Journal of Renewable Energy Science, Technology and Economics
ISSN 2395 – 2644 (print) ***Vol 1, Issue 1 - May 2015***

Investigation of Unsteady Diurnal Thermal Behaviour of Building Walls Exposed to Periodic Solar Thermal Excitation

Saboor S[1], Ashok Babu T. P.[2*]

[1]Research Scholar, Mechanical Engineering Department, National Institute of Technology Karnataka, Surathkal, India.

[2]Professor, Mechanical Engineering Department, National Institute of Technology Karnataka, Surathkal, India.

*** tpashok@rediffmail.com, tpashok@gmail.com**

ABSTRACT:

The energy consumption associated with cooling of the buildings is around 40%. The appropriate building material and thickness in the building construction can reduce the cooling loads in the buildings. This paper describes the unsteady diurnal thermal characteristics such as, admittance, transmittance, decrement factor and time lag of the building walls exposed to periodic thermal excitation. The computer simulation program has been developed to compute unsteady thermal characteristics of the homogeneous and composite walls. The simulation program employs the cyclic admittance method. Six wall materials such as, burnt brick, cellular concrete, cinder concrete, laterite stone, lime stone and dense concrete are selected for the study. From the results it is observed that the cellular concrete gives the lowest decrement factor (0.497) and the highest time lag (7.28h) among all six studied wall materials. The impact of using different outside and inside plaster thickness for walls on the decrement factor and time lag is also analysed. For the investigation, six configurations such as, wall without plaster (C-I), wall with outside plaster (C-II), wall with inside plaster (C-III), wall with inside and outside plaster (C-IV), wall with outside plaster thickness more than inside plaster thickness (C-V) and wall with inside plaster thickness more than outside plasterthickness (C-VI) are considered. From the results, it is noted that the wall with outside plaster more than the inside plaster (C-V) is the best configuration for burnt brick, laterite stone, lime stone and dense concrete composite walls from lower decrement factor and higher time lag point of view. And it is also observed that wall with inside plaster more than outside plaster (C-VI) is the best configuration for cellular concrete and cinder concrete composite walls from lower decrement factor and higher time lag. The optimum wall thickness at which maximum heat storage is possible has been computed for the six wall materials. Results show that the homogeneous cellular concrete walls store maximum energy at minimum thickness (0.083m) of the wall among all six studied homogeneous wall materials. The best configuration for reduced cooling loads based on the admittance and transmittance values has been established for six wall materials.

1. INTRODUCTION:

Buildings are responsible for about 40% of total energy use in the world and they also account for more than 40% of the global carbon dioxide emissions. With recent boom in construction sector, there has been a sudden increase in energy consumption, especially in countries like India and China. India has substantial climatic variations from region to region. Climatic building design is the most important factor in ensuring energy efficiency in buildings. Buildings with climate responsive design can consume around 10% - 15% less energy as compared to conventional buildings without incurring any incremental cost [1]. Thus, it is essential to focus on the vital aspect of energy efficiency at the design stage of the building itself.

The effects of thermo physical properties and thickness of building wall on time lag and decrement factor have been investigated using crank Nicolson method by many researchers [2]. And also Effects of Wall's insulation thickness and position on time lag and decrement factor were studied in detail [3]. The present study focuses mainly on the effects of outside and inside plaster thicknesses on thermal admittance, thermal transmittance, decrement factor and time lag.

2. DYNAMIC DIURNAL WALL RESPONSE CHARACRTERISTICS

The present study focuses on the cyclic response admittance method. The cyclic-response admittance method attempts to consider the effects of dynamic conditions on fabric heat transfer, fabric thermal sorption and storage, effectively by determining unsteady-state multiplier factors for application to the steady-state properties of the fabric. Normally, under simplified steady-state conditions, the difference between indoor and outdoor air temperatures is taken to produce a thermal gradient across the thickness of the wall, the profile of which is determined by the thermal properties of the wall material and its corresponding surface resistances. Instead of the outside air temperature the admittance model uses the hypothetical sol–air temperature, as a single point variable to establish this thermal gradient. This represents the rate of heat flow into the external wall surface by convection from the surrounding air plus shortwave solar radiation and radiative exchange to the surroundings. Analogous to sol–air temperature, the environmental temperature is a single point hypothetical temperature that represents the rate of heat flow into the internal wall surface by convection from the room and radiation from surrounding objects.

The cyclic admittance method is used to calculate these unsteady- state parameters values uses matrices to simplify the temperature and energy cycles for a composite building fabric element that is subjected to sinusoidal temperature variations at the sol–air node.

The temperature distribution in a homogeneous wall subjected to one dimensional heat flow is given by the diffusion equation and its solution is as follows [4],

$$\frac{\partial^2\theta}{\partial X^2} = \frac{\rho Cp}{k}\frac{\partial\theta}{\partial t} \qquad 1.)$$

$$\begin{bmatrix} T_e \\ q_e \end{bmatrix} = \begin{bmatrix} cosh(z+jz) & \left(sinh(z+jz)\right)/c \\ \left(sinh(z+jz)\right)\times a & cosh(z+jz) \end{bmatrix}\begin{bmatrix} T_i \\ q_i \end{bmatrix} \qquad 2.)$$

Where, cyclic thickness $(z) = \sqrt{\pi\rho c_p X^2/\lambda P} = \sqrt{\pi Cr/P}$ and Characteristic admittance of slab$(a) = \sqrt{j2\pi\lambda\rho c_p/P} = \sqrt{j2\pi C/rP}$.

Transmission matrix of a single wall layer can be written as,

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} \qquad 3.)$$

Where,

$$A = (\cosh(z)\cos(z)) + j\,(\sinh(z)\sin(z))$$

$$B = \left([[\cosh(z)\sin(z) + \sinh(z)\cos(z)]/\sqrt{2}] + j[[\cosh(z)\sin(z) - \sinh(z)\cos(z)]/\sqrt{2}]\right)/a$$

$$C = \left(-[[\cosh(z)\sin(z) - \sinh(z)\cos(z)]/\sqrt{2}] + j[[\cosh(z)\sin(z) + \sinh(z)\cos(z)]/\sqrt{2}]\right).a$$

$$D = \cosh(z)\cos(z) + j(\sinh(z)\sin(z))$$

$$a = \left(\pi\rho c_p kX^2/P\right)^{1/2} z = \left(\pi\rho c_p X^2/kP\right)^{1/2}$$

Clearly, for a composite wall, the matrices of each of the layers can be multiplied together to give the relation between outside and inside as follows [5,6],

$$\begin{bmatrix} T_e \\ q_e \end{bmatrix} = \begin{bmatrix} 1 & -R_{se} \\ 0 & 1 \end{bmatrix} \begin{bmatrix} m_1 & m_2 \\ m_3 & m_1 \end{bmatrix} \begin{bmatrix} n_1 & n_2 \\ n_3 & n_1 \end{bmatrix} \cdots \begin{bmatrix} 1 & -R_{si} \\ 0 & 1 \end{bmatrix} \begin{bmatrix} T_i \\ q_i \end{bmatrix} \qquad 4.)$$

$$\begin{bmatrix} \theta_e \\ q_e \end{bmatrix} = \begin{bmatrix} M_1 & M_2 \\ M_3 & M_4 \end{bmatrix} \begin{bmatrix} T_i \\ q_i \end{bmatrix} \qquad 5.)$$

The cyclic thermal transmittance is

$$u = 1/M_2 \qquad 6.)$$

Thermal transmittance is is the steady state heat flow through the element per unit degree of temperature difference between the internal and external environmental temperatures per unit area. It is given as follows,

$$U = \frac{1}{R_{se} + \left(\frac{X_1}{k_1}\right) + \left(\frac{X_2}{k_2}\right) + \cdots R_{si}} \qquad 7.)$$

Thermal admittance is the amount of energy leaving the internal surface of the element into the room per unit degree of temperature swing. This is under theoretical conditions where the internal environmental temperature undergoes periodic oscillation and the external environmental temperature is constant.

$$y_i = \left(\frac{T_i}{\theta i}\right)_{T_e=0} = -\frac{M_1}{M_2} \qquad 8.)$$

$$Y = |y_i| \qquad 9.)$$

Decrement factor is the ratio of the peak heat flow out of the external surface of the element per unit degree of external temperature swing to the steady state heat flow through the element per unit degree of temperature difference between the internal and external environmental temperatures.

$$f_c = -\frac{1}{UM_2} \qquad 10.)$$

$$f = |f_c| \qquad 11.)$$

Decrement delay is the time lag between the timing of the internal temperature peak and the peak heat flow out of the external surface.

$$\phi = \frac{12}{\pi} arctan\left(\frac{Im(f_c)}{Re(f_c)}\right) \qquad 12.)$$

The optimum wall thickness at maximum heat storage capacity can be calculated as follows [7]

$$d = 1.18251\sqrt{\frac{\alpha P}{\omega}} \qquad 13.)$$

3. THERMAL PROPERTIES AND UNSTEADY STATE THERMAL CHARACTERISTICS OF WALLS

Table 1. Shows the thermal properties of the wall materials considered for the study. The total six wall materials have been considered for the study and their properties were taken from the Indian standard code IS 3792-1978. IS code [8] uses guarded hot plate method for the measurement of the thermal properties.Homogeneous walls are coded from W.M-1 to W.M-2. Thermal properties of laterite stone were measured experimentally using transient plane source method. Figure 1 shows the images of the wall materials. A computer simulation program was developed which uses a cyclic admittance method to compute unsteady thermal characteristics of the wall. The walls are considered as exterior walls and hence inside and outside surface resistances are taken as 0.13 W/m^2 K and 0.04 W/m^2 K respectively as per CIBSE standards. Table 2 shows the unsteady state thermal characteristics of homogeneous walls at 0.2 m thickness. Thermal transmittance is computed from the Eq. (6) and thermal admittance is computed using Eq. (9). Eq. (11) and Eq. (12) were used to calculate decrement factor and it's time lag respectively. Figure 2 shows the configuration of the composite walls and Table 3 shows the configuration of the composite wall with different wall and plaster thicknesses.The effects of outside and inside plaster thickness on the walls have been investigated. Composite walls are coded from C-I to C-VI.six configurations such as, wall without plaster (C-I), composite wall with outside plaster (C-II), composite wall with inside plaster (C-III), composite wall with inside and outside plaster (C-IV), composite wall with outside plaster more than inside plaster (C-V) and composite wall with inside plaster more than outside plaster (C-VI) are considered. Tables 4,5,6,7 and 8 show the unsteady state thermal characteristics of burnt bricks, cellular concrete, cinder concrete, laterite stone, lime stone and dense concrete composite walls respectively.

Table 1. THERMAL PROPERTIES OF WALL MATERIALS

S.No.	Wall material	Code	Thermal conductivity k (W/mK)	Density ρ (kg/m^3)	Specific heat capacity Cp (J/kgK)	Thermal diffusivity α (m^2/s) X 10^{-7}
1.	Burnt brick	W.M-1	0.811	1820	880	5.063
2.	Cellular concrete	W.M-2	0.188	704	1050	2.543
3.	Cinder concrete	W.M-3	0.686	1406	840	5.808
4.	Laterite stone	W.M-4	1.369	1000	1926	7.112
5.	Lime stone	W.M-5	1.80	2420	840	8.854
6.	Dense concrete	W.M-6	1.74	2410	880	8.204
7.	Cement plaster	P	0.721	1762	840	4.871

Figure 1. IMAGES OF WALL MATERIALS

Table 2. USTEADY THERMAL CHARACTERISTICS OF HOMOGENEOUS WALL MATERIALS AT 0.2 m

S.No.	Wall material	CODE	U (W/m^{2}K)	f	ϕ (h)	Y (W/m^{2}K)
1.	Burnt brick	W.M-1	2.401	0.549	5.954	4.618
2.	Cellular concrete	W.M-2	0.810	0.497	7.287	2.411
3.	Cinder concrete	W.M-3	2.167	0.641	5.176	4.078
4.	Laterite stone	W.M-4	3.165	0.563	5.446	5.263
5.	Lime stone	W.M-5	3.559	0.580	5.106	5.522
6.	Dense concrete	W.M-6	3.511	0.559	5.312	5.548

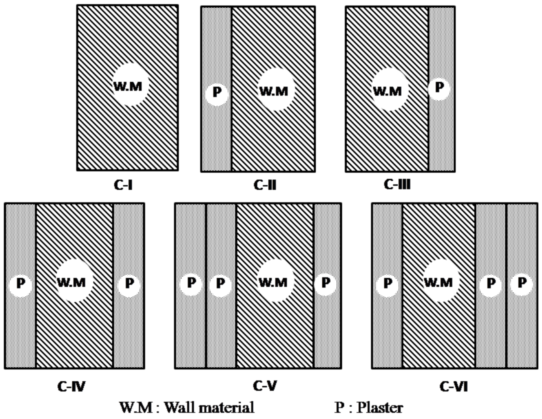


Figure 2. CONFIGURATIONS OF COMPOSITE WALLS

Table 3. CONFIGURATION OF COMPOSITE WALLS WITH DIFFERENT PLASTER THICKNESSES

S.No.	Configuration	Thickness of the wall from outside to inside (m)
1.	C-I	0.2 W.M
2.	C-II	0.0125 P + 0.2 W.M
3.	C-III	0.2 W.M + 0.0125 P
4.	C-IV	0.0125 P + 0.2 W.M + 0.0125 P
5.	C-V	0.0125 P + 0.0125 P + 0.2 W.M + 0.0125 P
6.	C-VI	0.125 0.2 W.M + 0.0125 P + 0.0125 P

Table 4. UNSTEADY STATE THERMAL CHARACTERISTICS OF BURNT BRICK COMPOSITE WALLS

Burnt brick walls					
S.No.	Configuration	U (W/m^2K)	f	ϕ (h)	Y (W/m^2K)
1.	C-I	2.40	0.549	5.954	4.618
2.	C-II	2.30	0.509	6.376	4.640
3.	C-III	2.30	0.511	6.355	4.579
4.	C-IV	2.216	0.473	6.775	4.595
5.	C-V	2.199	0.4661	6.859	4.597
6.	C-VI	2.199	0.4667	6.855	4.586

Table 5. UNSTEADY STATE THERMAL CHARACTERISTICS OF CELLULAR CONCRETE COMPOSITE WALLS

Cellular concrete walls					
S.No.	Configuration	U (W/m^2K)	f	ϕ (h)	Y (W/m^2K)
1.	C-I	0.810	0.497	7.287	2.411
2.	C-II	0.799	0.482	7.625	2.412
3.	C-III	0.799	0.468	7.868	2.994
4.	C-IV	0.788	0.454	8.206	2.993
5.	C-V	0.786	0.451	8.281	2.993
6.	C-VI	0.786	0.447	8.322	3.10

Table 6. UNSTEADY STATE THERMAL CHARACTERISTICS OF CINDER CONCRETE COMPOSITE WALLS

Cinder concrete walls					
S.No.	Configuration	U (W/m^2K)	f	ϕ (h)	Y (W/m^2K)
1.	C-I	2.167	0.641	5.176	4.078
2.	C-II	2.088	0.605	5.588	4.108
3.	C-III	2.088	0.600	5.627	4.196
4.	C-IV	2.015	0.564	6.036	4.219
5.	C-V	2.001	0.557	6.120	4.222
6.	C-VI	2.001	0.556	6.126	4.238

Table 7. UNSTEADY STATE THERMAL CHARACTERISTICS OF LATERITE STONE COMPOSITE WALLS

Laterite stone walls					
S.No.	Configuration	U (W/m^2K)	f	ϕ (h)	Y (W/m^2K)
1.	C-I	3.165	0.563	5.440	5.260
2.	C-II	3.001	0.511	5.887	5.310
3.	C-III	3.001	0.528	5.782	5.034
4.	C-IV	2.852	0.477	6.221	5.069
5.	C-V	2.824	0.468	6.303	5.075
6.	C-VI	2.824	0.471	6.287	5.027

Table 8. UNSTEADY STATE THERMAL CHARACTERISTICS OF LIME STONE COMPOSITE WALLS

Lime stone walls					
S.No.	Configuration	U (W/m^2K)	f	ϕ (h)	Y (W/m^2K)
1.	C-I	3.559	0.580	5.100	5.520
2.	C-II	3.352	0.521	5.559	5.585
3.	C-III	3.352	0.546	5.415	5.217
4.	C-IV	3.168	0.487	5.864	5.265
5.	C-V	3.133	0.477	5.947	5.273
6.	C-VI	3.133	0.481	5.926	5.209

Table 9. UNSTEADY STATE THERMAL CHARACTERISTICS OF DENSE CONCRETE COMPOSITE WALLS

Dense concrete walls					
S.No.	Configuration	U (W/m^2K)	f	ϕ (h)	Y (W/m^2K)
1.	C-I	3.510	0.559	5.312	5.548
2.	C-II	3.309	0.500	5.760	5.605
3.	C-III	3.309	0.525	5.618	5.236
4.	C-IV	3.130	0.468	6.062	5.279
5.	C-V	3.096	0.458	6.145	5.285
6.	C-VI	3.096	0.462	6.125	5.222

4. RESULTS AND DISCUSSIONS

4.1 Optimum wall thicknesses:

The most important point to consider is the rate of transfer of heat energy between the internal surface of the wall and the environmental node. The rate of flow of this heat energy, for each degree of deviation about the mean environmental temperature value, is known as the thermal admittance. It is the unsteady-state parameter that positively indicates the ability of the fabric to absorb and store heat energy from the environmental node. Both thermal transmittance and the thermal admittance are the measures of the flow of heat through the wall. For better insulation, thermal transmittance should be as low as possible, whereas thermal admittance should be as high as possible. Wall storage energy thickness of the various walls can be calculated by Eq. (13). At this optimum thickness of the wall the wall has the maximum thermal heat capacity. Figure 3 shows the admittance and the transmittance of the homogeneous walls considered for the study. The optimum wall thickness values of burnt brick, cellular concrete, cinder concrete, laterite stone, lime stone and dense concrete are found to be 0.118m, 0.083m, 0.126m, 0.139m, 0.110m and 0.106m respectively. It is observed that cellular concrete has the least optimum wall thickness value among all the studied homogeneous walls.

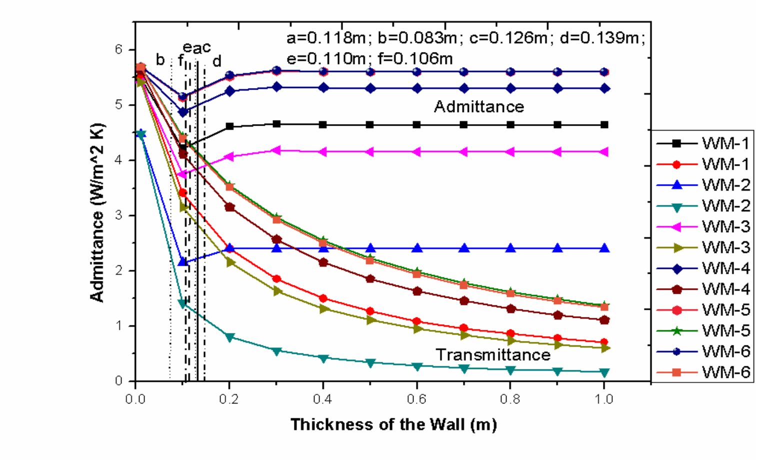
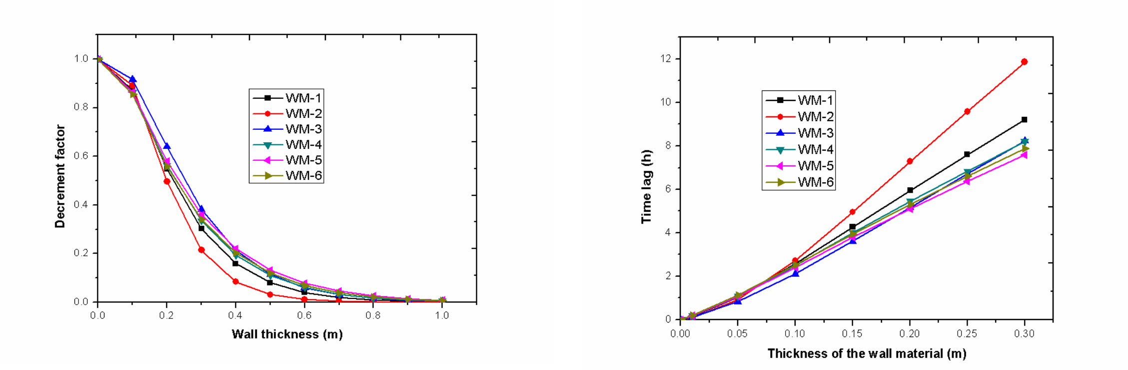


Figure 3. ADMITTANCE AND TRANSMITTANCE OF HOMOGENEOUS WALL MATERIALS

4.2 Decrement factor and time lag of homogeneous wall materials:

The decrement factor decreases and it's time lag value increases with an increase in the thickness of the wall. The decrement factor should be as minimum as possible and it's time lag should be as maximum as possible for reduced cooling loads in the buildings. Figure 4 (a) shows the decrement factor of homogeneous wall and Figure 4 (b) shows the time lag of homogeneous walls considered for the study. From the results it is observed that the cellular concrete homogeneous walls have lowest decrement factor and highest time lag values at all wall thicknesses among the six wall materials studied. At 0.2 m wall thickness cellular concrete homogeneous walls have least decrement factor (0.497) and the highest time lag values (7.287h) among studied wall materials.



a.)

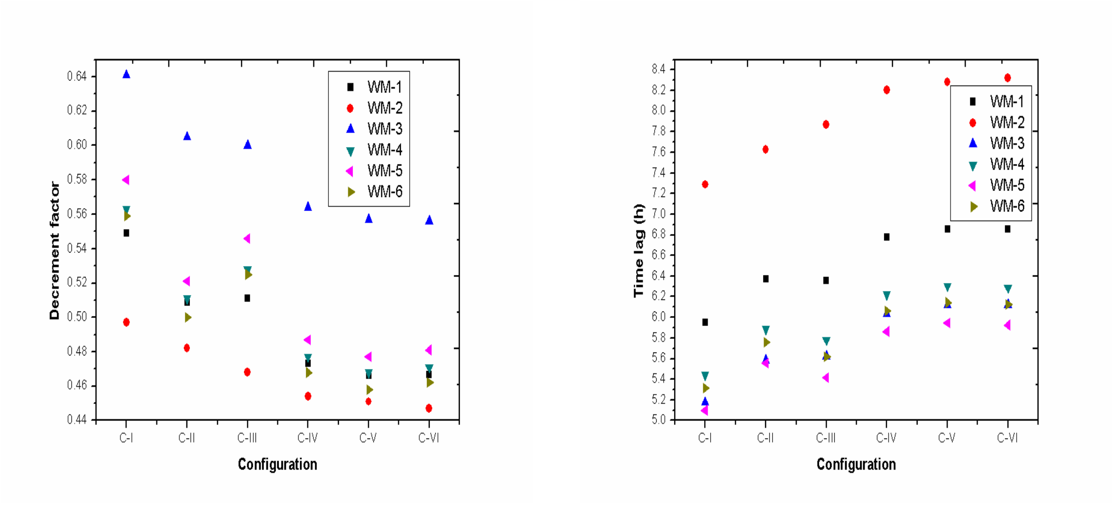
b.)

Figure 4.a.) DECREMENT FACTOR b.) TIME LAG OF HOMOGENEOUS WALL MATERIALS

The choice of preference of the wall materials from lower decrement factor and higher time lag point of view among studied walls is cellular concrete, burnt bricks, dense concrete, laterite stone, lime stone and cinder concrete.

4.3 Decrement factor and time lag of composite walls:

Figure 5 (a) shows the decrement factor of composite wall and Figure 5 (b) shows the time lag of composite walls for six different wall configurations. It is observed from the results that the composite wall with outside plaster thickness more than the inside plaster thickness (C-V) is the best configuration for burnt brick (W.M-1), laterite stone (W.M-4), lime stone (W.M-5) and dense concrete (W.M-6) walls from lower decrement factor and higher time lag point of view. The composite wall with inside plaster thickness more than outside plaster thickness (C-VI) is observed to be the best for cellular concrete (W.M-2) and cinder concrete (W.M-3) walls from lower decrement factor and higher time lag point of view. Cellular concrete composite walls with onside plaster more than the outside plaster thickness is observed to be the best among all the wall materials and all configurations studied due to their lower decrement factor (0.447) and highest time lag values (8.32h).



a.) **b.)**

Figure 5. a.) DECREMENT FACTOR b.) TIME LAG OF COMPOSITE WALLS

4.4 Admittance and transmittance of composite walls:

For reduced cooling loads, admittance should be as high as possible and transmittance should be as low as possible. The outside and inside plaster thickness of a wall adversely affects its admittance and transmittance values. Figure 6 shows the admittance and the transmittance of the composite walls of different configurations. From the results it is observed that the admittance values are maximum (with least thermal transmittance) in the composite walls with inside plaster thickness more than outside plaster thickness (C-VI) for cellular concrete and cinder concrete walls. It can also be observed that the admittance values are maximum (with least thermal transmittance) in the composite walls with outside plaster thickness more than the inside plaster thickness (C-V) for burnt brick, laterite stone, lime stone and dense concrete walls.

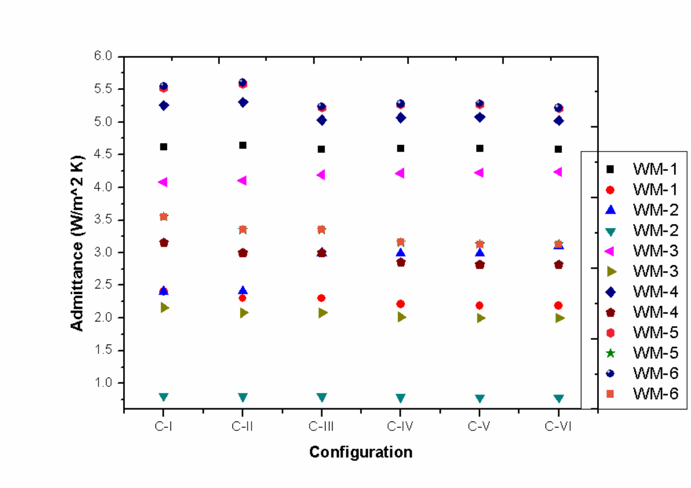


Figure 6. ADMITTANCE AND TRANSMITTANCE OF COMPOSITE WALLS

5. CONCLUSIONS

- Cellular concrete walls give the lowest decrement factor (0.497) and highest time lag (7.28h) values among six studied homogeneous walls. Hence, cellular concrete wall materials among six studied wall materials are recommended for reduced cooling loads in the buildings.
- For reduced cooling loads in the buildings, composite walls with outside plaster thickness more than the inside plaster thickness (C-V) is recommended for burnt brick, laterite stone, lime stone and dense concrete walls whereas composite walls with inside plaster thickness more than the outside plaster thickness (C-VI) is recommended for cellular concrete and cinder concrete walls from lower decrement factor, lower thermal transmittance, higher admittance and higher time lag point of view.
- The cellular concrete homogeneous walls have least optimum fabric energy storage (0.083 m) among all six studied wall materials. With these walls maximum amount of energy and material can be saved during construction.

REFERENCES

[1] GRIHA, 2011. Technical manual for trainers on building and system design optimization renewable energy application., TERI, India.

[2] Asan, H., Sancaktar, Y.S., 1998. “Effects of Wall’s thermo physical properties on time lag and decrement factor”. *Energy and Buildings* 28, 159-166.

[3] Asan, H., 1998. “Effects of Wall’s insulation thickness and position on time lag and decrement factor”. *Energy and Buildings* 28, 299–305.

[4] Davies, M.G., 2004. *Building Heat Transfer*, John-Wiley & sons Ltd. pp. 335-351.

[5] CIBSE, 2006. CIBSE Environmental Design Guide-A. 7th ed., chartered Institution of Building services engineers, London.

[6] Pipes L.A., 1957. Matrix Analysis of heat transfer problems, Journal of Franklin Institute. 623, pp.195-206.

[7] Magyari, E., Keller, B., 1998.The storage capacity of a harmonically heated slab revisited, International journal of heat and mass transfer, 41(10), pp.1199-1204.

[8] IS: 3792 1978. Indian standard guide for heat insulation of non industrial buildings, Indian standards institution, New delhi, India., pp.1-39.