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The influence of exterior surface solar absorptivity on thermal characteristics and optimum insulation thickness

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ABSTRACT

In this study, the influence of exterior surface solar absorptivity on the thermal characteristics and optimum insulation thickness is investigated under dynamic thermal conditions. Numerical model based on an implicit finite difference method under steady periodic conditions is used to determine thermal characteristics such as yearly cooling and heating transmission loads, yearly averaged time lag and decrement factor. Later, these loads are used as inputs to an economic model for the determination of the optimum insulation thickness. The investigation is carried out for a south-facing wall in the climatic conditions of Elazığ, Turkey. Solar absorptance of external surface is assumed to be varying from 0 to 1 with an increment of 0.2. Extruded polystyrene as insulation material is selected. As the absorptance increases, heating and total transmission loads decrease while cooling transmission load increase. It is seen that the increase rate in the cooling load ranges from 66.26% to 331.28% while reduction rates in the heating and total loads range from 6.72% to 33.65% and from 2.57% to 12.90%, respectively. The results show that for uninsulated and insulated walls, solar absorptivity has a great effect on the yearly transmission loads while it has a small effect on the yearly averaged time lag. On the other hand, decrement factor is almost unaffected by solar absorptance. The results also show that solar absorptivity has a very small effect on the optimum insulation thickness and payback period, but a more significant effect on energy savings.

1. Introduction

An important form of heat that affects the indoor temperature of a building is that from solar radiation. Some of this enters the building through the windows and some is absorbed at the outer surfaces of the external walls and roof and distributed as heat to the inside air [1]. The fraction of solar irradiation absorbed by a surface is called absorptivity and is important since it affects considerably the outdoor and indoor environment [2]. The effect of wall and roof absorptances on heating, cooling and total loads was studied by Shariah et al. [1]. Their results showed that, for not insulated buildings, as the absorptance was changed from one to zero, the total energy load decreased by 32%, while for insulated buildings, it decreased by 26% in Amman, whereas this decrease was about 47% for not insulated and 32% for insulated buildings in Aqaba. Kontoleon and Bikas [2] investigated the effect of outdoor absorption coefficient of an opaque wall on time lag, decrement factor and temperature variations by employing a dynamic thermal-network model. Results showed that maximum time lag values were obtained with one insulation layer on the outer surface and the other in the mid-center plane of the masonry, while minimum decrement factor values and temperature variations were obtained by placing the two insulation layers on the outer and inner surfaces. By using above same model, the effect of wall orientation and exterior surface solar absorptivity on time lag and decrement factor for several insulated wall configurations was investigated by Kontoleon and Eumorfopoulou [3]. Their results showed that wall surfaces with east orientation caused the maximum values of time lag, while wall surfaces with west orientation led to minimum values of time lag, for all the insulation positions and allocations. Results also showed that for east oriented wall surfaces, minimum values of the decrement factor were achieved and therefore reduced temperature fluctuations at the interior surface of the walls; whereas, maximum values of this parameter appeared for wall surfaces with north orientation. These studies did not include effect of solar absorptivity on insulation thickness. The objective of the present study is to investigate the influence of exterior surface solar absorptivity on both thermal characteristics and optimum insulation thickness.

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Nomenclature

$a_B, a_E, .., a_W$	coefficients in finite difference equations
B,S	labels of boundary nodes in Fig. 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)
E,I,J,P,W	labels of internal nodes in Fig. 2
e,i,j,w	labels of control volume boundaries in Fig. 2
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	incident total solar radiation for vertical surfaces (W/m^2)
I_d	direct solar radiations on the horizontal surface (W/m^2)
I_y	diffuse solar radiations on the horizontal surface (W/m^2)
I_a	total solar radiations on the horizontal surface (W/m^2)
i	interest rate
k	thermal conductivity (W/m K)
L_i	insulation thickness (m)
q_i	heat flux at indoor surface of the wall (W/m^2)
Q_g	total heat gain per year (W/m^2)
Q_l	total heat loss per year (W/m^2)
PWF	present worth factor
t	time (s)
T_i	indoor air temperature (°C)
T_o	outdoor air temperature (°C)
$T_{x=L}$(max)	maximum of indoor surface temperature (°C)
$T_{x=L}$(min)	minimum of indoor surface temperature (°C)
$T_{x=0}$(max)	maximum of outdoor surface temperature (°C)
$T_{x=0}$(min)	minimum of outdoor surface temperature (°C)

Greek letters

α	solar absorptivity of outdoor surface of wall
δ	declination angle (deg.)
Δx	space step (m)
Δt	time step (s)
η_s	efficiency of the heating system
ϕ	latitude (deg.)
Φ	time lag (h)
F	decrement factor
γ	surface azimuth angle (deg.)
ω	hour angle (deg.)
ρ	density (kg/m^3)

Various methods exist for calculation the heat-transfer characteristics of building components. It is known that finite element techniques are suitable for solving partial differential equations with boundary conditions that cannot be handled with finite difference methods [4]. A dynamic software for simulating building performance (e.g. ESP-r) uses the finite element approach. This programme has been validated as capable of handling composite-wall constructions and complex processes (e.g. solar, heat and mass transfer) in a building envelope. Other validated software for building simulation includes Energy Plus and TRNSYS. However, in general, problem can be reduced to solving time-dependent heat conduction equation through a composite structure. In this study, the differential equation formulated under some assumptions is solved by employing implicit finite-difference method.

The heating and cooling loads of buildings comprise a large part of the building's energy consumption. Most of these loads are due to heat transmission across the building envelope. Therefore, one of the most effective ways to reduce these loads from the point of view of energy conservation is the use of thermal insulation in the building envelope. As thickness of insulation applying on external walls of buildings increases, the heat transmission load decreases. But, the cost of insulation material increases linearly with increasing insulation thickness. The optimum insulation thickness is value minimizing the total cost which is sum of the cost of insulation material and the present value of energy consumption cost over the lifetime of 10 years of the building and must be determined by using a cost analysis.

In literature, different methods were used to estimate the transmission loads required in the determination of the optimum insulation thicknesses. One of the most common methods is the degree-days (or degree-hours) concept [5–13]. This method is a simple and crude method applied under static conditions. Dynamic transient models based on numerical and analytical methods were considered to obtain highly accurate results on the determination of optimum insulation thickness. Numerical methods were based on the finite volume implicit procedure under steady periodic conditions [14–17]. Besides, an analytical method based on Complex Finite Fourier Transform was used in the analyses of the optimum insulation thickness [18,19].

In recent years, there has been growing interest in analyzing the dynamic thermal characteristics of building envelopes to understand their thermal performance, optimal management and use of energy in buildings. The research helps to reduce building energy use by choosing the building elements with better thermal performance, and to reduce the size of the air-conditioning system in the buildings, while a desirable indoor environmental quality is created for occupants in the buildings [20].

The present study deals with the determination of heat-transfer characteristics and optimum insulation thickness of building exterior walls by considering exterior surface solar absorptivity. The yearly cooling and heating transmission loads, yearly averaged time lag and decrement factor are calculated with respect to solar absorptivity varying from 0 to 1 for uninsulated and insulated walls under dynamic thermal conditions. Then, the optimum insulation thicknesses, energy savings and payback periods with respect to external surface solar absorptivity values are calculated by considering both heating and cooling loads.

2. Mathematical formulation

This study is carried out for a south-facing wall, which is exposed to periodic solar radiation and outdoor environmental temperature on the outside and is in contact with the room air at fixed design temperature on the inside (Fig. 1a). A composite wall structure consisting of N parallel layers with different thickness and physical properties is illustrated in Fig. 1b. The mathematical model is formulated using the following assumptions [16,17].

1. No heat generation.
2. Constant thermal properties.