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Effect of Air Space Thickness within the External Walls on the Dynamic Thermal Behaviour of Building Envelopes for Energy Efficient Building Construction

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Abstract

This paper presents the comprehensive investigation of the effect divided air space thickness within the wall on unsteady heat transfer characteristics such as thermal transmittance, thermal admittance, decrement factor and time lag of five building material walls for energy efficient building enclosure design. The five building material composite walls such as laterite stone, mud brick, cellular concrete, dense concrete and cinder concrete with total thirty configurations were studied. A computer simulation program was developed to compute unsteady heat transfer characteristics using the cyclic admittance procedure. From the results, it is observed that the decrement factor decreases with the increase in the divided air space thickness within the composite wall for all building materials. Dense concrete was observed to be the energy efficient from the lowest decrement factor point of view among five studied building materials. Dense concrete decrement factor decreases by 23.65% for 0.02 m air space thickness compared to the conventional composite wall without air space. It is also noticed that the time lag increases with the increase in the divided air space thickness within the composite wall for all building materials. Cellular concrete was observed to be the energy efficient from highest time lag perspective among five studied building materials. Cellular concrete time lag increases by 6.23% for 0.02 m air space thickness compared to the conventional composite wall without air space. The results of the study help in designing energy efficient building enclosures.

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Keywords: energy efficient building envelopes; decrement factor; time lag; air space thickness; admittance

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Nomenclature

Cp	Specific heat capacity	**α**	Thermal diffusivity
k	Thermal conductivity	**ρ**	Density

1. Introduction

The building sector is responsible for about 33% of power consumption in India, with the commercial sector and residential sector accounting for 8% and 25% respectively as per Energy conservation building code, India. An appropriate design of building enclosures helps in providing desired comfort with least possible power consumption. The study of unsteady thermal characteristics of the walls plays significant role in the design of energy efficient walls. These dynamic characteristics were first introduced by Loudon [1] and further modified by Millibank and Davies [2,3]. Later Loveday and Taki suggested radiative heat transfer coefficient about 4 W/m^2 K to CIBSE standards normal exposure of 2 m/s wind speed values [4]. Previously, Thermo physical property changes and thickness of a wall material of a building on time lag and decrement factor using the crank Nicolson method were reported [5]. Wall's insulation thickness and position on time lag and decrement factor were also studied in detail by many researchers [6]. Unsteady thermal characteristics of building materials using admittance method were presented. The present study presents the effect of divided air space thickness within the external walls on unsteady thermal response characteristics such as, admittance, transmittance, decrement factor and time lag using the cyclic response admittance method for energy efficient building enclosure design.

2. Admittance procedure for unsteady dynamic thermal behavior of walls

The temperature distribution in a homogeneous wall subjected to one dimensional heat flow through the wall is given by the diffusion equation,

$$\frac{\partial^2 T(X,t)}{\partial X^2} = \frac{\rho Cp}{k}\frac{\partial T(X,t)}{\partial t} \quad (1)$$

Solution to Fourier equation can be written as [7],

$$T(x,t) = [Asinh(\alpha x + j\alpha x) + Bcosh(\alpha x + j\alpha x)]exp(j2\pi t/P) \quad (2)$$

Where, $\alpha = \sqrt{\pi\rho c_p/\lambda P}$.

When the conducting medium finite thickness slab X, temperature and flows at the two surfaces are considered then the above equation can be related and arranged in matrix form as,

$$\begin{bmatrix} T_i \\ q_i \end{bmatrix} = \begin{bmatrix} cosh(x+jx) & \big(sinh(x+jx)\big)/c \\ \big(sinh(x+jx)\big) \times c & cosh(x+jx) \end{bmatrix} \begin{bmatrix} T_o \\ q_o \end{bmatrix} \quad (3)$$

Where, T_o is outside and T_i is inside cyclic temperature fluctuation about mean value, q_o is cyclic heat flux occurring at outside surface, q_i is cyclic heat flux occurring at inside surface, cyclic thickness $(x) = \sqrt{\pi\rho c_p X^2/\lambda P} = \sqrt{\pi Cr/P}$ and Characteristic admittance of slab$(c) = \sqrt{j2\pi\lambda\rho c_p/P} = \sqrt{j2\pi C/rP}$.

Transmission matrix of single layer can be written as,

$$\begin{bmatrix} A_1 + jA_2 & (A_3 + jA_4)/c \\ (-A_4 + jA_3).c & A_1 + jA_2 \end{bmatrix} \quad (4)$$

Where, constants $A_1 = \cosh(x)\cos(x), A_2 = \sinh(x)\sin(x),$
$A_3 = [\cosh(x)\sin(x) + \sinh(x)\cos(x)]/\sqrt{2}$ and $A_4 = [\cosh(x)\sin(x) - \sinh(x)\cos(x)]/\sqrt{2}$.

Transmission matrix of surface internal and external film resistances can be written as,

$$e_{si} = \begin{bmatrix} 1 & -R_{si} \\ 0 & 1 \end{bmatrix} \; and \; e_{so} = \begin{bmatrix} 1 & -R_{so} \\ 0 & 1 \end{bmatrix} \quad (5)$$

Transmission matrix for two layer composite wall with air space at the centre of the wall can be written as,

$$\begin{bmatrix} T_i \\ q_i \end{bmatrix} = \begin{bmatrix} 1 & -R_{si} \\ 0 & 1 \end{bmatrix} \begin{bmatrix} a_1 & a_2 \\ a_3 & a_1 \end{bmatrix} \begin{bmatrix} 1 & -R_a \\ 0 & 1 \end{bmatrix} \begin{bmatrix} b_1 & b_2 \\ b_3 & b_1 \end{bmatrix} \begin{bmatrix} 1 & -R_{so} \\ 0 & 1 \end{bmatrix} \begin{bmatrix} T_0 \\ q_o \end{bmatrix} \tag{6}$$

Where, a and b represent number of layers of the wall.

Transmission matrix can be further reduced as follows,

$$\begin{bmatrix} T_i \\ q_i \end{bmatrix} = \begin{bmatrix} e_1 & e_2 \\ e_3 & e_4 \end{bmatrix} \begin{bmatrix} T_o \\ q_o \end{bmatrix} \tag{7}$$

The decrement Factor (f) is the attenuation of the sinusoidal heat wave as it passes through the building wall. It is dimensionless and it can be calculated by [8],

$$f = \left| -\frac{1}{Ue_2} \right| \tag{8}$$

The decrement delay (ϕ) is the time lag between the timing of the peak internal temperature and the peak heat flow out of the outer surface. It can be calculated by

$$\phi = \frac{12}{\pi} arctan \left(\frac{Im(-\frac{1}{Ue_2})}{Re(-\frac{1}{Ue_2})} \right) \tag{9}$$

The thermal admittance (Y) is the amount of energy leaving the internal wall surface into the room per unit degree of temperature swing. It can be calculated by,

$$Y = \left| \left(\frac{q_i}{\theta i} \right)_{T_o=0} \right| = \left| -\frac{e_1}{e_2} \right| \tag{10}$$

The optimum fabric thickness at maximum heat capacity can be calculated as follows [9]

$$L_{opt} = 1.18251\sigma_L \tag{11}$$

Where, $\sigma_L = \sqrt{2}a/\omega$ is penetration length where thermal effects exist.

3. Building material thermal properties and their unsteady thermal response characteristics

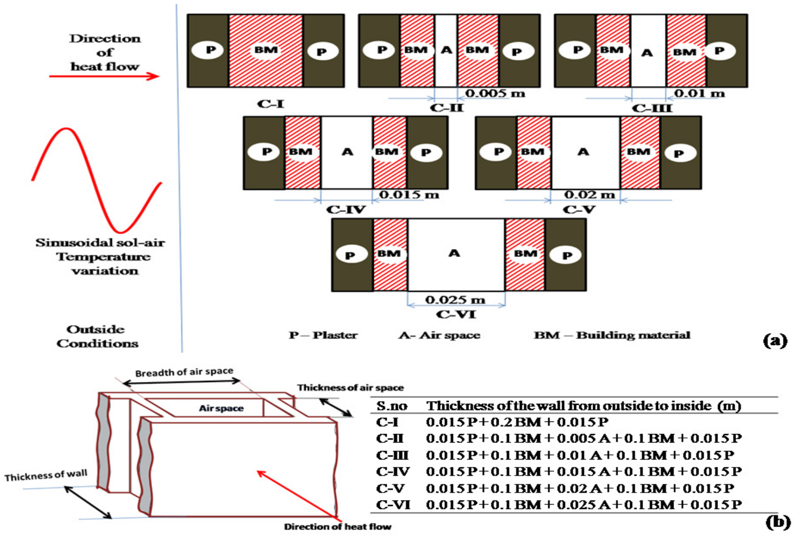
The thermal properties of building materials were taken from the Indian standard guide for heat insulation of non industrial buildings as per IS code 3792-1978 [10] as shown in Table 1. Thermal properties of laterite stone were measured using the transient plane source method experimentally at K-Analys, Sweden. Five building materials were selected for the study and they are coded from BM-1 to BM-5. The cement plaster was represented by code P. The air space resistances are 0.11, 0.15, 0.17, 0.18 and 0.18 m^2K/W for air space thickness 0.005, 0.01, 0.015, 0.02 and 0.025 m, respectively for air space breadth ≥0.2 m as per the CIBSE standards.

Table 1. Thermal properties of building materials

S.No.	Wall material	Code	k (W/mK)	ρ (kg/m^3)	Cp (J/kgK)	α (m^2/s) X 10^{-7}
1.	Laterite stone	BM-1	1.369	1000	1926	7.112
2.	Mud brick	BM-2	0.75	1731	880	4.92
3.	Cellular concrete	BM-3	0.188	704	1050	2.543
4.	Dense concrete	BM-4	1.74	2410	880	8.204
5.	Cinder concrete	BM-5	0.686	1406	840	5.808
6.	Cement plaster	P	0.721	1762	840	4.871

Table 2. Effect of air space thickness on unsteady thermal characteristics of Laterite and mud brick walls

		Laterite stone (BM-1)				Mud brick (BM-2)			
S.NO.	Configuration	U (W/m^2K)	Y (W/m^2K)	f	ϕ (h)	U (W/m^2K)	Y (W/m^2K)	f	ϕ (h)
1.	C-I	2.790	5.030	0.461	6.372	2.090	4.500	0.466	6.950
2.	C-II	2.138	5.103	0.397	7.601	1.700	4.582	0.422	7.836
3.	C-III	1.970	5.144	0.378	7.855	1.592	4.614	0.408	8.049
4.	C-IV	1.895	5.163	0.370	7.960	1.542	4.630	0.401	8.141
5.	C-V	1.860	5.171	0.366	8.008	1.519	4.637	0.398	8.183
6.	C-VI	1.860	5.171	0.366	8.008	1.519	4.637	0.398	8.183

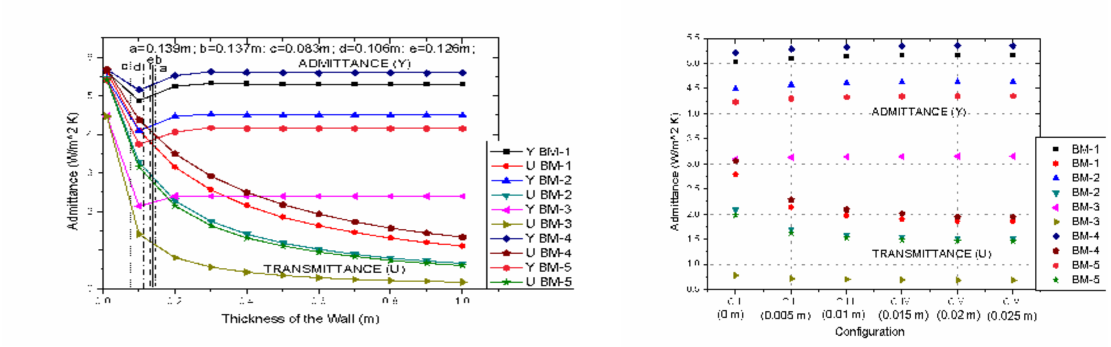


S.no	Thickness of the wall from outside to inside (m)
C-I	0.015P+0.2BM+0.015P
C-II	0.015P+0.1BM+0.005A+0.1BM+0.015P
C-III	0.015P+0.1BM+0.01A+0.1BM+0.015P
C-IV	0.015P+0.1BM+0.015A+0.1BM+0.015P
C-V	0.015P+0.1BM+0.02A+0.1BM+0.015P
C-VI	0.015P+0.1BM+0.025A+0.1BM+0.015P

Fig.. 1. (a) Configuration of composite walls with different air spaces; (b) Wall structure with divided air space

Table 3. Effect of air space thickness on unsteady thermal characteristics of Cellular, dense and cinder concrete walls

	Cellular concrete (BM-3)				Dense concrete (BM-4)				Cinder concrete (BM-5)			
Configuration	U	Y	f	ϕ	U	Y	f	ϕ	U	Y	f	ϕ
C-I	0.78	3.10	0.447	8.397	3.06	5.22	0.452	6.207	1.98	4.24	0.549	6.209
C-II	0.72	3.13	0.430	8.762	2.29	5.28	0.378	7.602	1.63	4.30	0.513	6.931
C-III	0.70	3.14	0.425	8.876	2.09	5.33	0.358	7.872	1.53	4.33	0.501	7.114
C-IV	0.69	3.15	0.423	8.929	2.01	5.35	0.349	7.981	1.48	4.34	0.495	7.195
C-V	0.68	3.15	0.421	8.955	1.94	5.36	0.345	8.030	1.46	4.35	0.492	7.232
C-VI	0.68	3.15	0.421	8.955	1.94	5.36	0.345	8.030	1.46	4.35	0.492	7.232



(a) (b)

Fig. 2. (a) Thermal transmittance and admittance of building materials; (b) air space effect on transmittance and admittance

4. Results and discussions

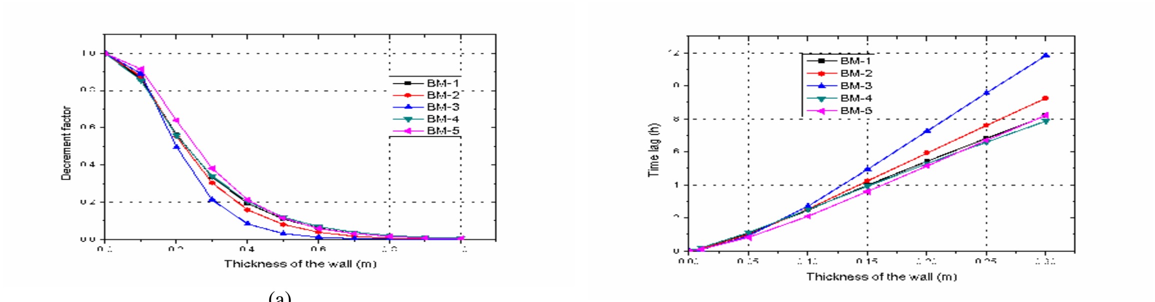
4.1. Thermal transmittance and admittance of homogeneous and composite building materials

Thermal transmittance is a measure of thermal insulation of the wall. It gives the heat loss through a given thickness of the wall. The lower thermal transmittance value signifies the better thermal performance. The higher thermal admittance signifies the better thermal mass. From Fig. 2 (a), it is observed that cellular concrete is the best from the lowest thermal transmittance perspective and dense concrete is the best from the highest thermal admittance perspective for all thicknesses of the walls among five building materials studied. From the results, it is observed that cellular concrete has the least optimum fabric thickness (0.083 m) and the laterite stone has the highest fabric thickness (0.139 m) among five studied building materials. From Fig. 2 (b), it is obvious that thermal transmittance decreases and thermal admittance increases with the increase in the divided air space thickness up to 0.02 m of the air space thickness afterwards thermal transmittance and thermal admittance remain constant. This is because of constant air gap resistance of the air space after 0.02 m. From the results, it is clear that among five materials studied, dense concrete has the highest admittance value at all divided air space thicknesses and recommended for high thermal mass. Cellular concrete has the least thermal transmittance value at all divided air space thicknesses among five studied building materials and recommended for high thermal insulation.

4.2. Decrement factor and time lag of homogeneous building materials

The thermal heat capacity of the wall slows down the heat transfer from outside to inside of the wall. The thermal heat storage capacity of the building material can be determined by the decrement factor and it's time lag. Fig. 3 (a) shows the decrement factor of homogeneous building materials and Fig. 3 (b) shows the time lag of homogeneous building materials studied. From the results it is observed that at 0.2 m wall thickness building materials, laterite stone (BM-1), Mud brick (BM-2), Cellular concrete (BM-3), Dense concrete (BM-4) and Cinder concrete (BM-5) have decrement factors, 0.563, 0.554, 0.497, 0.559 and 0.641and 5.44 h, 5.95 h, 7.28 h, 5.31 h and 5.17 h time lags, respectively. Among five building materials studied in the paper, cellular homogeneous building materials (BM-3) are the best materials from lowest decrement factor (0.497 at 0.2 m) and highest time lag (5.31 h at 0.2m) perspective. BM-3 is the best from lower decrement factor and higher time lag perspective for all wall thicknesses.

4.3. Effect of air space thickness on decrement factor and time lag

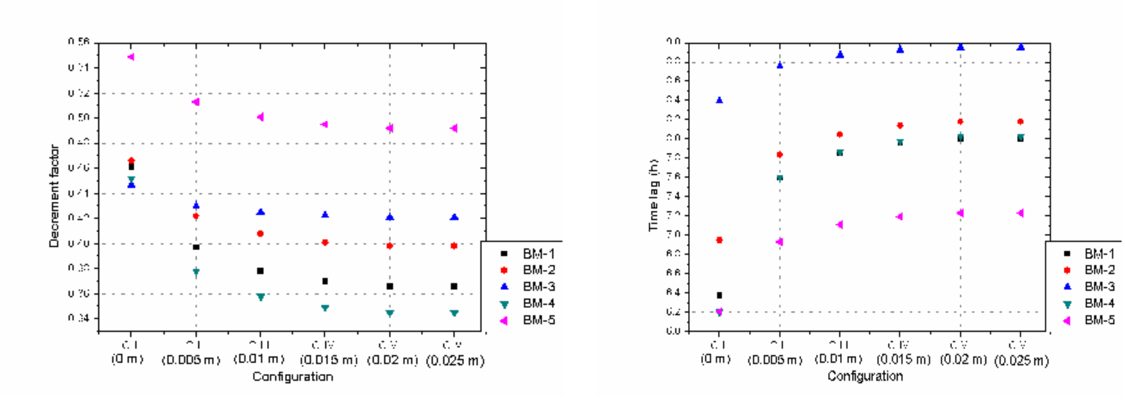


(a)

(b)

Fig. 3. (a) Decrement factor of building materials;(b) Time lag of building materials as a function of thickness

Fig. 4 (a) shows that decrement factor decreases with the increase in the air space thickness within the wall up to 0.02 m and afterwards it remains constant for all materials. This is because of the constant air gap resistance of 0.18 m^2 K/W after 0.02 m thickness of the air space. The decrement factor of building materials; laterite stone, Mud brick, Cellular concrete, Dense concrete and Cinder concrete decrease by 20.60%, 14.59%, 5.81%, 23.67% and 10.38%, respectively, from without air space configuration (C-I) to 0.02 m air space thickness configuration (C-V). From the results, it is also observed that dense concrete has the least decrement factor for all air space thicknesses. Fig. 4 (b) shows the effect of divided air space thickness on time lag of composite walls. From the results, it is observed that time lag increases with the increase in the air space thickness within the wall up to 0.02 m and afterwards it remains constant for all materials. The time lag of building materials; laterite stone, Mud brick, Cellular concrete, Dense concrete and Cinder concrete increase by 20.42%, 15.06%, 6.23%, 22.70% and 14.14%, respectively, from without air space configuration (C-I) to 0.02 m air space thickness configuration (C-V).



(a) (b)

Fig. 4. (a) Effect of air space thickness on decrement factor;(b) Effect of air space thickness on time lag.

5. Conclusions

Thermal transmittance decreases and admittance increases with the increase in the divided air space thickness. Decrement factor decreases with the increase in the divided air space thickness within the composite wall for all building materials. Dense concrete was observed to be the energy efficient from the lowest decrement factor point of view among five studied building materials. Time lag increases with the increase in the divided air space thickness within the composite wall for all building materials. Cellular concrete was observed to be the energy efficient from the highest time lag perspective among five studied building materials.

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