HEFAT2012
9th International Conference on Heat Transfer, Fluid Mechanics and Thermodynamics
16 – 18 July 2012
Malta

COMPARISON OF THERMAL PERFORMANCE OF DIFFERENT WALL STRUCTURES

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ABSTRACT

This study deals with comparison of thermal performance of six different wall structures for a south-facing wall. Numerical model based on an implicit finite difference method under steady periodic conditions is used to determine of heat transmission loads of multilayer walls. 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. Building walls made of brick, concrete and ytong are performed for uninsulated and insulated wall structures. The investigation is carried out for July 21 and January 21 chosen to represent typical summer and winter conditions in İzmir, Turkey. Expanded polystyrene (EPS) as insulation material is selected. It is seen that the maximum temperature swings in both summer and winter occur for the wall made with concrete while minimum temperature swings occur for ytong wall. Besides, insulated wall significantly reduces peak load and load fluctuations at inside surface, compared with uninsulated wall. Results show that time lag of ytong wall without insulation is obtained as 12.95 h while time lags of brick and concrete walls with 10 cm EPS insulation are obtained as 8.35 h and 7.47 h, respectively. Results also show that peak load of ytong wall without insulation is equal peak load when brick and concrete walls are insulated with EPS at 4.25 cm and 4.75 cm thicknesses, respectively.

INTRODUCTION

Energy consumption is rapidly increasing due to the population increase and urbanization. As a result, energy consumption is one of the most significant problems of the last century and energy resources become more valuable to the modern world. It is estimated that Turkey's population will be over 100 millions by 2020. Turkey's energy consumption has increased by an average of 4.4% in the recent years. According to the planning studies; Turkey's final consumption of primary energy is estimated to be 130 mtoe (million tons of oil equivalent) in 2005, 171 mtoe in 2010, and 298 mtoe in 2020 [1]. Energy consumption in the building sector is one of the main parts of the total energy consumption in most countries. In Turkey, the energy amount used in the residential and commercial buildings is about 30% of total energy. In addition, it is 82% of energy for heating in the buildings [2].

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

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. Of importance too is to provide means to increase time lag and decrease decrement factor through increasing thermal energy storage capability. The latter is usually regulated through thermal mass in the building envelope [3].

The studies that deal with the thermal performance of specific building components, and not the building as a whole, have their own merits. Al-Sanea [4] investigated the evaluation and comparison of the thermal performance of building roof elements using the climatic conditions of Riyadh [4]. Al-Sanea and Zedan [5] 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. Al-Regib and Zubair [6] 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. Asan [7] investigated the optimum insulation position for six different configurations from maximum time lag and minimum decrement factor point of view.

Thermal performance and optimum insulation thickness of building walls constructed of five different structure materials and two different insulation materials were investigated under dynamic thermal conditions [8]. Yumrutaş et al. [9] 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 [10] 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. Insulation location on heating and cooling for six characteristic exterior wall configurations was analysed by Kossecka and Kosny [11]. 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. Bojic and Loveday [12] investigated influence of layer distribution and thickness on the thermal behaviour. 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. 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 [13]. The location of insulation to minimize heat gain and losses in the building walls was analysed for three different climatic locations of Turkey [14].

In this study, thermal performance of six different wall structures is compared for climate conditions of İzmir, Turkey. For this purpose, the numerical method based on an implicit finite difference method which has been previously validated is used to determine peak transmission load, time lag and decrement factor of the building walls made of brick, concrete and ytong.

MATHEMATICAL FORMULATION

A composite wall structure consisting of M parallel layers 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.

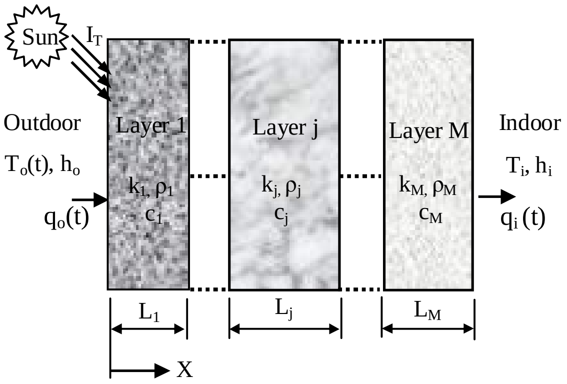


Figure 1 M-layered composite wall

Assuming no heat generation, constant thermal properties and one-dimensional heat transfer, time-dependent heat conduction equation in a multi layer wall may be written as [3]:

$$\frac{\partial^2 T_j}{\partial x^2} = \frac{1}{a_j}\frac{\partial T_j}{\partial t} \tag{1}$$

where $a_j (= k_j /(r_j c_j))$ 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:

$$-k_1\left(\frac{\partial T}{\partial x}\right)_{x=0} = h_0(T_e(t) - T_{x=0}) \tag{2}$$

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

where h_o and h_i are the combined (convective and radiative) heat-transfer coefficients at the outdoor and the indoor wall surfaces, respectively. 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 [15]:

$$T_e = T_o + \frac{a\ I_T}{h_o} - \frac{e\ \Delta R}{h_o} \tag{4}$$

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 0 for vertical surfaces.

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

$$I_T = R_b \; I_b + (I_d + I \;\; r_g)/2 \qquad (5)$$

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 for vertical walls surfaces is calculated as:

$$R_b = \frac{\cos d \, \sin f \, \cos g \, \cos w + \cos d \, \sin g \, \sin w - \sin d \, \cos f \, \cos g}{\cos f \, \cos d \, \cos w + \sin f \, \sin d} \qquad (6)$$

where d , f , w and g are declination angle, latitude angle, hour angle and surface azimuth angle, respectively. g 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. $-180^o < g < +180^o$. Detailed calculation procedures are given by Duffie and Beckman [16].

The transient heat conduction problem has been previously solved by employing implicit finite-difference method, and detailed calculation procedures are given in reference [17]. The numerical solution is carried through a number of cycles until a study periodic state is fully obtained.

The instantaneous heating and cooling transmission loads are calculated from wall inner surface temperature obtained from the solution as:

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

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 [17]:

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

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

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.

THE STRUCTURE OF BUILDING WALLS

To compare the thermal performance of six different wall structures, building walls made of brick, concrete and ytong are performed for uninsulated and insulated wall structures as shown in Figure 2.

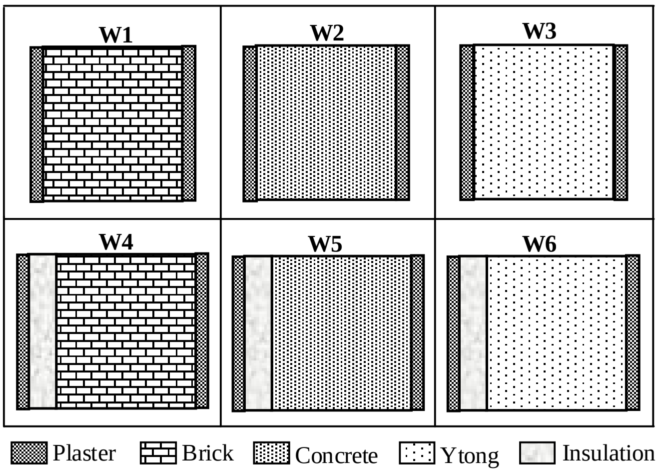


Figure 2 Different wall structures

The thicknesses of brick, concrete and ytong is 20 cm, each one of cement plaster in the interior and exterior surface of walls is 2 cm, and thickness of insulation is increased from 0.5 cm to 10 cm. Expanded polystyrene (EPS) are selected as insulation material. Thermal properties of materials used in the wall structure are given in Table 1.

Table 1 Thermal properties of materials [9]

Material	k (W/m K)	r (kg/m^3)	c (J/kg K)
Brick	0.69	1580	840
Concrete	1.37	2076	880
Ytong	0.15	1580	840
EPS	0.038	18	1500
Plaster	0.70	2778	840

RESULTS AND DISCUSSION

In this study, thermal performance of six different wall structures is investigated numerically by using an implicit finite difference method under steady periodic conditions. The investigation is carried out for a south-facing wall at the climatic conditions of İzmir, Turkey. The investigation is also carried out for July 21 and January 21 chosen to represent typical summer and winter conditions. The averages of the hourly outdoor air temperatures recorded in meteorological data over the years 2005-2010 are used in the calculations [18]. The indoor air temperatures for winter and summer conditions are taken to be 20 and 23 ^{o}C, respectively. 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 [19].

The daily variation of the sol-air temperature for summer and winter conditions is shown in Figure 3. It is seen that the sol-air temperature is maximum at 12:00 in winter while it is maximum at 13:00 in summer.

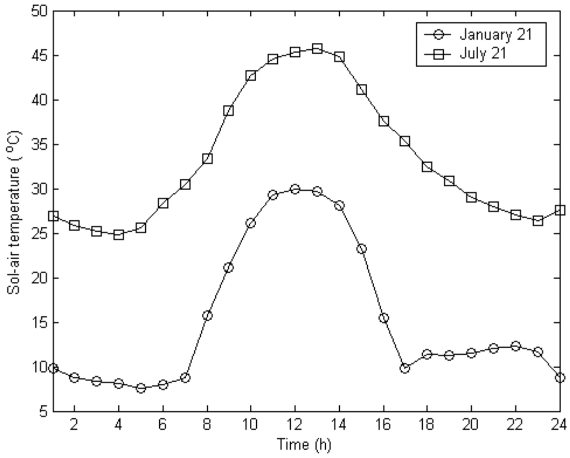
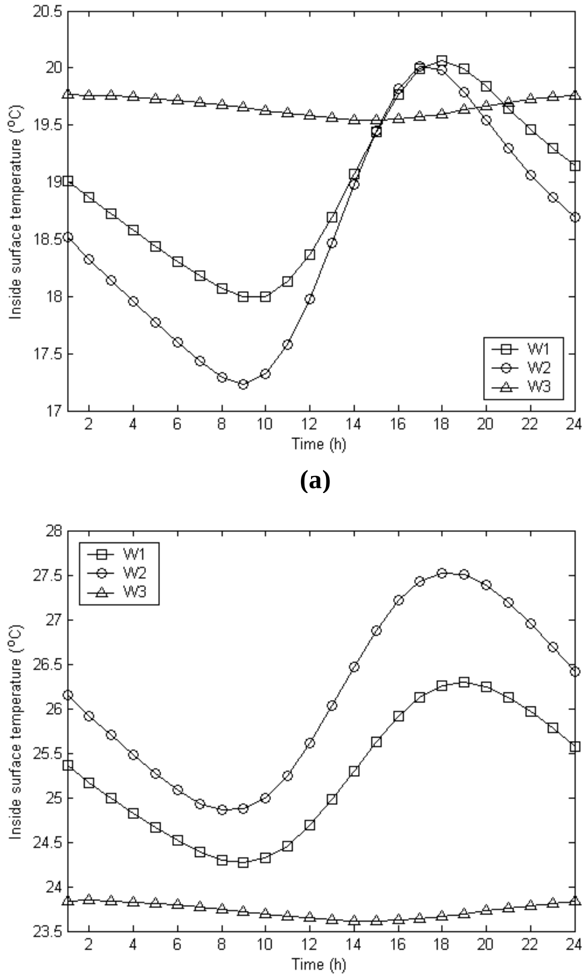


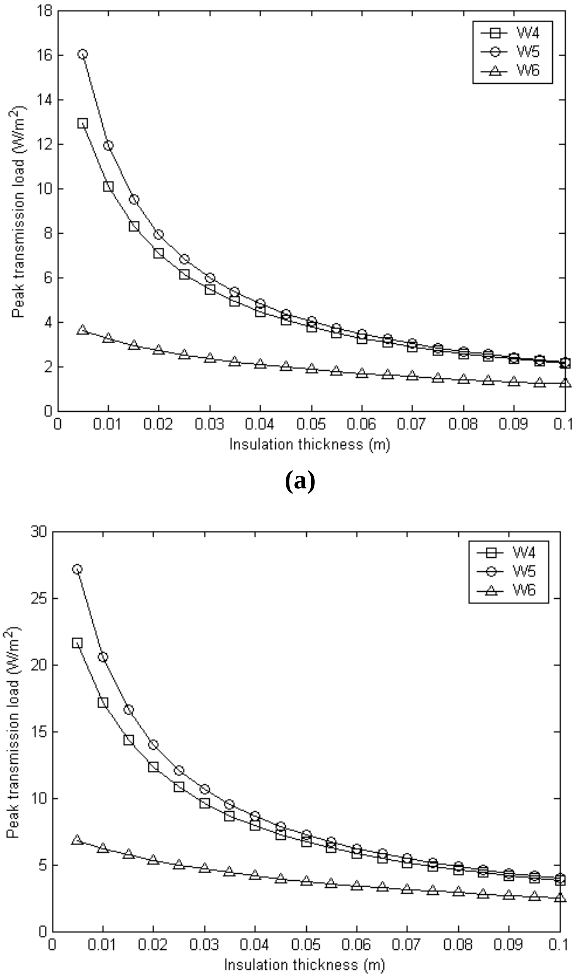
Figure 3 Variation of the sol-air temperature for January 21 for July 21 in İzmir



(a)

(b)

Figure 4 Hourly variation of inside surface temperatures of the uninsulated walls constructed of brick, concrete and ytong: (a) for January 21 (b) for July 21

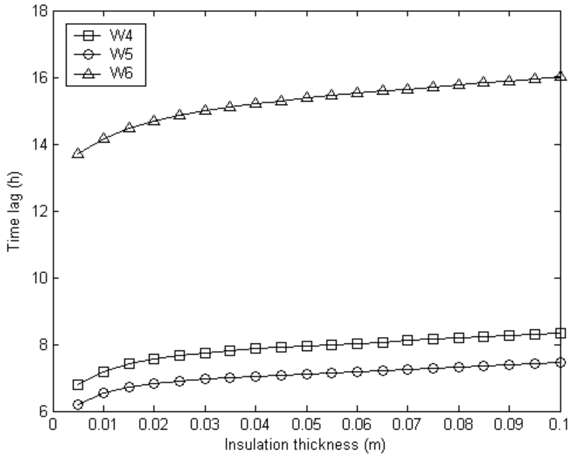


(a)

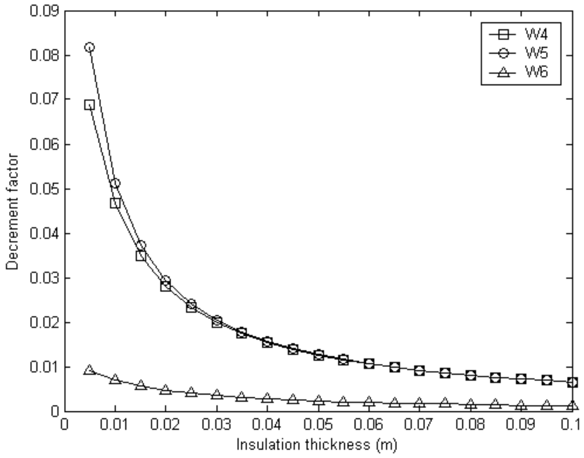
(b)

Figure 5 Variation of peak transmission loads versus insulation thickness of the insulated walls constructed of brick, concrete and ytong: (a) for January 21 (b) for July 21

Figure 4(a) and (b) shows hourly variation of inside surface temperatures of uninsulated walls constructed of brick, concrete and ytong for January 21 and July 21, respectively. It is seen that in both summer and winter, the maximum temperature swings occur for wall W2 constructed of concrete while the minimum temperature swings occur for wall W3 made of ytong. The variation of peak transmission loads versus insulation thickness by applying insulation in three different walls for winter and summer conditions is shown in Figure 5(a) and (b), respectively. As expected, peak transmission loads decrease as the insulation thickness increases. But, this decrease is more rapid at smaller values of insulation thickness. However, it is seen that as the insulation thickness increases, peak loads becomes closer for three wall structures.



(a)



(b)

Figure 6 Variation of time lag and decrement factor versus insulation thickness of the insulated walls constructed of brick, concrete and ytong for July 21

Table 2 Peak load, time lag and decrement factor of uninsulated and 4 cm insulated wall structures in winter and summer conditions

Month	Wall structures	Peak load	Time lag	Decrement factor
21 January	W1	18.13	4.98	0.1201
	W2	24.90	4.37	0.1796
	W3	4.10	12.17	0.0113
	W4	4.45	6.61	0.0154
	W5	4.79	5.73	0.0149
	W6	2.06	14.73	0.0025
21 July	W1	29.62	5.90	0.1241
	W2	40.76	5.29	0.1839
	W3	7.58	12.95	0.0125
	W4	7.91	7.86	0.0154
	W5	8.60	7.04	0.0157
	W6	4.15	15.20	0.0028

Figure 6(a) and (b) shows variation of time lag and decrement factor versus insulation thickness of the insulated walls constructed of brick, concrete and ytong for July 21. As the insulation thickness increases, the decrement factor and peak transmission loads decrease while time lag increases. For 4 cm insulation thickness, this decrement in peak transmission load is 73% for brick, 78% for concrete and 45% for ytong in summer. Besides, as seen in Table 2, for brick, concrete and ytong walls without insulation (W1, W2 and W3) in summer, time lag is obtained as 5.9, 5.29 and 12.95 h while decrement factor is obtained as 0.1241, 0.1839 and 0.0125.

CONCLUSION

This study deals with comparison of thermal performance of different wall structures in the climatic conditions of İzmir, Turkey. The investigation is carried out by using an implicit finite difference method for multilayer walls under steady periodic conditions. For this purpose, a computer program is developed in the Matlab. It is seen that the insulated wall significantly reduces peak load and load fluctuations at inside surface, compared with uninsulated wall. Results show that time lag of ytong wall without insulation is obtained as 12.95 h while time lags of brick and concrete walls with 10 cm EPS insulation are obtained as 8.35 h and 7.47 h, respectively. Results also show that peak load of ytong wall without insulation is equal peak load when brick and concrete walls are insulated with EPS at 4.25 cm and 4.75 cm thicknesses, respectively. In this case, it is seen that the isolation of the brick and concrete is more significant than that of wall with ytong.

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