Thermal performance of the building walls

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Abstract

A building's climatic-response is determined by the prevalent exposure conditions (micro-climate) and the ability of the building envelope to regulate thermal transmittance (building physics). This ability to passively thermo-regulate indoor thermal comfort is determined by the materials configuring the envelope geometry. Various building envelope configurations are feasible depending on available/accessible building resources. In this study, the thermal performance of a building envelope, viz., a masonry wall has been investigated. The theoretical investigation is carried out under steady periodic conditions (occurring in natural building environments). A numerical model based on the implicit Finite Difference Method (FDM) has been developed for the computation of thermal transmittance. Six different wall configurations have been identified based on those typically used in commercial and residential buildings in India. The influences of both material thermal properties and external surface heat-transfer coefficient on the time lag and decrement factor have been investigated. The heat load transmission through the interior wall surface has also been studied. Most studies have arrived at time lag and decrement factor as critical performance measures of a building envelope, but under constant exterior surface heat transfer coefficient considerations. While it has been observed that the heat transfer coefficient does not remain constant, its variation has a bearing on both the time lag and decrement factor, and require careful investigation. The results of the numerical analysis show that decrement factor decreases while exterior heat transfer coefficient increases. Further, the thermal properties, thickness and material assembly are other important factors that determines interior surface instantaneous heat load. Further, it was observed that walls with the higher time lags and lower decrement factors were suited for adoption in tropical regions. The current study attempts to augment existing knowledge of building climatic-response leading to appropriate envelope design-configurations for various climatic zones.

1. Introduction

Buildings are large energy consumers in many countries, and energy demand is growing every day. Energy required in building is mostly towards providing thermal comfort. Energy savings in a building can be achieved by appropriate energy efficient design of building envelopes. Building envelope comprise a configuration of building materials, the thermophysical properties of which determine the climatic response of the envelope. To reduce the energy consumption in buildings, it is necessary to understand the thermal performance of the building envelope on the indoor environment. The two parameters, which evaluate the thermal performance of walls are time lag and decrement factor (Xing Jin, 2012). These are influenced by the external and internal surface temperatures of the wall. In general, higher time lag and lower decrement factor is the preferred thermal performance in tropical regions to minimize energy consumption. The objective of the current study is to carry out thermal performance analysis of building walls attributed to the thermal properties of the construction materials.

2. Previous Studies

Salient studies that are related to the thermal performance of building walls are reviewed in this section. Asan and Sancaktar (1998) found that the thermophysical properties have a profound effect on the time lag and decrement factor, and they computed time lag and decrement factor for different building materials. Asan (2006) found that the thickness and type of the material have a very profound effect on the time lag and decrement factor. Koray Ulgen (2002) investigated the effects of a wall's thermophysical properties on time lag and decrement factor experimentally and theoretically. Kontoleon and Bikas (2007) studied 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; Kontoleon and Eumorfopoulou (2008) studied to determine how time lag and decrement factor are affected by wall orientation and exterior surface solar absorptivity, for specific climatic conditions. Ozel (2012) studied the influence of exterior surface solar absorptivity on thermal characteristics and optimum insulation thickness of building walls, through an implicit finite difference method under steady periodic conditions.

Emad Al-Regib and Syed M. Zubair (1995) studied the transient effect of heat transfer through the walls used for the positioning of insulating materials by employing finite difference method (explicit method) to solve this problem. Asan (1998 and 2000) carried out analysis using finite difference methods (Crank-Nicolson method) for the investigating the insulation thickness and it optimum portion in wall for maximum time lag and minimum decrement factor. Al-Sanea (2000) developed a numerical model based on the finite-volume and implicit procedure developed for the computation of the time-dependent and nonlinear temperature variations through composite layers, and to evaluate thermal performance of building walls. Ozel and Pihtili (2007) carried out finite-difference analysis (implicit method) to determine optimum location and distribution of insulation in a wall. Ozel (2011) determined the thermal performance and optimum insulation thicknesses of building walls using an implicit finite difference method.

Vijayalakshmi et al. (2006) investigated the thermal behaviour of opaque wall materials under the influence of solar energy and analyzed the influence of thermophysical properties of different wall types on the interior environment. Finite difference analysis was carried out and the results compared with the experimental findings.

In this study, the thermal performance of building wall has been investigated numerically. The effects of wall configurations on time lag and decrement factor, interior surface instantaneous heat load and the influence of exterior surface heat transfer coefficient on the time lag and decrement factors has been studied.

3. Time lag and decrement factor

Time lag and decrement factors are very important thermal performance characteristics that influence the heat storage capabilities of any materials. These can be obtained based on the materials' thermophysical properties (Asan, 1998).

Time lag (Φ) is the time difference between the temperature maximum at the outside and inside when subjected to periodic conditions of heat flow (IS 3792-1978), and a decrement factor is the ratio of the maximum outside and inside surface temperature amplitudes (Koenigsberger, 1973). The schematic of time lag and decrement factor is shown in Figure 1.

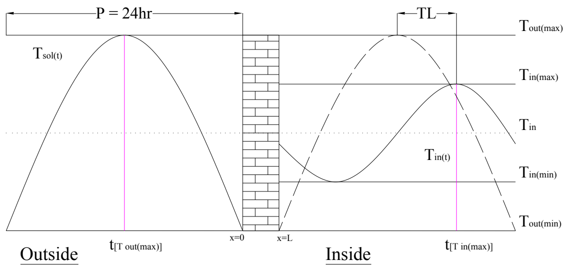

Fig. 1 – The schematic representation of time lag and decrement factor

$$\Phi = t_{[T_{in}(\max)]} - t_{[T_{out}(\max)]} \quad (1)$$

where, $t_{[Tin\ (max)]}$ and $t_{[Tout\ (max)]}$ are the time of day when the inside and outside surface temperatures reach maximum.

$$DF = \frac{T_{in(\max)} - T_{in(\min)}}{T_{out(\max)} - T_{out(\min)}} \quad (2)$$

where, $T_{in\ (max)}$ and $T_{in\ (min)}$ are the maximum and minimum inside surface temperatures, $T_{out\ (max)}$ and $T_{out\ (min)}$ are the maximum and minimum outside surface temperatures.

4. Methods

The heat transfer through the walls is assumed one-dimensional. Figure 2 shows the schematic representation of heat transfer through the wall. Some of the wall sections consist of a number of layers with different thicknesses and thermal properties. The outside surface is exposed and subjected to the sol-air temperature. The inside wall surface is in contact with constant room air temperature. The sol-air temperature includes the combined effect of the outside temperature and solar radiation. The sol-air temperature is assumed to show sinusoidal variations during a 24-hour period.

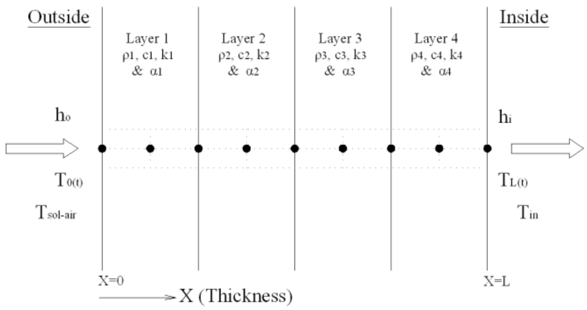

Fig. 2 – The schematic representation of heat transfer through the wall

The general governing one dimensional transient heat conduction equation is as follows:

$$k\frac{\partial^2 T}{\partial x^2} = \rho cp\frac{\partial T}{\partial t} \qquad (3)$$

where, k is the thermal conductivity, ρ is the density and Cp is the specific heat capacity at constant pressure of the building wall materials.

To solve equation (3), it is necessary to specify two boundary conditions and one initial condition. Convection boundary conditions on both the inside and outside surface of a wall are present. The boundary condition at the inside surface is

$$k\left(\frac{\partial T}{\partial x}\right)_{x=0} = h_i[T_{x=0}(t) - Ti] \qquad (4)$$

where, h_i is the inside surface heat transfer coefficient, for still air $h_{conv,in}$ = 9.36 $Wm^{-2}K^{-1}$ is considered in the study, as per Indian standard 3792-1978.

Similarly, the boundary condition at the outside surface can be written as

$$k\left(\frac{\partial T}{\partial x}\right)_{x=L} = h_o[T_{sa}(t) - T_{x=L}(t)] \qquad (5)$$

where, h_0 is the outside surface convective heat transfer coefficient. Ito et al. (1972) obtained h_o for an actual building as a function of wind speed (v) and direction as h_o = 18.63 $V^{0.605}$ in $Wm^{-2}K^{-1}$ (for the windward surface)

where, $V = \begin{cases} 0.25v & \text{for } v > 2m/s \\ 0.50v & \text{for } v < 2m/s \end{cases}$

In this study the outside surface heat transfer coefficient is considered for the various wind speeds from 1 to 10 m/sec.

h_i is the wall inside surface heat transfer coefficient, h_o is the wall outside surface heat transfer coefficient, T_x=0 is the wall inside surface temperature, T_x=L is the wall outside surface temperature and $T_{sol}(t)$ is the sol-air temperature (sol-air temperature).

The equation for sol-air temperature is taken as follows (*Asan, 1998*):

$$t_{sa}(\tau) = \frac{t_{max} - t_{min}}{2}\sin\left(\frac{2\pi\tau}{P} - \frac{\pi}{2}\right) + \frac{t_{max} - t_{min}}{2} + t_{min} \quad (6)$$

where, P is duration (24hrs), T_{max} and T_{min} are the maximum and minimum outdoor temperature, respectively.

Figure 3 illustrates the profile of this sol-air temperature and the one which was obtained from real climatological data by Threlkeld (1970) is presented. As seen from Figure 3, Eq. (4) has been found to be a very reasonable choice for sol-air temperature and also adopted by Asan (1998, 1998, 2000, 2006) and Xing Jin (2012).

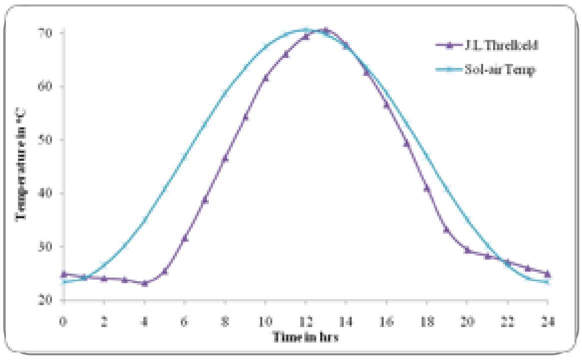

Fig. 3 – Comparison of sol-air temperatures

In this computation, indoor temperature T_{in} is taken to be constant (T_{in} = 25°C), T_{max} = 36.6°C, T_{min}=13°C, h_i=9.36 W/m²K, as per IS 3792–1978, for inside surface heat transfer coefficient at still air.
As an initial condition, assuming the temperature distribution across the wall is constant at the beginning, so the initial condition is

$$T_{x\,(t=0)} = 25^oC \quad (7)$$

5. Numerical solution procedure

The one dimensional transient heat transfer problem is solved by the Finite Difference Method (FDM) using implicit method (backward difference). Although the implicit method needs more time to calculate, the advantage of this method has no limitation on time interval and is stable. The finite-difference equations systems are solved by using program in M.S Excel. The sol-air temperature is repeated on successive days until a steady periodic solution is obtained. The finite difference equations are derived for inside and outside surface boundary nodes, interior nodes and interface nodes between two layers as shown in figure 2 and solved.
The temperature distribution across the wall section is obtained under different outside surface heat transfer coefficients. The outside side heat transfer coefficient is influenced by the wind velocity and direction, surface shape and roughness and, temperature difference between surface and air (Cole and Sturrock, 1977). The heat flux taking place during the 24h period on the inside surface of the wall is calculated by the following equations:

$$q_i = h_i(T_{in}(t) - T_{in}) \quad (8)$$

6. Building wall configurations and thermal properties

The wall structures investigated are shown schematically in Figures 4 to 9. These wall structures are commonly used in India. Thermal properties of materials used in the wall structures are given in Table 3. Fundamental thermo-physical properties are thermal conductivity, density and specific heat capacity. Derived thermal properties are thermal diffusivity, thermal inertia & thermal mass.
Thermal diffusivity is a measure of the rate at which a temperature propagates from one point to another point in a material. Thermal inertia is the degree of slowness with which the temperature of a body approaches that of its surroundings and which is dependent upon its absorptivity, its specific heat, thermal conductivity, dimensions and other factors.

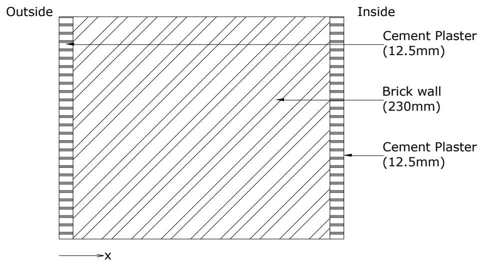

Fig.4 – Schematic of wall configuration *W1*

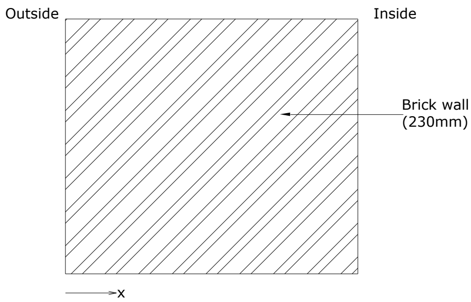

Fig.5 – Schematic of wall configuration W2

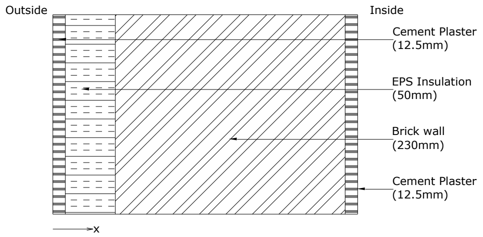

Fig.6 – Schematic of wall configuration W3

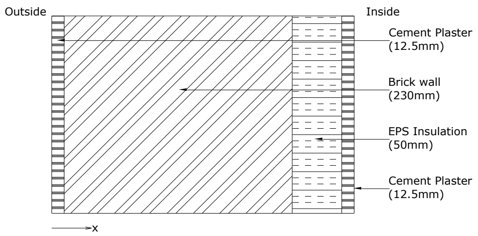

Fig.7 – Schematic of wall configuration W4

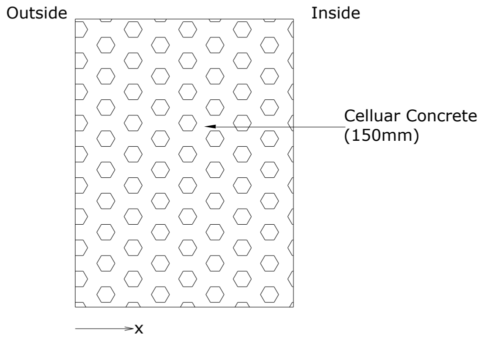

Fig.8 – Schematic of wall configuration W5

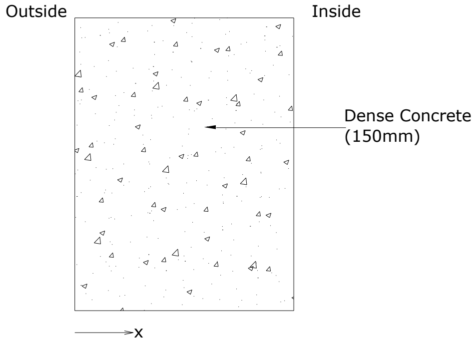

Fig.9 – Schematic of wall configuration W6

Material	k* (W/m K)	ϱ* (kg/m³)	Cp* (J/kg K)	α (x 10^{-7}) (m^2/s)	Thermal mass C (kJ/K m^2) (= ϱ Cp) (x 10^6)	Thermal inertia (k ϱ Cp)$^{1/2}$ (J m^{-2} K^{-1} $S^{-1/2}$)
Cement plastering	0.721	1762	840	4.87	1.480	1033.02
Brick wall	0.811	1820	880	5.06	1.601	1139.69
EPS insulation	0.035	24	1340	10.8	0.032	33.55
Cellular concrete	0.188	704	1050	2.54	0.739	372.78
Dense concrete	1.740	2410	880	8.20	2.120	1920.98

Table 1: – Thermal properties of wall building materials (Source: Indian Standard 3792-1978)

7. Results and discussions

Figure 10 groups the building materials based on thermal conductivity as low thermal conductivity materials such as Expanded Polystyrene (EPS) insulation and cellular concrete, and moderate thermal conductivity materials such as cement plastering, brick wall, and dense concrete walls have been adopted for the study.

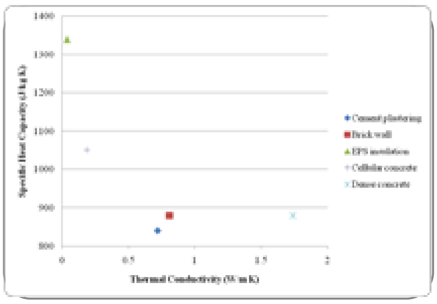

Fig. 10 – Specific heat capacity – thermal conductivity of building materials (compiled from Indian Standard 3792-1978)

8. Effects of wall configuration on time lag and decrement factor

The thermal performance of various walls configurations are tabulated in Table 2. The heat flow through the material is combined influence of the heat storing capacity and thermal resistance characteristics of the wall elements, which controls and regulates the indoor temperature conditions. The amount of heat stored in the wall depends largely on the thermal mass (volumetric heat capacity) of the material. The higher the thermal mass, the more heat it can store and the less heat will be transmitted on to the inside surface of wall (*van Straaten, 1967*).

The building envelope configuration and its thermophysical properties such as heat capacity and thermal diffusivity of the building wall material affect the time lag and decrement factor. Building walls with lower thermal transmittance (U) value has better capability to reduce indoor surface temperature variations. Thermal transmittance (U) is a measure of the rate of heat loss of building component; it is expressed as $Wm^{-2}K^{-1}$.

From Table 2 it can be seen that the lower the value of thermal transmittance (U), the higher the time lag will be and the decrement factor is also reduced. Most of the studies show, to delay the temperature fluctuation on the inside surface compared with outside surface, and to reduce the inside temperature fluctuation amplitude. The walls should have a higher time lag and lower decrement factor, because it is required to maintain inside temperature fairly at constant temperature.

To achieve better thermal performance of the walls, it is desirable to combine different wall layers of materials having different thermophysical properties (*Koray Ulgen, 2002), (Vijayalakshmi, 2006*).

SI No.	Description of walls (from outside to inside)	Identification	U ($Wm^{-2}K^{-1}$)	R (m^2KW^{-1})	Time lag (hrs)	Decrement Factor
1	12.5mm CP + 230mm BW + 12.5mm CP	W1	2.09	0.478	7.262	0.174
2	230mm BW	W2	2.25	0.444	5.912	0.157
3	12.5mm CP + 50mm EPS + 230 BW + 12.5mm CP	W3	0.52	1.923	12.275	0.009
4	12.5mm CP + 230 BW + 50mm EPS + 12.5mm CP	W4	0.52	1.923	8.375	0.016
5	150mm Cellular concrete	W5	1.04	0.961	4.837	0.104
6	150mm Dense concrete	W6	3.63	0.275	2.512	0.488

Table 2: Thermal performance of various walls (Note: Outside surface heat transfer coefficient, ho = 18.63 $Wm^{-2}K^{-1}$ - Inside surface heat transfer coefficient, hi = 9.36 $Wm^{-2}K^{-1}$)

9. Effect of wall configuration on instantaneous transmission load

Figure 11 shows the variation of the inside surface heat fluxes with time for all six types of walls. The analysis is carried out for heat transfer coefficient values of h_o = 18.63 $Wm^{-2}K^{-1}$ and h_i = 9.36 $Wm^{-2}K^{-1}$. In the figure positive values indicate heat gain and negative values indicate heat loss through the wall from inside surface.

Figure 11 shows the variation of the inside surface heat fluxes with time for all six type of walls. The peak heat flux is obtained as 15.97, 11.81, -11.76, 2.17, 28.78 and 31.93 Wm^{-2} for W1, W2, W3, W4, W5 and W6 respectively. Results shows that the maximum peak loads occur for the wall made with W1, W2, W5 and W6.

Besides, it is seen that the highest heat gain and loss are obtained for the W6 (dense concrete) wall which has the highest thermal conductivity, while the lowest heat gain and loss are obtained for the W3 and W4 walls which has the highest thermal

resistivity. Similar kinds of conclusions were drawn by Ozel (2011) using the theoretical models.
The heat grained by the walls is stored inside the various layers of the structure and then dissipated to the inside. This has a great advantage in reducing the rate of heat flux transmission into the indoor environment as indicated in figure 11 for W3 and W4 walls by relatively small inside-surface heat flux.
In this study, it is clearly understood the importance of the materials' thermal properties and building envelope configuration, which significantly vary the dynamics of heat transfer through the building envelope. Significant improvement in the rate of heat loss/gain in the building can be achieved through multi-layered W3 and W4 wall types.

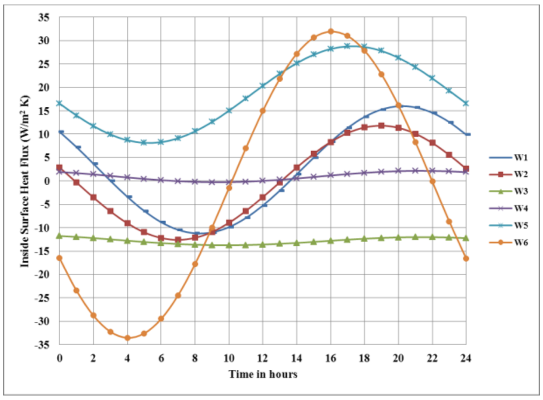

Fig. 11 – Variation of the inside surface heat fluxes with time for all walls

10. Effects of outside surface heat transfer coefficient on time lag and decrement factor

The higher the rate of air movement across a surface, the higher the rate of heat transfer will be and consequently the higher the surface coefficient. The outside surface convective boundary condition is a function of heat transfer coefficient (h_o) (Cole and Sturrock, 1977). The analysis of wall thermal performance is carried out under various wind speeds to study the effects of h_o on time lag and decrement factor.
The contribution of the convective heat transfer component at the outside surface shows a more complicated pattern; however, it has in general an adverse effect on the indoor cooling/ heating loads (*Sami A. Al-Sanea, 2000*). These loads depend on the rate of heat transfer through the walls from the outside surface to inside surface. The rate of heat flow through the wall depends on thermal inertia of wall materials which depend on the material density (characteristic porosity), specific heat and thermal conductivity. Higher the thermal inertia of material; higher will be the heat flow rate through wall and also effects on the time lag and decrement factor.
Figures 12 and 13 show the variation of time lag and decrement factor with varying h_o for all six types of walls. It can be clearly seen from Figures 12 and 13 that there is not much influence/variation in the time lag and decrement factor under various outside surface convective heat transfer coefficient (h_o) conditions. The influence of surface heat transfer coefficient is negligible on the time lag and decrement factors. These mainly depend on the specific heat capacity and thermal diffusivity of the building materials and not on the surface heat transfer coefficient. From figure 13, W6 wall show a decreasing trend in the decrement factor as heat transfer coefficient increases. Due to the higher heat transfer coefficient and thermal inertia there will be a moderation in the temperature amplitude between outdoor and indoor temperature.
Thermal inertia of materials plays a major role in regulating the heat transfer from outdoor to indoor environment and vice-versa. These will influence time lag and decrement factor of building material.

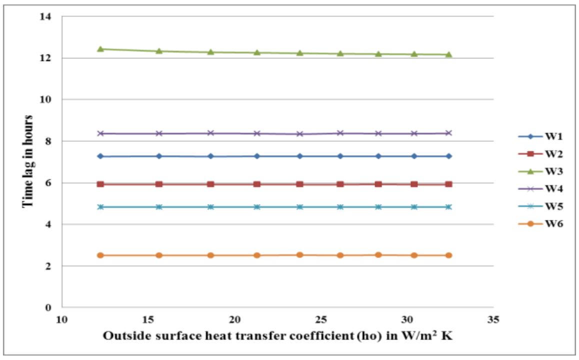

Fig. 12 – The variation of time lag with varying ho for walls

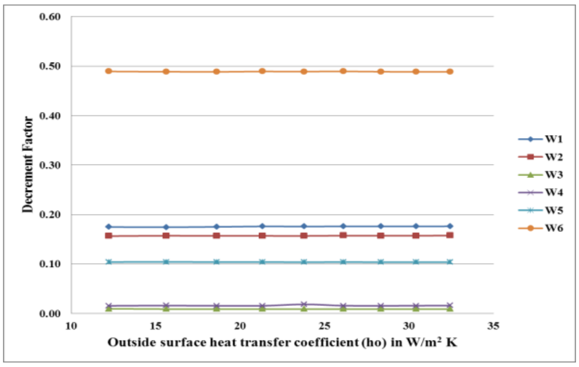

Fig. 13 – The variation of decrement factor with varying h_o for walls

11.Conclusions

This study reveals the importance of the building wall configuration. To achieve a better thermal performance of the walls, it is desirable to have a multi-layered wall comprising materials of different thermophysical properties. It was found that different wall configurations have a strong effect on time lag and decrement factor. The inside surface heat flux in a building wall also depends on the wall configuration, its corresponding thermal transmittance and heat storage capacity. Further, from the results it can be concluded that the materials having higher thermal inertia when subjected to higher surface heat transfer coefficients, lower the decrement factor. The results obtained are useful for designing appropriate building envelope configurations for passive solar building.

12.Nomenclature

Symbols

k	Thermal Conductivity ($Wm^{-1}K^{-1}$)
ϱ	Density (kgm^{-3})
Cp	Specific heat capacity ($Jkg^{-1}K^{-1}$)
t	Time (sec)
T	Temperature (°C)
h	Heat transfer coefficient ($Wm^{-2}K^{-1}$)
v	Wind velocity / wind speed
α	Thermal diffusivity (m^2s^{-1})
C	Thermal mass ($kJK^{-1}m^{-2}$)
U	Thermal transmittance ($Wm^{-2} K^{-1}$)
R	Total thermal resistance (m^2KW^{-1})

Subscripts/Superscripts

i, in	Inside
o, out	Outside
sa	Sol-air temperature
min	Minimum
max	Maximum
t	time

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