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EFFECTS OF WALL ORIENTATION AND THERMAL INSULATION ON TIME LAG AND DECREMENT FACTOR

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ABSTRACT

In this study, effect of wall orientation on time lag and decrement factor is investigated numerically using an implicit finite difference method under steady periodic conditions. The investigation is carried out for three different insulation materials in the climatic conditions of Istanbul, Turkey. For this purpose, the outside surface of the wall is exposed to periodic solar radiation and outdoor environmental temperature. The inside surface is exposed to room air maintained at constant indoor design temperature. The insulation is placed at outside of wall. It is seen that as expected, as the insulation thickness increases, decrement factor decreases while time lag increases. Results show that wall orientation has a great effect on time lag while it has a small effect on decrement factor. It is seen that maximum time lag and minimum decrement factor are obtained in an east oriented wall.

INTRODUCTION

Building energy requirement for the winter and summer seasons constitutes loss or gain through windows, walls, roofs, infiltration and equipment. In many buildings, walls and roofs have very significant fraction of heat gains for the heating or cooling loads. Accurate determination of the heat gain through the walls and roofs of a building is very important in order to select a suitable air conditioning system for the efficient utilization of energy [1].

Climatisation of buildings could be managed by passive and active solar systems. Active systems need heat transfer and store fluids, control and transfer elements in order to collect and store solar energy [2]. In passive systems, building walls are used as thermal storage elements, and energy stored in the walls during the day can be used for heating the building at night. Further, a decrease in the indoor temperatures can be reduced when the heating system is switched off [3, 4]. There are two parameters to evaluate the thermal performance of the wall, which are the time lag and the decrement factor, respectively. The time it takes for the temperature wave to propagate from the outer surface to the inner surface is named as time lag and the decreasing ratio of its temperature amplitude is named as decrement factor. In general, if the time lag of the wall is high and the decrement factor of the wall is low, the fluctuation of the indoor air temperature will be small, and the thermal comfort of the room will be enhanced [5].

NOMENCLATURE

a	**[-]**	solar absorptivity of outdoor surface of wall
c	[J/kg K]	specific heat
h	[W/m^{2}K]	heat transfer coefficient
I_T	[W/m^2]	incident total solar radiation for vertical surfaces
I_b	[W/m^2]	beam solar radiations on the horizontal surface
I_d	[W/m^2]	diffuse solar radiations on the horizontal surface
I	[W/m^2]	total solar radiations on the horizontal surface
k	[W/m K]	thermal conductivity
q_i	[W/m^2]	heat flux at indoor surface of the wall
t	[s]	time
T	[^{o}C]	temperature

Special characters

a	[m^2/s]	thermal diffusivity
d	[deg.]	declination angle
f	[deg.]	latitude
Φ	[h]	time lag
F	**[-]**	decrement factor
g	[deg.]	surface azimuth angle
w	[deg.]	hour angle
ρ	[kg/m^3]	density

Subscripts

i	inside
j	Layer number
max	maximum
min	minimum
o	outside
$x=L$	indoor surface
$x=o$	outdoor surface

Asan [6] investigated the optimum insulation position for six different configurations from maximum time lag and minimum decrement factor point of view. Ozel and Pihtili [7] investigated optimum location and distribution of insulation layers point of view maximum time lag and minimum decrement factor for various wall orientations. Yumrutaş et al. [8] developed a theoretical methodology to find total equivalent temperature difference values based on time lag and decrement factor. For this purpose, one-dimensional transient heat transfer problem for multilayer flat roofs and walls of buildings was solved by complex finite Fourier transform (CFFT) technique. Konteleon and Bikas [9] 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. Al-Sanea et al. [10] investigated effects of thermal mass on transmission loads, energy storage rate, dynamic thermal resistance, time lag, and decrement factor in building walls for same nominal resistance value. In another study, 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 [11].

In literature, studies dealing with effect of wall orientation on them are in a limited number although there are many studies related to time lag and decrement factor. In this study, effect of wall orientation and thermal insulation on time lag and decrement factor is investigated numerically for three different insulation materials under climatic conditions of Istanbul, Turkey. The results are compared with similar studies under different climatic conditions and different insulation materials

MATHEMATICAL FORMULATION AND CALCULATION PROCEDURE

A composite wall structure consisting of 2 cm external plaster, insulation material, 20 cm brick block and 2 cm internal plaster is shown schematically in Figure 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.

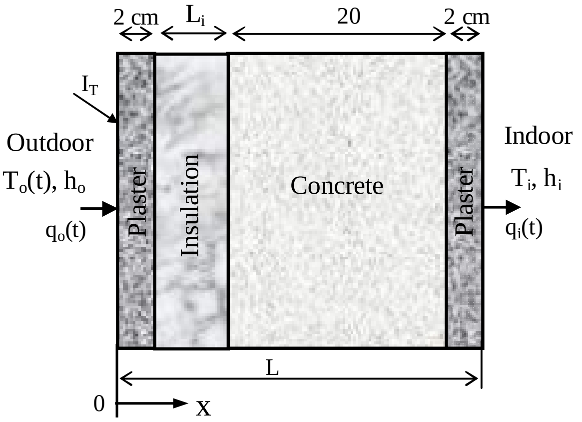


Figure 1 Composite wall structure

The transient one-dimensional heat conduction equation through the composite wall may be written as:

$$\frac{\partial^2 T_j}{\partial x^2} = \frac{1}{\alpha_j}\frac{\partial T_j}{\partial t} \qquad (1)$$

where $\alpha_j (= k_j/(\rho_j c_j))$ is the thermal diffusivity of the *j*th layer. ρ_j, c_j , k_j and T_j are the density, the specific heat, the thermal conductivity and the temperature of the *j*th layer, respectively.

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

$$-k_p\left(\frac{\partial T}{\partial x}\right)_{x=0} = h_0(T_e(t) - T_{x=0}) \qquad (2)$$

$$-k_p\left(\frac{\partial T}{\partial x}\right)_{x=L} = h_i(T_{x=L} - T_i) \qquad (3)$$

where h_o and h_i are the combined (convective and radiative) heat-transfer coefficients at the outdoor and the indoor wall surfaces, respectively. k_p is thermal conductivity of plaster. 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 [12]:

$$T_e = T_o + \frac{\alpha\, I_T}{h_o} \qquad (4)$$

where T_o is the outdoor air temperature. I_T and α denote the total solar radiation and solar absorbtivity of the outdoor wall surface, respectively. The total solar radiation (I_T) for vertical surfaces is calculated as:

$$I_T = R_b\, I_b + (I_d + I\, \rho_g)/2 \qquad (5)$$

Where I_b, I_d and I are beam, diffuse and total solar radiations on the horizontal surface. ρ_g is ground reflectance. 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 for vertical walls surfaces is calculated as:

$$R_b = \frac{\cos\delta \sin\phi \cos\gamma \cos\omega + \cos\delta \sin\gamma \sin\omega - \sin\delta \cos\phi \cos\gamma}{\cos\phi \cos\delta \cos\omega + \sin\phi \sin\delta} \qquad (6)$$

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. $-180^o < \gamma < +180^o$. Detailed calculation procedures are given by Duffie and Beckman [13].

The transient heat conduction problem has been previously solved by employing implicit finite-difference method, and detailed calculation procedures are given in reference [7]. The numerical solution is carried through a number of cycles until a steady periodic state is fully obtained.

The instantaneous transmission load is calculated from wall inner surface temperature as:

$$q_i = h_i (T_{x=L} - T_i) \tag{7}$$

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 [7]:

$$\Phi = t_{T_{x=L}(\max)} - t_{T_{x=0}(\max)} \tag{8}$$

$$f = \frac{T_{x=L}(\max) - T_{x=L}(\min)}{T_{x=0}(\max) - T_{x=0}(\min)} \tag{9}$$

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.

RESULTS AND DISCUSSION

In this study, effect of wall orientation on time lag and decrement factor is investigated by using an implicit finite difference method for climatic conditions of Istanbul, Turkey. The investigation is carried out for three different insulation materials: Extruded polystyrene (XPS), expanded polystyrene (EPS) and glass wool. The thickness of insulation is increased from 0.5 cm to 10 cm. Thermal properties of materials used in the wall structure are given in Table 1 [1,8]. Calculations are made for July 21 and, the averages of the hourly outdoor air temperatures recorded in meteorological data over the years 2005-2010 are used in the calculations [14]. The indoor air temperature is taken to be 23 °C. 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 [15]. Figure 2 shows variation of incident solar radiation for all wall orientations in summer. The value of the solar reflectance of ground is taken as 0.2.

Table 1 Thermal properties of materials

Material	Thermal conductivity k (W/m K)	Density ρ (kg/m^3)	Specific heat c (J/kg K)	Heat capacity ρ.c (kJ/ m^{3}K)
Plaster	0.70	2778	840	2333.52
Concrete	1.37	2076	880	1826.88
XPS	0.034	22	1280	28.16
EPS	0.038	18	1500	27.00
Glass wool	0.038	24	700	16.80

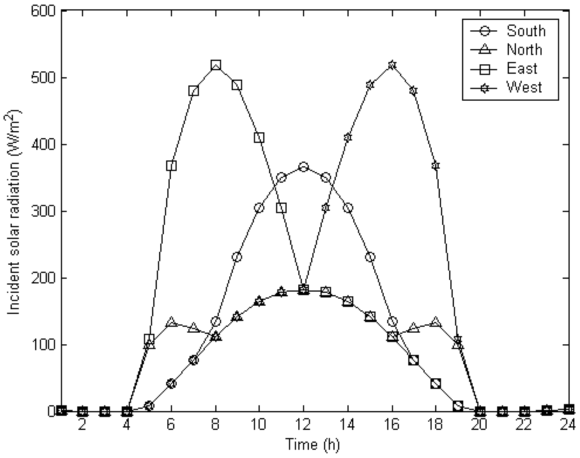
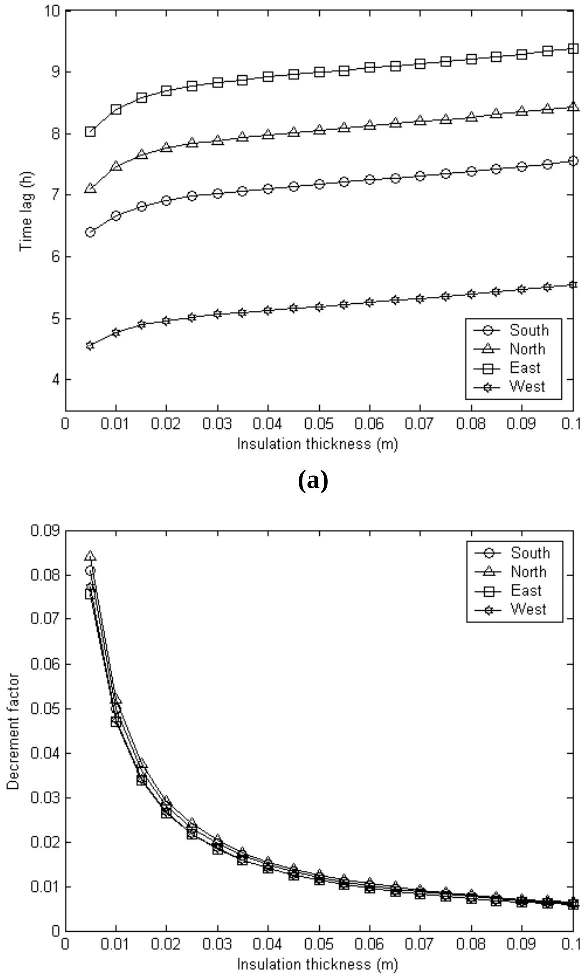


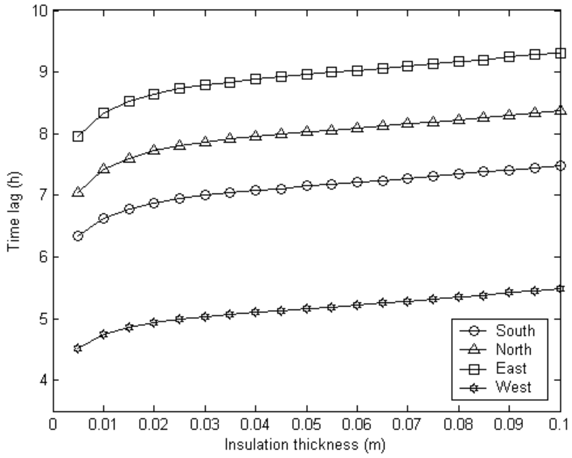
Figure 2 Daily variation of incident solar radiation for July 21 in Istanbul



(a)

(b)

Figure 3 Variation of time lag and decrement factor versus insulation thickness of Extruded polystyrene insulated wall for the all wall orientations in July 21



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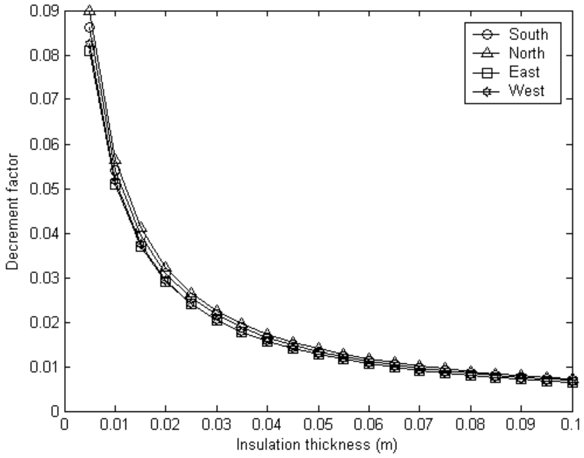
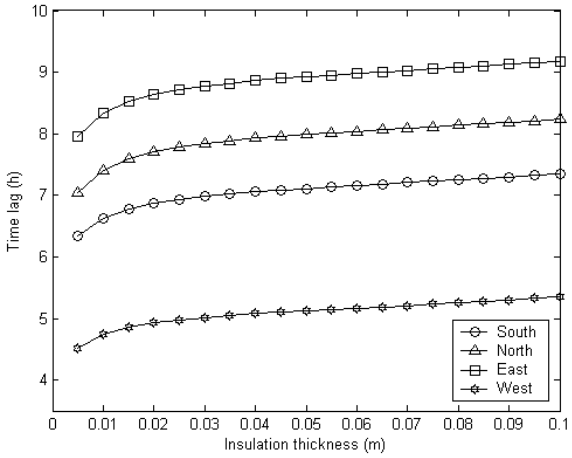


(b)

Figure 4 Variation of time lag and decrement factor versus insulation thickness of Expanded polystyrene insulated wall for the all wall orientations in July 21



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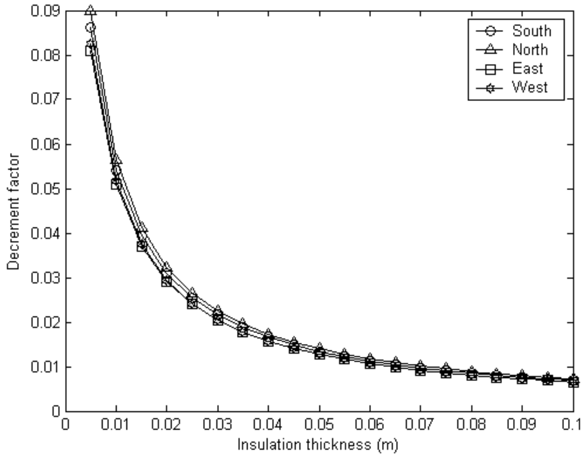
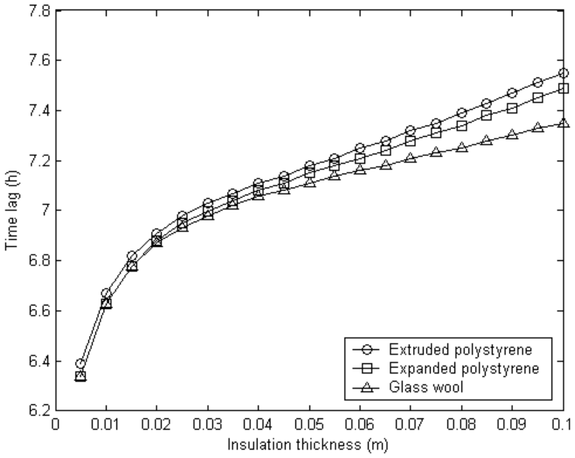


(b)

Figure 5 Variation of time lag and decrement factor versus insulation thickness of Glass wool insulated wall for the all wall orientations in July 21



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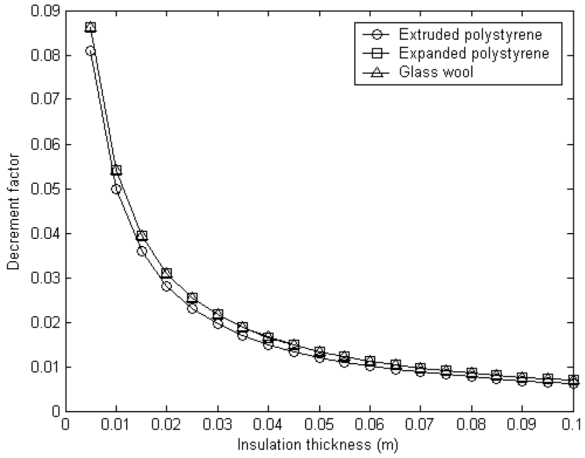

(b)

Figure 6 Variation of time lag and decrement factor versus insulation thickness of a south oriented wall for three different insulation materials in July 21

Figure 3(a) and (b) shows variation of time lag and decrement factor versus insulation thickness of extruded polystyrene insulated wall for the all wall orientations in July 21. The variations of time lag and decrement factor for expanded polystyrene and glass wool are shown in Figure 4 and 5, respectively. It is seen that for three different insulation materials, maximum time lag are obtained for east oriented wall while minimum time lag are obtained for west oriented wall. This conclusion can be supported by incident solar radiation for the all wall orientations in Figure 2. Because of solar radiation, maximum temperature on the outside surface is reached earlier for east wall while it is reached later for west wall compared to the other orientations. The results show that wall orientation has a profound effect on the time lag while it has a small effect on the decrement factor. For example, for 4 cm XPS insulated wall, values of time lag of south, north, east and west oriented walls are obtained as 7.11, 7.98, 8.92 and 5.13 h, respectively. On the other hand, values of decrement factor to these orientations are obtained as 0.0149, 0.0155, 0.0141 and 0.0141. Besides, it is seen that as the insulation thickness increases, the decrement factor decreases while time lag increases. The similar conclusions were obtained by using different climatic conditions and insulation materials [16-18].

Figure 6(a) and (b) shows variation of time lag and decrement factor versus insulation thickness of a south oriented wall for three different insulation materials in July 21. It is seen that maximum time lag and minimum decrement factor occur for XPS insulation material. It is also seen that decrement factors obtained for expanded polystyrene (EPS) and glass wool insulation materials which have the same thermal conductivity are the same. The insulation material which has the highest heat capacity and the lowest thermal conductivity gives maximum time lag. On the other hand, the insulation material which has lowest thermal conductivity gives minimum decrement factor. These results are in harmony with those obtained by references [17-19] under different climatic conditions and different insulation materials.

CONCLUSION

In this study, effect of wall orientation on time lag and decrement factor is investigated numerically for three different insulation materials under climatic conditions of Istanbul, Turkey. Results show that wall orientation has a great effect on time lag while it has a small effect on decrement factor. It is seen that maximum time lag and minimum decrement factor are obtained in an east oriented wall.

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