Energy and Buildings 72 (2014) 288–295

Contents lists available at ScienceDirect

Energy and Buildings

journal homepage: www.elsevier.com/locate/enbuild

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

Meral Ozel*

Department of Mechanical Engineering, Firat University, 23279 Elazığ, Turkey

ARTICLE INFO

Article history:
Received 19 December 2012
Received in revised form 11 October 2013
Accepted 1 November 2013

Keywords:
Insulation location
Heat transfer characteristics
Optimum insulation thickness

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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* Tel.: +90 0424 2370000/5338.
E-mail address: mozel@firat.edu.tr

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http://dx.doi.org/10.1016/j.enbuild.2013.11.015

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

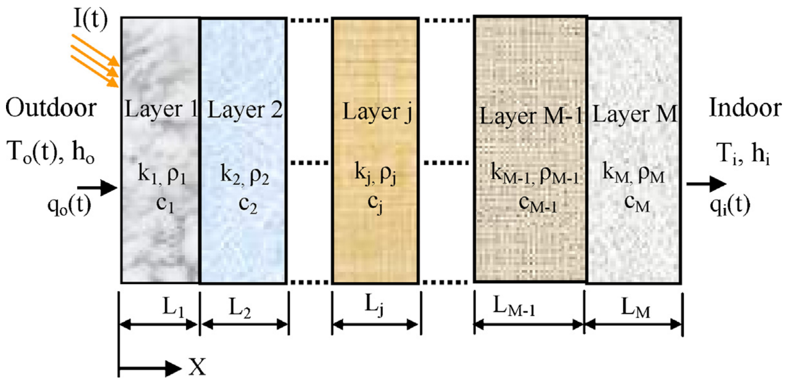

Fig. 1. M-layered composite wall.

performance. The investigation are carried out under dynamic thermal conditions using climatic conditions of Elazığ (latitude: 38.41°N, longitude: 39.14°E) which is a cold city located on Turkey's Eastern Anatolia. Firstly, thermal characteristics such as yearly cooling and heating transmission loads, yearly averaged time lag and decrement factor are determined in the case that insulation is placed at outside, inside and middle of wall. Secondly, insulation thickness is optimized by using a cost analysis for three different insulation positions. Then, thermal performances of three different wall structures under optimal insulation conditions are compared.

2. Mathematical formulation and calculation procedure

A composite wall structure consisting of M parallel layers with different thickness and physical properties is shown schematically in Fig. 1. The outside surface of the wall is exposed to periodic solar radiation and outdoor environmental temperature while the inside surface is exposed to room air maintained at constant indoor design temperature.

Assuming no heat generation, constant thermal properties, one-dimensional heat transfer and negligible interface resistance, time-dependent heat conduction equation in a multi layer wall may be written as [23]:

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

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 jth layer, respectively. The thermal conduction at the interfaces between the layers may be expressed by equations

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

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

As initial condition, an arbitrary uniform temperature field is assumed. The initial condition, the boundary conditions at the outdoor and indoor wall surfaces are as follows, respectively:

$$T_j(x, 0) = F_j, \quad j = 1, 2, \ldots, M \tag{4}$$

$$-k_1 \left(\frac{\partial T}{\partial x} \right)_{x=0} = h_0 (T_e(t) - T_{x=0}) \tag{5}$$

$$-k_M \left(\frac{\partial T}{\partial x} \right)_{x=L} = h_i (T_{x=L} - T_i) \tag{6}$$

where F_j is an arbitrary uniform temperature across the wall. h_o and h_i are the combined (convective and radiative) heat-transfer coefficients at the outdoor and the indoor wall surfaces, respectively. T_i is the indoor air temperature. T_e is the sol-air temperature including the effect of solar radiation on the outdoor temperatures and is expressed as follows [42]:

$$T_e = T_o + \frac{a I_T}{h_o} - \frac{\varepsilon \Delta R}{h_o} \tag{7}$$

where T_o is the outdoor air temperature. I_T and a denote the total solar radiation and solar absorbtivity of the outdoor wall surface, respectively. $\varepsilon \Delta R / h_o$ is the correction factor and is assumed to be 4 °C for horizontal surfaces and 0 for vertical surfaces from ASHRAE [43].

The total solar radiation (I_T) for vertical surfaces is calculated as:

$$I_T = R_b I_b + \frac{I_d + I\rho_g}{2} \tag{8}$$

where I_b, I_d and I are beam, diffuse and total solar radiations on the horizontal surface. Ground reflectance ρ_g is usually taken as 0.2. The geometric factor R_b is the ratio of beam radiation on the tilted surface to that on a horizontal surface at any time and is calculated as:

$$R_b = \frac{\cos \theta}{\cos \theta_z} \tag{9}$$

where θ and θ_z are incidence and zenith angles, respectively. These angles for vertical wall surfaces are defined as:

$$\begin{aligned} \theta = {} & \sin \delta \sin \phi \cos \beta - \sin \delta \cos \phi \sin \beta \cos \gamma \\ & + \cos \delta \cos \phi \cos \beta \cos \omega \\ & + \cos \delta \sin \phi \sin \beta \cos \gamma \cos \omega + \cos \delta \sin \beta \sin \gamma \sin \omega \end{aligned} \tag{10}$$

$$\theta_z = \cos \phi \cos \delta \cos \omega + \sin \phi \sin \delta \tag{11}$$

where δ, ϕ, ω and γ are declination angle, latitude angle, hour angle and surface azimuth angle, respectively. γ is zero for an inclined plane facing south. It is taken as negative from the south to the east, and the north, and positive from south to west, and the north, i.e. $-180° < \gamma < +180°$. Detailed calculation procedures for Eqs. (8)–(11) are given by Duffie and Beckman [44].

The transient heat conduction problem expressed by Eqs. (1)–(6) was solved by using an implicit finite difference method. Detailed calculation procedures are given in reference [16]. The numerical solution gives the temperature distribution across the composite wall thickness at any time instant. It is assumed that the boundary condition on the outside surface is periodic, i.e. the daily cycle of the outdoor air temperature and the solar radiation is repeated on consecutive days, and a steady periodic solution is obtained.

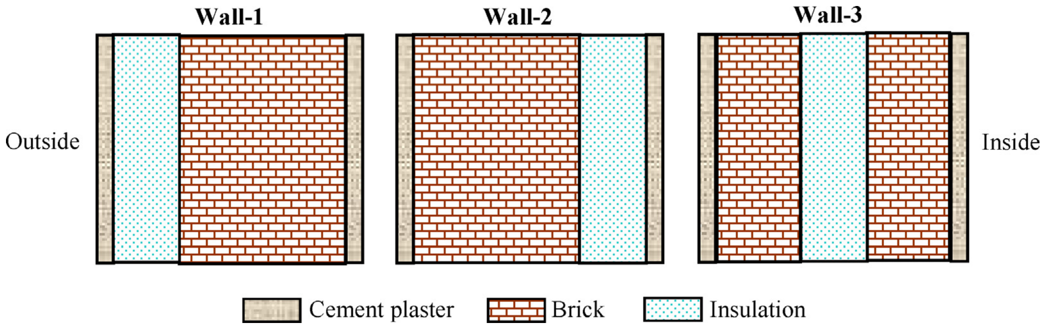

Fig. 2. Wall configurations composed of brick, insulation and plaster (outside insulation (Wall-1), inside insulation (Wall-2) and middle insulation (Wall-3)).

The instantaneous transmission heat load is obtained as following:

$$q_i = h_i(T_{x=L} - T_i) \tag{12}$$

Calculations are made for a representative day for each month of the year for a given insulation thickness. The 15th day of each month of the year is considered as a representative day and instantaneous heat load is obtained. To calculate daily total load, this instantaneous load is integrated over 24 h periods. Yearly heating and cooling loads are separately calculated from daily transmission loads which are added over all year.

The time lag is defined as the time that sinusoidal temperature wave reaches from outdoor surface of wall to indoor. On the other hand, the decrement factor is defined as reduction ratio in amplitude of the temperature wave at the indoor surface compared to the outside surface. The time lag and decrement factor are computed using the following relations [16]:

$$\Phi = t_{T_{x=L}(\max)} - t_{T_{x=0}(\max)} \tag{13}$$

$$f = \frac{T_{x=L}(\max) - T_{x=L}(\min)}{T_{x=0}(\max) - T_{x=0}(\min)} \tag{14}$$

where $t_{T_{x=L}(\max)}$ and $t_{T_{x=0}(\max)}$ represent the time that indoor surface temperatures and outdoor surface temperatures are being maximum, respectively. $T_{x=L}(\max)$, $T_{x=L}(\min)$ and $T_{x=0}(\max)$, $T_{x=0}(\min)$ are maximum and minimum temperatures on the indoor and outdoor surfaces of wall, respectively. The time lag and decrement factor are calculated for the representative day of each month of the year. Then, the yearly average time lag and decrement factor are determined as the arithmetic average of these monthly values

3. The structure of building walls

The thermal characteristics of insulated walls are evaluated for three different wall structures. Insulation is placed at outside (Wall-1), inside (Wall-2) and middle (Wall-3) of wall as shown in Fig. 2. Total thickness of brick is 20 cm (20 cm as one layer and 10 cm as two layers), thickness of insulation is increased from 0.5 cm to 10 cm, and each one of cement plaster in the interior and exterior surface of walls is 2 cm. Extruded polystyrene (XPS) as insulation material are selected. Thermal properties of materials used in the wall structure are given in Table 1.

Table 1
Thermophysical properties of building materials.

Material	k (W/mK)	ρ (kg/m^3)	c (J/kg K)
Brick block	0.620	1800	840
Extruded polystyrene	0.029	35	1213
Cement plaster	0.72	1865	840

4. Cost analysis and optimization of insulation thickness

Thermal insulation of buildings reduces the need for space heating and cooling and consequently reduces the cost of consumed energy. However, purchase and installation of insulation layer increase the initial cost of the construction. Therefore, an economic analysis should be performed in order to estimate the optimum insulation thickness which minimizes the total cost including the insulation and the energy consumption costs [33].

The total cost is the sum of the cost of insulation material and the present worth of the cost of energy consumption over the life time of the building. It is written as:

$$C_t = \text{PWF}\left(\frac{Q_l C_F}{H_u \eta_s} + \frac{Q_g C_E}{\text{COP}(3.6 \times 10^6)}\right) + C_i L_i \tag{15}$$

where Q_g and Q_l are the total heat gain and loss per year (or yearly cooling and heating loads) (W/m^2), respectively. C_F and C_E are costs of fuel ($/kg) and electricity ($/kWh), respectively. H_u is lower heating value of the fuel (J/kg), η_s is the efficiency of the heating system and *COP* is performance of cooling system. 3.6×10^6 is added as conversion of units. is the cost of insulation material per unit volume ($/m^3), L_i is the insulation thickness (m) and, PWF are the present worth factor and depends on the inflation rate g, and the interest rate *i*. In this case, PWF for the lifetime of *N* years is defined as below:

$$\text{PWF} = \frac{(1+r)^N - 1}{r(1+r)^N}, \quad i > g \quad r = \frac{i-g}{1+g} \tag{16}$$

In this study, coal as fuel in heating and electricity in cooling are used. The parameters used in calculations are given in Table 2.

Table 2
The parameters used in calculations.

Parameter	Value
Coal (in heating)	
C_F	0.3777 $/kg
H_u	29.307×10^6 J/kg
η_s	65%
Electricity (in cooling)	
C_E	0.1894 $/kWh
COP	2.5
Insulation	
C_i	304.23 $/m^3
Interest rate, *i*	8.75%
Inflation rate, *g*	7.50%
Lifetime, *N*	20 years

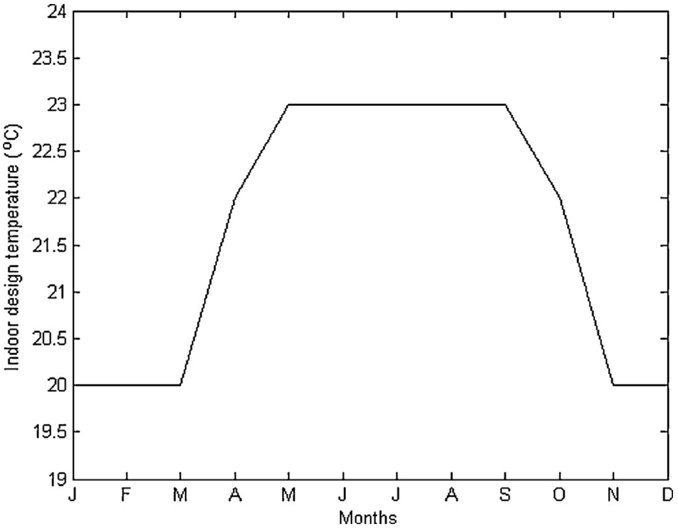

Fig. 3. Indoor design temperatures selected for the representative day of each month.

5. Results and discussion

5.1. Environmental conditions for thermal analysis

The investigation is carried out for a south-facing wall at the climatic conditions of Elazığ, Turkey. The outdoor air temperatures in Elazığ are obtained by averaging hourly measurements recorded in meteorological data over the years 2000–2010 [45]. The hourly solar radiation flux on the wall is calculated by using isotropic sky model given in Duffie and Backman [44], and by using solar radiation measured on the horizontal surface. The constant indoor air temperatures selected for the representative day of each month are given in Fig. 3. The solar absorptivity of opaque wall is selected to be equal to 0.8 for dark-colored surfaces, and the combined heat-transfer coefficients at the indoor and the outdoor wall surfaces are taken to be 9 and 22 W/m^{2}K, respectively [36]. The variations of the sol-air temperature and outdoor air temperature for summer and winter conditions are shown in Fig. 4(a) and (b), respectively. As seen from these figures, the maximum outdoor temperature appears at 16:00 for July 15 and at 14:00 for January 15. The sol-air temperature reaches its maximum peak value earlier than the maximum outdoor temperature in both summer and winter conditions since the incident solar radiation is maximum at 12:00 for a wall with south orientation.

5.2. The thermal characteristics of building walls

In this study, thermal characteristics such as yearly cooling and heating transmission loads, yearly averaged time lag and decrement factor for three different insulation positions are determined using an implicit finite difference method under steady periodic conditions.

5.2.1. Yearly heating and cooling transmission loads

Fig. 5 indicates variation of yearly cooling and heating transmission loads versus insulation thickness for three different insulation positions. It is seen that as the insulation thickness increases, transmission loads decrease. But, this decrease is more rapid at smaller values of insulation thickness. However, it is seen that yearly transmission loads are unaffected by insulation location. Insulation placed at outside, inside and middle of wall (Wall-1, Wall-2 and Wall-3) provides almost equal yearly cooling and heating transmission loads.

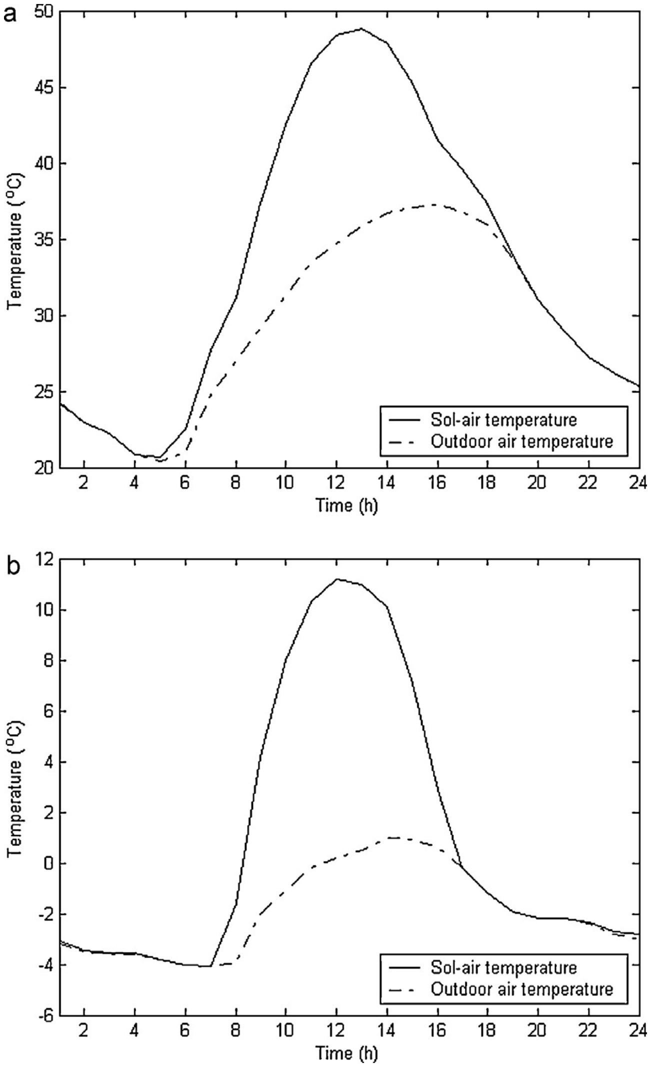

Fig. 4. The variation of the sol-air temperature and outdoor air temperature: (a) for July 15 and (b) for January 15.

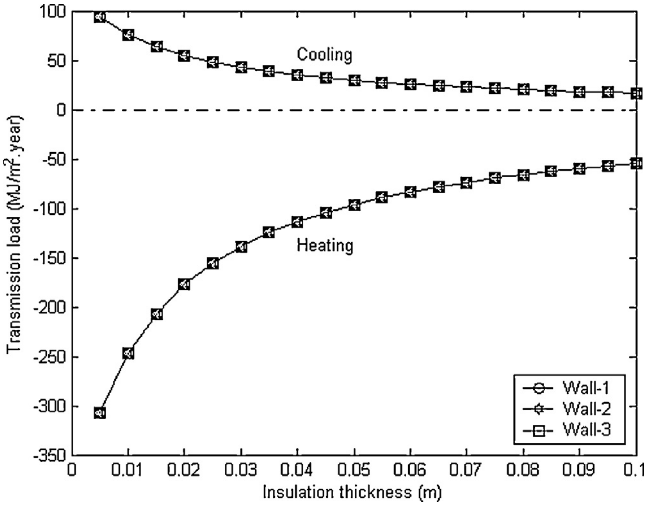

Fig. 5. Variation of yearly cooling and heating transmission loads versus insulation thickness for three different wall structures.

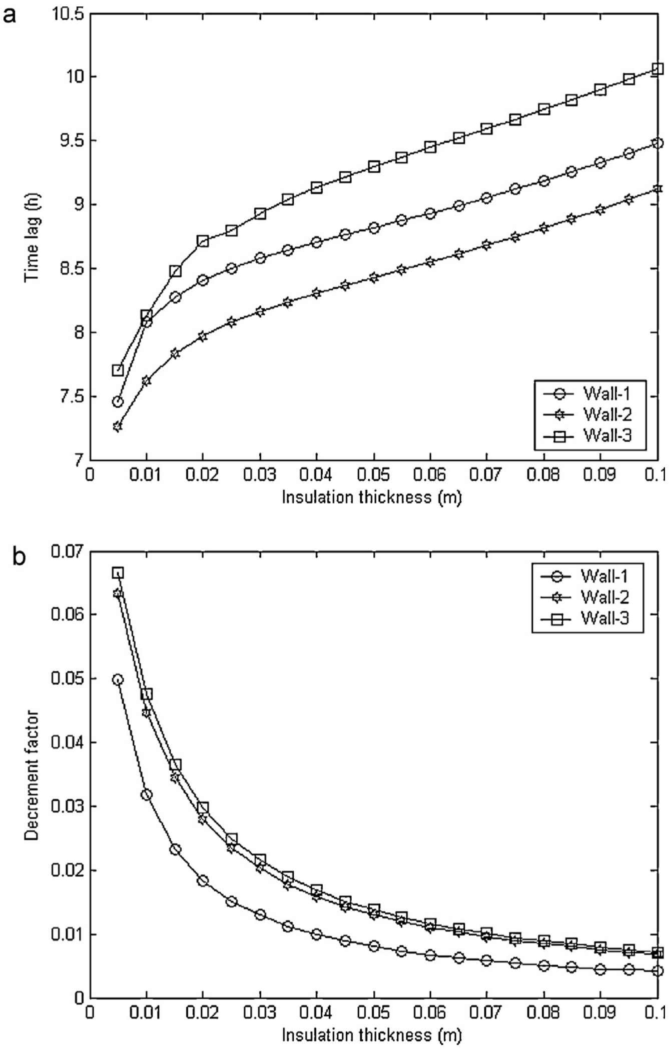

Fig. 6. Variation of yearly averaged time lag and decrement factor versus insulation thickness for three different wall structures.

5.2.2. *Yearly averaged time lag and decrement factor*

Fig. 6 presents variations of yearly averaged time lag and decrement factor with insulation thickness with respect to insulation location. It is seen that as the insulation thickness increases, decrement factor decreases while time lag increases, as expected. Maximum time lag is obtained for Wall-3 while minimum time lag is obtained for Wall-2. Minimum decrement factor is achieved for Wall-1 while maximum decrement factor is achieved for Wall-3. As the insulation thickness increases, values of decrement factor obtained for Wall-2 and Wall-3 become closer.

5.3. *Optimization of insulation thickness*

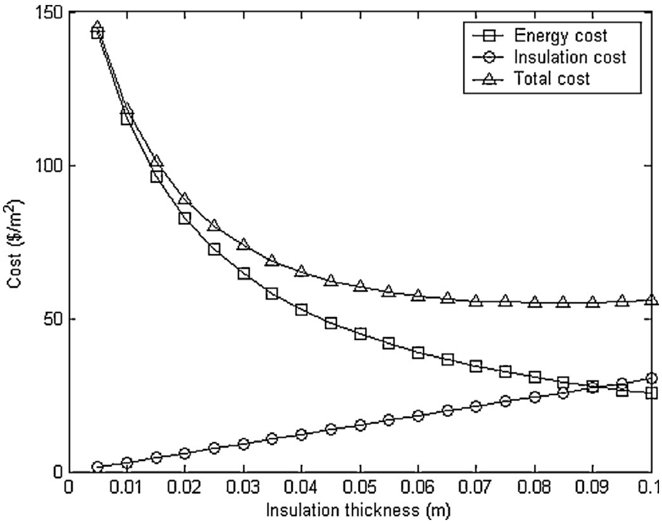

Fig. 7. Variation of cost with insulation thickness for Wall-1 (outside insulation).

Fig. 7 shows variation of cost with insulation thickness for Wall-1. While the energy cost decreases with increasing insulation thickness, the insulation cost increases linearly with insulation thickness. Total cost is sum of insulation and energy cost. The insulation thickness at which the total cost is the minimum is considered as the optimum insulation thickness. It is seen that the optimum insulation thicknesses for three different walls remain the same because transmission loads used as inputs to an economic model stay unaltered regardless of location of insulation. These results are the same with those obtained by Al-Sanea and Zedan [8] in a different climate. The optimum insulation thickness is obtained to be 8.2 cm for investigated insulation positions.

5.4. *Thermal performance of walls under optimal insulation conditions*

The yearly transmission loads, yearly averaged time lag and decrement factor obtained under optimal insulation conditions (at 8.2 cm insulation thickness) are indicated in Table 3. The yearly cooling and heating transmission loads for three different insulation positions are obtained as 19.7 and 64.6 MJ/m^2 yr, respectively. It is seen that the best thermal performance from maximum time lag and minimum decrement factor point of view is obtained for Wall-1 (outside insulation).

Fig. 8 shows peak transmission loads for the representative days of each month with respect to different insulation positions. Maximum of peak cooling transmission load occurs in July while maximum value of peak heating transmission load occurs in January and February for all walls. Wall-1 gives the lowest peak cooling and heating transmission loads for all months.

Fig. 9(a) and (b) shows hourly variation of inside surface heat flux of three different wall structures under optimal insulation conditions (at 8.2 cm insulation thickness) for July 15 and January 15, respectively. It is seen that the maximum heat flux swings and peak load in both summer and winter occur for Wall-3 while Wall-1 gives the smallest fluctuation.

Temperature distributions across wall thickness at different times with an interval of 3 h in July 15 are shown in Fig. 10(a)–(c) for three different walls. It is noted that temperature fluctuations on the outside surfaces of walls are fairly high. The insulation layer causes a substantial temperature drop across its thickness. As expected, the steepest change in temperature occurs in the insulation layer. It is seen that the greatest temperature drop and

Table 3
The yearly cooling and heating transmission loads, yearly averaged time lag and decrement factor obtained under optimal insulation conditions for three different insulation positions.

Wall structures	Optimum insulation thickness (m)	Cooling load	Heating load (MJ/m^2 yr)	Time lag (h)	Decrement factor
Wall-1	0.082	19.76	64.64	9.21	0.0050
Wall-2	0.082	19.77	64.66	8.84	0.0082
Wall-3	0.082	19.77	64.66	9.77	0.0087

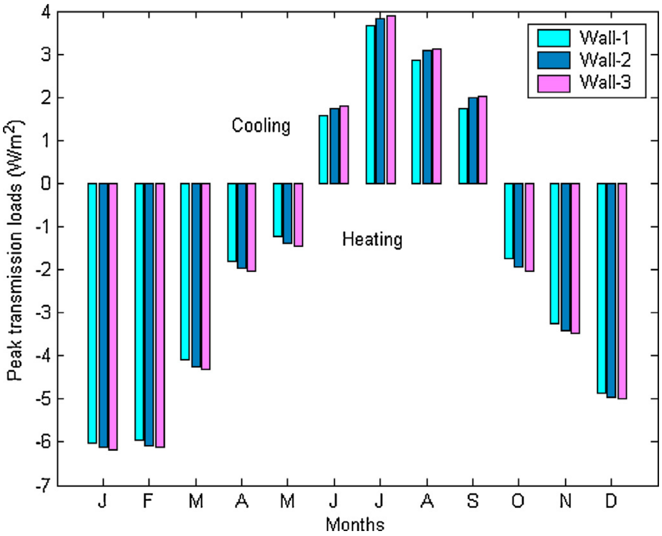

Fig. 8. Peak cooling and heating transmission loads for the representative days of each month with respect to three different wall structures under optimal insulation conditions.

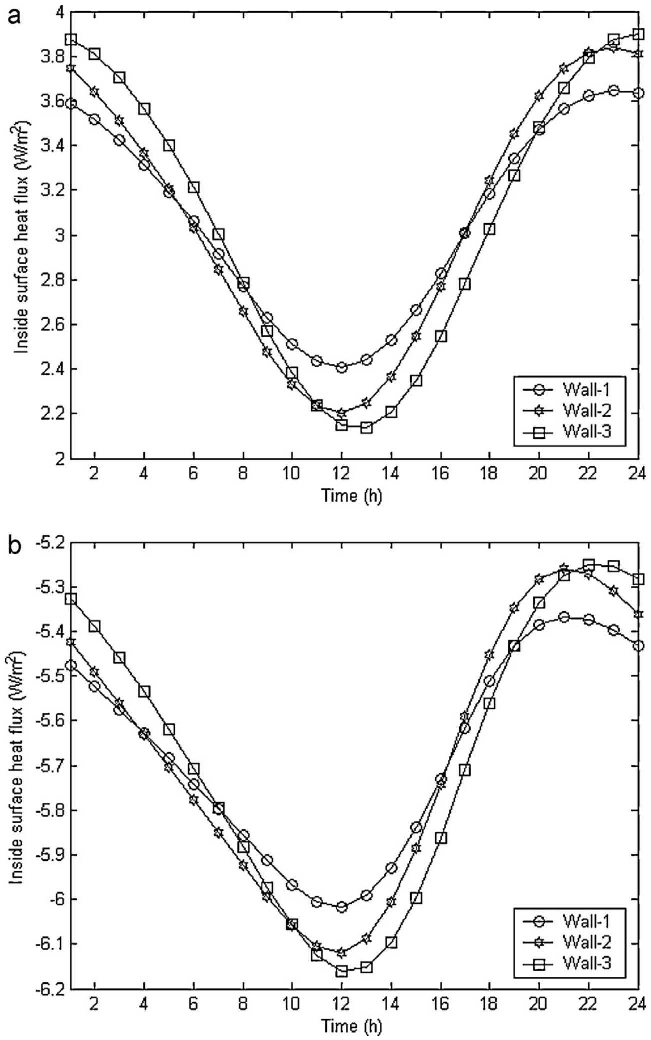

Fig. 9. Hourly variation of inside surface heat flux of three different wall structures under optimal insulation conditions: (a) for July 15 and (b) for January 15.

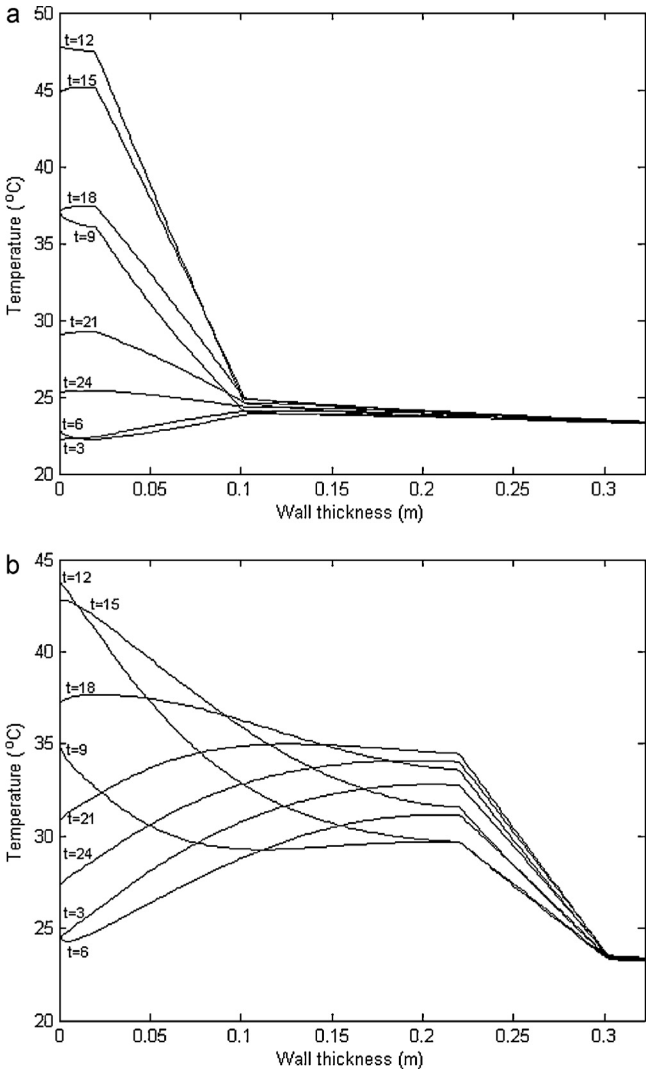

Fig. 10. Temperature distribution across the wall thickness at different times of the day under optimal insulation conditions in July 15: (a) for Wall-1 (outside insulation), (b) for Wall-2 (inside insulation) and (c) for Wall-3 (middle insulation).

minimum temperature fluctuations at the inner surface of wall occur when insulation is placed on the outside surface (Wall-1). The wall with inside insulation leads to smaller temperature fluctuations compared to insulation in the middle of the wall.

6. Conclusion

This study deals with the effect of insulation location on the heat transfer characteristics of building walls and optimization of insulation thickness. 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 wall. Firstly, thermal characteristics such as yearly cooling and heating transmission loads, yearly averaged time lag and decrement factor are determined using an implicit finite difference method under steady periodic conditions for three different insulation positions. Results show that yearly transmission loads are unaffected by insulation location, whereas insulation location has a significant effect on the yearly averaged time lag and decrement factor.

Secondly, insulation thickness is optimized by using a cost analysis over lifetime of 20 years of the building. The optimum insulation thickness is found to be 8.2 cm for three different insulation positions. It is seen that optimum insulation thickness is unaffected by insulation location as previously found in [8] under different climatic conditions.

Finally, thermal performances of three different wall structures are compared using optimum insulation thickness. The maximum temperature swings and peak load occur in the case that insulation is placed at middle of wall while outside insulation gives the smallest fluctuation. Results show that the best thermal performance is obtained when insulation is placed at outside of wall.

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