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Effect of insulation location on dynamic heat-transfer characteristics of building external walls and optimization of insulation thickness

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ABSTRACT

In this study, the effect of insulation location on the heat transfer characteristics of building walls and optimization of insulation thickness are investigated numerically using an implicit finite difference method under steady periodic conditions. The investigation is carried out for a south-facing wall in the climatic conditions of Elazığ, Turkey. For this purpose, insulation is placed at outside, inside and middle of the wall. Firstly, thermal characteristics such as cooling and heating transmission loads, time lag and decrement factor are determined for each insulation position. Then, the insulation thickness is optimized by using a cost analysis over a building lifetime of 20 years. Results show that insulation location has a significant effect on the yearly averaged time lag and decrement factor. However, yearly transmission loads and hence, optimum insulation thickness are not affected by insulation location. It is seen the maximum temperature swings and peak load in both summer and winter occur in the case that insulation is placed at middle of wall while wall with outside insulation gives the smallest fluctuation.

1. Introduction

The demand for energy is increasing worldwide because of increasing population and improving standards of living. Most power generation plants still use fossil fuels which are being depleted at an unsustainable rate resulting in higher prices and adverse environmental effects. In addition to utilizing renewable energy sources, energy conservation is still the most effective means for dealing with these problems [1]. In many countries, building energy consumption accounts for approximately 40% of global energy demands [2–6], and the energy requirement for space heating and cooling of a building is approximately 60% of the total energy consumed in buildings, which accounts for the largest percentage of energy usage. The proper design and selection of a building envelope and its components are an efficient means to reduce the space heating-cooling loads. As such, thermal insulation is one of the most valuable tools in achieving energy conservation in buildings [6].

Insulated building walls are integrated parts of a building envelope. They protect the inner space from extreme weather conditions and damp down large fluctuations in temperature. As such, the building envelope should provide the necessary thermal comfort for the occupants as well as reduce energy consumption requirements for cooling and heating. This is usually done through increasing thermal resistance of this envelope and, hence, reducing transmission loads. Therefore, addition of thermal insulation is important, particularly in regions with extreme climates [7]. Insulation materials are not heat storage media; nevertheless, they have been shown to give similar effects on time lag (increase time between occurrence of peak temperatures at wall outer and inner surfaces) and decrement factor (reduce wall inner surface temperature fluctuation) as those given by heat storage materials (thermal mass). Besides, thermal characteristics under dynamic conditions are affected by relative locations (distribution) of thermal mass and insulation layers [8].

In literature, there are many studies on location of insulation in the wall [9–22]. Al-Sanea and Zedan [9] studied the effect of insulation location on the heat transfer characteristics of building walls under steady periodic conditions. In their study, the thermal performance with an insulation layer placed on the inside of a wall structure was compared to that when the insulation layer was placed on the outside. The same authors [10] showed that the insulation layer location had significant effect on the instantaneous and daily mean loads under initial transient conditions. It was recommended that for spaces where the air conditioning system is switched on and off intermittently, the insulation should be placed on the inside. Al-Regib and Zubair [11] presented an analysis of transient heat transfer through insulated walls for three different cases. The results indicated that cooling loads for buildings were smaller for insulation placed on the outdoor surface than for insulation placed on the indoor surface. Bojic et al. [12] demonstrated that providing thermal insulation in the envelope of residential

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Nomenclature

a	solar absorptivity of outdoor surface of wall
c	specific heat (J/kg K)
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/kg)
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)
N	lifetime (years)
PWF	present worth factor
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)
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

δ	declination angle (deg.)
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)
θ	incidence angle (deg.)
θ_z	zenith angle (deg.)

buildings would lead to a reduction of the yearly maximum cooling demand, and largest reduction of around 10.5% was found when this thermal insulation was put either at the indoor side or at the outer side. Al-Sanea [13] compared the thermal performance of different roofs and showed that a slightly better thermal performance was achieved by locating the insulation layer closer to the inside surface of the roof structure. Asan [14] investigated the optimum insulation position for total six different configurations. His results showed that placing half of the insulation in the middle of the wall and the half of it in the outside surface of the wall gave very high time lags and low decrement factors. The most suitable location of insulation on the roof from maximum load leveling point of view was analyzed using implicit finite difference method for twelve different roof configurations by Ozel and Pihtili [15]. By using same method, Ozel and Pihtili [16] investigated optimum location and distribution of insulation layers from point of view maximum time lag and minimum decrement factor for various wall orientations. In these two studies, the best result was obtained when each one of three equal pieces insulation layers were placed on the outdoor surface, middle and the indoor surface of roof/wall. The location of insulation to minimize heat gain and losses in the building walls was also analyzed for three different climatic locations of Turkey by the same authors. They showed that the different climate conditions have not a noticeable effect on the location of insulation [17].

Bojic and Loveday [18] investigated influence of layer distribution and thickness on the thermal behavior. In their studies, it was shown that for intermittent heating plant operation as opposed to intermittent heating and cooling plant operation, the insulation/masonry/insulation structure saves 32–72% more energy compared with the masonry/insulation/masonry structure. Konteleon and Bikas [19] evaluated effect of temperature variances on thermal inertia factors for characteristic wall configurations. Therefore, they employed a lumped thermal-network model and showed conclusion that consideration of material configuration for wall formations have a very profound impact on the temperature fluctuations in the inner surface of building envelopes. In another study of the same authors, the effect of outdoor absorption coefficient of an opaque wall on time lag, decrement factor and temperature variations was investigated by employing a dynamic thermal-network model [20]. Kossecka and Kosny [21] analyzed insulation location on heating and cooling for six characteristic exterior wall configurations. They showed that the best thermal performance was obtained when massive material layers were located at the inner side and directly exposed to the interior space. 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 [22].

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 electric energy consumption over the lifetime of the building is a minimum [23].

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 [4,24–31]. 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 [8,23,32–39]. Besides, an analytical method based on complex finite Fourier transform was used in the analyses of the optimum insulation thickness [40,41].

In literature, although there are many studies on the determination of the optimum insulation thickness, the studies obtained by using dynamic models considering the transient thermal behavior of building envelope and solar radiation are in a limited number as mentioned above. The main objective of the present study is to optimize the insulation thickness depending on insulation location, and to determine the wall structure supplying the best thermal