation thickness. The optimum insulation thicknesses, energy savings and payback periods are calculated by using life-cycle cost analysis over lifetime of 20 years of the building. Results show that the optimum insulation thicknesses vary between 5.4 and 19.2 cm, energy savings vary between 86.26 and 146.05 $/m^2, and payback periods vary between 3.56 and 8.85 years for different insulation materials. The environmental impacts of thermal insulation are also investigated. It is seen that by applying optimum insulation thickness in uninsulated wall, yearly fuel consumption and emissions are decreased by 68–89.5% depending on insulation materials.

1. Introduction

Today, world energy consumption contributes to pollution, environmental deterioration and global greenhouse emissions. Increases in energy consumption are driven by population growth and economic development that tend to increase energy use per capita. Thus the inevitable increase in population in the near future and the economic development that must necessarily occur in many countries pose serious implications for the environment. Since the early 1980s the relationship between energy use and environmental impacts has received much attention, and a number of international activities have focused on this topic [1]. The energy consumption is distributed among four main sectors such as industrial, building (residential/commercial), transportation and agriculture [2].

Globally, buildings are responsible for approximately 40% of the total world annual energy consumption. Most of this energy is for the provision of lighting, heating, cooling, and air conditioning. Increasing awareness of the environmental impact of carbon dioxide (CO_2) and nitrogen oxides (NO_x) emissions and chlorofluorocarbons (CFCs) triggered a renewed interest in environmentally friendly cooling, and heating technologies. Under the 1997 Montreal Protocol, governments agreed to phase out chemicals used as refrigerants that have the potential to destroy stratospheric ozone. It was therefore considered desirable to reduce energy consumption and decrease the rate of depletion of world energy reserves and pollution of the environment. One way of reducing building energy consumption is to design buildings, which are more economical in their use of energy for heating, lighting, cooling, ventilation and hot water supply [3].

The employ of thermal insulation is one of the most effective ways of building energy conservation for cooling and heating. Therefore, the selection of a proper insulation material and determination of optimum insulation thickness are particularly vital [4]. It is well known that the heat-transmission load decreases without a limit with increasing insulation thickness, however, the rate of decrease drops quite fast as the thickness increases. From a purely conservation point of view, the designer should select an insulation material with the lowest possible thermal conductivity and the highest thickness that the owner can afford. However, the cost of insulation increases linearly with its thickness, and there is a point, for each type of insulation material, beyond which the saving in energy consumption will not compensate for the extra cost of insulation material. Thus, there must be an optimum insulation thickness at which the total cost of the insulation material plus the present worth of energy consumption over the lifetime of the building is a minimum [5].

In literature, there are many studies on the determination of the optimum insulation thicknesses on the building walls. The most of these studies use degree-days (or degree-hours) concept which is a simple and crude model applied under static conditions [6–12]. However, more accurate results were obtained with numerical and

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Nomenclature

A_s	annual energy savings ($\$/m^2$)
c	specific heat (J/kg K)
C_A	yearly total cost of energy ($\$/m^2$ year)
$C_{A,C}$	yearly energy cost for cooling per unit area ($\$/m^2$ year)
$C_{A,H}$	yearly energy cost for heating per unit area ($\$/m^2$ year)
C_i	cost of insulation material per unit volume ($\$/m^3$)
C_E	cost of electricity ($/kWh)
C_F	fuel cost ($/kg)
g	inflation rate
h_i	heat-transfer coefficient at the indoor surface of wall (W/m^2 K)
h_o	heat-transfer coefficient at the outdoor surface of wall (W/m^2 K)
H_u	lower heating value of the fuel (J/m^3)
I_T	incident total solar radiation for vertical surfaces (W/m^2)
I_b	beam solar radiations on the horizontal surface (W/m^2)
I_d	diffuse solar radiations on the horizontal surface (W/m^2)
I	total solar radiations on the horizontal surface (W/m^2)
i	interest rate
k	thermal conductivity (W/m K)
L_i	insulation thickness (m)
M_F	yearly fuel consumption (kg/m^2 year)
p_b	payback period (year)
PWF	present worth factor
q_i	heat flux at indoor surface of the wall (W/m^2)
Q_g	total heat gain per year of insulated wall (W/m^2)
Q_l	total heat loss per year of insulated wall (W/m^2)
t	time (s)
T_i	indoor air temperature (°C)
T_o	outdoor air temperature (°C)

Greek letters

α	solar absorptivity of outdoor surface of wall
η_s	efficiency of the heating system
ρ	density (kg/m^3)
θ	incidence angle (°)
θ_z	zenith angle (°)

analytical methods considering the transient thermal behaviour of building envelope. While some authors used dynamic time dependent method based on the finite volume implicit procedure to compute the yearly transmission loads through the wall under steady periodic conditions [5,13–16], the others used an analytical method based on Complex Finite Fourier Transform [17,18].

Air pollution is becoming a great environmental concern in Turkey. Air pollution from energy utilization in the country is due to the combustion of coal, lignite, petroleum, natural gas, wood and agricultural and animal wastes. On the other hand, owing mainly to the rapid growth of primary energy consumption and the increasing use of domestic lignite, SO_2 emissions, in particular, have increased rapidly in recent years in Turkey [19].

In literature, there are also a few studies on environmental impact of thermal insulation. Çomaklı and Yüksel [20] investigated environmental impact of heat insulation used for reduction heat losses in buildings. They determined that CO_2 emission amounts decreased 50% by means of optimum insulation thickness used and

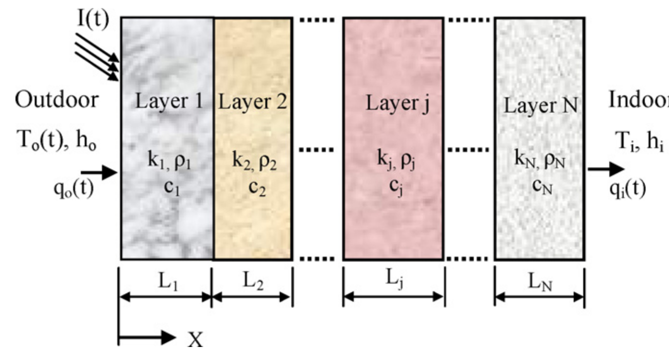

Fig. 1. *N*-layered composite wall.

other energy savings methods in buildings. Dombaycı [21] investigated the environmental impact of optimum insulation thickness. In the calculations, coal was used as the fuel source and the expanded polystyrene as the insulation material. He found that when the optimum insulation thickness is used, the emissions of CO_2 and SO_2 are decreased by 41.53%. Mahlia and Iqbal [22] investigated potential cost savings and emission reductions achieved by installing different insulation materials of optimum thickness in building's walls. The paper also investigated the effect when air gaps are introduced in the wall. They found that by introducing optimal thickness of different insulation materials and by having air gaps of 2, 4 and 6 cm, energy consumption and emissions can be reduced by 65–77%, in comparison to a wall without insulation or air gaps. In another study, the effects of air gap in the composite wall construction on the optimum insulation thickness, total cost, energy saving, payback period, fuel consumption, and emissions of CO_2 and SO_2 were investigated for a prototype building in a sample city, Karabuk [23].

The present study aims determination of optimum thicknesses and environmental impacts of different insulation materials under dynamic thermal conditions. Thermal parameters such as the yearly cooling and heating transmission loads, yearly averaged time lag and decrement factor are calculated under steady periodic conditions by using an implicit finite difference method which has been previously validated. Transmission loads are used as inputs to an economic model for the determination of the optimum insulation thickness over lifetime of 20 years of the building. The optimum insulation thicknesses, energy savings, payback periods, fuel consumption, and emissions of CO_2 and SO_2 are calculated for four different insulation materials.

2. Mathematical formulation

The transient one-dimensional heat conduction equation in a multilayer wall consisting of *N* parallel layers in perfect thermal contact as illustrated in Fig. 1 is given by:

$$k_j \frac{\partial^2 T_j}{\partial x^2} = \rho_j c_j \frac{\partial T_j}{\partial t}, \quad j = 1, 2, \ldots, N \tag{1}$$

where *x* and *t* are the space and time coordinates, respectively. T_j is the temperature, ρ_j, c_j and k_j are the density, the specific heat and the thermal conductivity of the *j*-th layer, respectively. The thermal conduction at the interfaces between the layers may be expressed by equations:

$$T_j = T_{j+1}, \quad j = 1, 2, \ldots\ldots, (N-1) \tag{2}$$

$$k_j \frac{\partial T_j}{\partial x} = k_{j+1} \frac{\partial T_{j+1}}{\partial x}, \quad j = 1, 2, \ldots, (N-1) \tag{3}$$

The outside surface of the wall is exposed to periodic solar radiation and outdoor environment temperature while the inside