INVESTIGATION OF UNSTEADY THERMAL RESPONSE CHARACTERISTICS OF HOLLOW BRICKS EXPOSED TO SINUSOIDAL SOLAR THERMAL EXCITATION

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ABSTRACT
This paper presents the unsteady thermal response characteristics such as, admittance, transmittance, decrement factor, time lag, surface factor, surface factor time lag and areal thermal heat capacity of hollow bricks with different materials and varying air gap in hollow bricks for reducing heat gain into the buildings. A computer simulation program was developed which employs a cyclic admittance method. The results showed that thermal admittance, surface factor time lag, decrement factor time lag and areal thermal heat capacity values increase and thermal transmittance and decrement factor decrease with the increase in the number of air gaps in hollow bricks.

INTRODUCTION
The building sector is responsible for 33% of energy consumption in India, with commercial building sector and residential building sector responsible for 8% and 25% respectively (ECBC, 2009). Buildings with climate responsive design consume around 10% to 15% less energy as compared to conventional buildings. The building envelope is the most important and fundamental part of building. Building envelopes consist of walls, roofs, ground, doors and windows. These building envelopes help in blocking or attenuating the heat transfer, airflow and day lighting into the building. The effects of thermal properties and thickness of building walls on decrement factor and decrement factor time lag have been investigated using Crank Nicolson method was reported earlier (Asan et al., 1998). The effects of Wall’s insulation thickness and insulation position in the wall on time lag and decrement factor were studied in detail (Asan, 1998; Asan, 2000; Ashok babu et al., 2014). Thermal response characteristics of homogeneous and composite building and insulating materials in India were studied in detail (Saboor et al., 2014). The cyclic admittance method was used to study the moisture content dependent parameters (Hall et al., 2008). The present study uses the cyclic response admittance method to calculate unsteady state thermal response characteristics of the solid and hollow bricks.

Bricks are the most widely used and the most important building materials for the construction of walls. Proper design of bricks can save both material and energy. Thus, it is imperative to pay attention to the crucial aspect of energy efficient brick design. This paper presents the unsteady thermal performance characteristics of various solid and hollow bricks exposed to sinusoidal periodic thermal excitation. The results of the study help to dampen high outside temperature variation on inside thermal comfort.

UNSTEADY STATE THERMAL PROPERTIES OF BRICKS
The admittance procedure was used to calculate unsteady state thermal response parameters values using 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 environmental node.

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

\[
\frac{\partial^2 \theta}{\partial X^2} = \frac{\rho C_p \partial \theta}{k \partial t}
\]  

(1)

Where, \( \theta \) is temperature, \( X \) is the thickness of the material (m), \( \rho \) is density in kg/m\(^3\), \( C_p \) is specific heat capacity in J/kg K and \( k \) is thermal conductivity in W/m K. \( t \) is time in s.

The boundary conditions are,

\[
\begin{align*}
\left. \frac{\partial \theta}{\partial X} \right|_{X=0} &= h_i (\theta_{in}(t) - \theta) \\
\left. \frac{\partial \theta}{\partial X} \right|_{X=L} &= h_o (\theta_{out}(t) - \theta)
\end{align*}
\]

Where, \( h_i \) is brick inner surface heat transfer coefficient, \( h_o \) is brick outer surface heat transfer coefficient, \( \theta_{in} \) is indoor room air temperature and \( \theta_{out} \) is sol-air temperature.

![Figure 1 Brick with indoor and outdoor conditions](image-url)
The solution to the Eq. (1) can be written as (Davies, 2004; Pipes 1957),

\[
\frac{T_j}{q_i} = \left[ \frac{cosh(z + jz)}{(sinh(z + jz))} \right] A + jB = (C + jD)/a
\]

(2)

Where:
- cyclic thickness \( (z) = \sqrt{\pi p c e^2/\lambda p} = \sqrt{\pi T e/\lambda P} \)
- Characteristic admittance of slab \( a = \sqrt{2\pi p c e^2/\lambda p} = \sqrt{2\pi T e/\lambda P} \)

\[
\begin{bmatrix}
A + jB \\
(C + jD)/a \\
(-D + jC)/a \\
A + jB
\end{bmatrix}
\]

(3)

Where:
- \( A = \cosh(z) \cos(z) \)
- \( B = \sinh(z) \sin(z) \)
- \( C = [\cosh(z) \sin(z) + \sinh(z) \cos(z)]/\sqrt{2} \)
- \( D = [\cosh(z) \sin(z) - \sinh(z) \cos(z)]/\sqrt{2} \)

The matrix form of solid brick can be written as shown in Eq. (4)

\[
\begin{bmatrix}
\theta_1 \\
\theta_2 \\
\theta_3 \\
\theta_4
\end{bmatrix} = \begin{bmatrix}
1 & 0 & -R_w & 1 \\
1 & 0 & -R_w & 1 \\
1 & 0 & 1 & 0 \\
1 & 0 & 1 & 0
\end{bmatrix}
\begin{bmatrix}
m_1 & m_2 & m_3 & m_4 \\
n_1 & n_2 & n_3 & n_4 \\
q_1 & q_2 & q_3 & q_4 \\
1 & 1 & 1 & 1
\end{bmatrix}
\]

(4)

The matrix form of hollow brick with two air gaps is as shown in Eq. (5)

\[
\begin{bmatrix}
\theta_1 \\
\theta_2 \\
\theta_3 \\
\theta_4
\end{bmatrix} = \begin{bmatrix}
1 & 0 & 0 & 0 \\
1 & 0 & 1 & 0 \\
1 & 0 & 0 & 0 \\
1 & 0 & 0 & 0
\end{bmatrix}
\begin{bmatrix}
m_1 & m_2 & m_3 & m_4 \\
n_1 & n_2 & n_3 & n_4 \\
q_1 & q_2 & q_3 & q_4 \\
1 & 1 & 1 & 1
\end{bmatrix}
\]

(5)

The matrix form of hollow brick with three air gaps can be written as shown in Eq. (6)

\[
\begin{bmatrix}
\theta_1 \\
\theta_2 \\
\theta_3 \\
\theta_4
\end{bmatrix} = \begin{bmatrix}
1 & 0 & 0 & 0 \\
1 & 0 & 0 & 0 \\
1 & 0 & 0 & 0 \\
1 & 0 & 0 & 0
\end{bmatrix}
\begin{bmatrix}
m_1 & m_2 & m_3 & m_4 \\
n_1 & n_2 & n_3 & n_4 \\
q_1 & q_2 & q_3 & q_4 \\
1 & 1 & 1 & 1
\end{bmatrix}
\]

(6)

Where, \( m, n \) and \( o \) are the elements of the walls.

\[
\begin{bmatrix}
\theta_1 \\
\theta_2 \\
\theta_3 \\
\theta_4
\end{bmatrix} = \begin{bmatrix}
A_1 & A_2 & A_3 & A_4 \\
B_1 & B_2 & B_3 & B_4 \\
C_1 & C_2 & C_3 & C_4 \\
D_1 & D_2 & D_3 & D_4
\end{bmatrix}
\]

(7)

Thermal transmittance (U) 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.

\[
U = \frac{1}{R_{sw} + \frac{1}{\alpha T_e} + \frac{2}{\lambda t_a} ... + \frac{1}{\alpha T_e} + \frac{2}{\lambda t_a} + R_{sw}}
\]

(8)

Thermal resistance for divided air spaces (Ra) for one dimensional horizontal heat flow can be calculated using Eq. (9)

\[
R_a = \frac{1}{1.25 + 2.32 \left(1 + \frac{1}{1 + \frac{2}{h} - \frac{1}{\lambda T_e}}\right)}
\]

(9)

Where: \( t_a \) is air space thickness and \( b_a \) is air space breadth.

The following are the unsteady properties derived by solving one dimensional diffusion equation under periodic convective boundary conditions (CIBSE, 2006).

Admittance (Y) of the brick can be defined as the ability of brick element to exchange heat with a space when it is subjected to cyclic variation in temperature.

\[
Y = \left| y_i \right| = \left| \frac{q_i}{q_{i+1}} \right| = -A_1/A_2
\]

(10)

The time difference between the timing of the peak heat flow at the internal surface and timing of the peak internal temperature is called admittance time lead (\( \omega \)) and can be calculated using Eq. (11)

\[
\omega = \frac{12}{\pi} \arctan \left( \frac{\text{Im}(y_i)}{\text{Re}(y_i)} \right)
\]

(11)

Decrement factor (f) is the ratio of the cyclic heat flux transmission from outside environment to the inside room to the steady state flux transmission.

\[
f = \left| f_i \right| = \left| \frac{1}{UA_2} \right|
\]

(12)

Decrement time lag (\( \phi \)) is the time lag between the timing of the internal temperature peak and the peak heat flow out of the external surface.

\[
\phi = \frac{12}{\pi} \arctan \left( \frac{\text{Im}(y_i)}{\text{Re}(y_i)} \right)
\]

(13)

Surface Factor (F) is the ratio of the variation of heat flow about its mean value readmitted to a space from the surface, to the variation of heat flow about its mean value absorbed at the surface.

\[
F = \left| F_i \right| = \left| 1 - R_{sw} \right|
\]

(14)

Surface factor time lag (\( \psi \)) is the time lag between the timing of the peak heat flow entering the surface and peak heat flow leaving the surface into the room.

\[
\psi = \frac{12}{\pi} \arctan \left( \frac{\text{Im}(F_i)}{\text{Re}(F_i)} \right)
\]

(15)

Areal thermal heat capacity (\( \chi \)) is the amount of energy stored in the element over the first half period of the heat flow swing per unit area of building element per unit degree of temperature swing. The same amount of heat is released in the following half period.

\[
\chi = \frac{1}{2\pi} \left[ \frac{A_1 - 1}{A_2} \right]
\]

(16)

DYNAMIC THERMAL RESPONSE OF SOLID AND HOLLOW BRICKS

Table 1 shows the thermo-physical properties of the brick materials considered for the study. In the table, \( k, p, C_p \) and \( \alpha \) represent the values of thermal conductivity, density, specific heat capacity and thermal diffusivity, respectively. Thermo-physical properties of bricks are taken from Indian standard code IS 3792:1978 and their characterization is as per the code (IS: 3792, 1978). Figure 2 shows the configuration of six different types of solid and hollow bricks taken for the study. The external dimensions of the brick are 0.29m X 0.14m X 0.09m.
as per the Indian standard code IS 3952:1988. The web thickness for all the hollow bricks studied is not less than 0.008m as per the IS code (IS: 3952, 1988). Table 2 shows the air space dimensions and their resistances calculated from Eq. (9). Air space resistance of brick hollow depends mainly on its thickness and breadth. The bricks are considered as external bricks therefore internal surface resistance Rsi is taken as 0.13 m² K/W and external surface resistance Rse is taken as 0.04 m² K/W as per CIBSE standards for computations of external solid and hollow bricks. The computer simulation program was developed to calculate all the unsteady thermal response characteristics of solid and hollow bricks. The results of the simulation program are confirming to CIBSE standards. The unsteady state thermal characteristics were measured for all the bricks considered for the study. Table 3, Table 4, Table 5, Table 6 and Table 7 show unsteady thermal response characteristics of both solid and hollow bricks made of concrete, burnt brick, mud brick, cinder concrete and cellular concrete, respectively.

Table 1 Thermo physical properties of the brick materials

<table>
<thead>
<tr>
<th>Brick material</th>
<th>Code</th>
<th>k</th>
<th>ρ</th>
<th>Cp</th>
<th>α X 10⁻⁷</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete block</td>
<td>CB</td>
<td>1.74</td>
<td>2410</td>
<td>880</td>
<td>8.204</td>
</tr>
<tr>
<td>Burnt brick</td>
<td>BB</td>
<td>0.811</td>
<td>1820</td>
<td>880</td>
<td>5.063</td>
</tr>
<tr>
<td>Mud brick</td>
<td>MB</td>
<td>0.75</td>
<td>1731</td>
<td>880</td>
<td>4.923</td>
</tr>
<tr>
<td>Cinder Concrete</td>
<td>CC</td>
<td>0.686</td>
<td>1406</td>
<td>840</td>
<td>5.808</td>
</tr>
<tr>
<td>Cellular concrete block</td>
<td>CCB</td>
<td>0.188</td>
<td>704</td>
<td>1050</td>
<td>2.543</td>
</tr>
</tbody>
</table>

Table 2 Air space dimensions and air space resistances of hollow bricks

<table>
<thead>
<tr>
<th>S.No.</th>
<th>Air space thickness tₐ (m)</th>
<th>Air space breadth bₐ (m)</th>
<th>Air space resistance Rₐ (m² K/W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.11</td>
<td>0.29</td>
<td>0.193</td>
</tr>
<tr>
<td>2</td>
<td>0.05</td>
<td>0.29</td>
<td>0.181</td>
</tr>
<tr>
<td>3</td>
<td>0.03</td>
<td>0.29</td>
<td>0.176</td>
</tr>
<tr>
<td>4</td>
<td>0.02</td>
<td>0.29</td>
<td>0.174</td>
</tr>
<tr>
<td>5</td>
<td>0.014</td>
<td>0.29</td>
<td>0.173</td>
</tr>
</tbody>
</table>

Table 3 Unsteady thermal response characteristics of concrete blocks

<table>
<thead>
<tr>
<th>CB Configuration</th>
<th>U (W/m²K)</th>
<th>f</th>
<th>φ (h)</th>
<th>V (W/m²K)</th>
<th>ω (h)</th>
<th>F</th>
<th>Ψ (h)</th>
<th>χ (J/m²K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C-a</td>
<td>3.994</td>
<td>0.736</td>
<td>3.672</td>
<td>5.335</td>
<td>0.983</td>
<td>0.374</td>
<td>1.875</td>
<td>70521</td>
</tr>
<tr>
<td>C-b</td>
<td>2.630</td>
<td>0.976</td>
<td>1.100</td>
<td>2.986</td>
<td>1.247</td>
<td>0.644</td>
<td>0.742</td>
<td>38711</td>
</tr>
<tr>
<td>C-c</td>
<td>1.802</td>
<td>0.938</td>
<td>2.005</td>
<td>2.692</td>
<td>2.198</td>
<td>0.731</td>
<td>1.004</td>
<td>47231</td>
</tr>
<tr>
<td>C-d</td>
<td>1.376</td>
<td>0.868</td>
<td>3.143</td>
<td>2.813</td>
<td>2.661</td>
<td>0.757</td>
<td>1.202</td>
<td>53999</td>
</tr>
<tr>
<td>C-e</td>
<td>1.110</td>
<td>0.764</td>
<td>4.452</td>
<td>2.973</td>
<td>2.780</td>
<td>0.756</td>
<td>1.323</td>
<td>57862</td>
</tr>
<tr>
<td>C-f</td>
<td>0.930</td>
<td>0.641</td>
<td>5.842</td>
<td>3.605</td>
<td>2.758</td>
<td>0.749</td>
<td>1.371</td>
<td>58885</td>
</tr>
</tbody>
</table>
Table 4 Unsteady thermal response characteristics of burnt bricks

<table>
<thead>
<tr>
<th>BB Configuration</th>
<th>U (W/m²K)</th>
<th>f</th>
<th>ϕ (h)</th>
<th>Y (W/m²K)</th>
<th>ω (h)</th>
<th>F</th>
<th>Ψ (h)</th>
<th>χ (J/m²K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C-a</td>
<td>2.919</td>
<td>0.746</td>
<td>3.935</td>
<td>4.040</td>
<td>1.364</td>
<td>0.505</td>
<td>1.554</td>
<td>62491</td>
</tr>
<tr>
<td>C-b</td>
<td>2.500</td>
<td>0.985</td>
<td>0.886</td>
<td>2.726</td>
<td>1.064</td>
<td>0.666</td>
<td>0.560</td>
<td>39126</td>
</tr>
<tr>
<td>C-c</td>
<td>1.720</td>
<td>0.960</td>
<td>1.612</td>
<td>2.314</td>
<td>2.002</td>
<td>0.755</td>
<td>0.766</td>
<td>35981</td>
</tr>
<tr>
<td>C-d</td>
<td>1.316</td>
<td>0.913</td>
<td>2.541</td>
<td>2.337</td>
<td>2.591</td>
<td>0.787</td>
<td>0.933</td>
<td>41953</td>
</tr>
<tr>
<td>C-e</td>
<td>1.064</td>
<td>0.836</td>
<td>3.640</td>
<td>2.464</td>
<td>2.832</td>
<td>0.793</td>
<td>1.053</td>
<td>46180</td>
</tr>
<tr>
<td>C-f</td>
<td>0.891</td>
<td>0.735</td>
<td>4.842</td>
<td>2.571</td>
<td>2.872</td>
<td>0.789</td>
<td>1.119</td>
<td>48322</td>
</tr>
</tbody>
</table>

Table 5 Unsteady thermal response characteristics of mud bricks

<table>
<thead>
<tr>
<th>MB Configuration</th>
<th>U (W/m²K)</th>
<th>f</th>
<th>ϕ (h)</th>
<th>Y (W/m²K)</th>
<th>ω (h)</th>
<th>F</th>
<th>Ψ (h)</th>
<th>χ (J/m²K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C-a</td>
<td>2.804</td>
<td>0.753</td>
<td>3.911</td>
<td>4.273</td>
<td>1.411</td>
<td>0.522</td>
<td>1.504</td>
<td>60797</td>
</tr>
<tr>
<td>C-b</td>
<td>2.482</td>
<td>0.986</td>
<td>0.851</td>
<td>2.689</td>
<td>1.030</td>
<td>0.669</td>
<td>0.532</td>
<td>27687</td>
</tr>
<tr>
<td>C-c</td>
<td>1.708</td>
<td>0.964</td>
<td>1.547</td>
<td>2.258</td>
<td>1.960</td>
<td>0.758</td>
<td>0.729</td>
<td>34264</td>
</tr>
<tr>
<td>C-d</td>
<td>1.308</td>
<td>0.919</td>
<td>2.441</td>
<td>2.264</td>
<td>2.568</td>
<td>0.791</td>
<td>0.892</td>
<td>40069</td>
</tr>
<tr>
<td>C-e</td>
<td>1.057</td>
<td>0.847</td>
<td>3.503</td>
<td>2.838</td>
<td>2.832</td>
<td>0.799</td>
<td>1.010</td>
<td>44300</td>
</tr>
<tr>
<td>C-f</td>
<td>0.886</td>
<td>0.750</td>
<td>4.671</td>
<td>2.490</td>
<td>2.887</td>
<td>0.796</td>
<td>1.078</td>
<td>46588</td>
</tr>
</tbody>
</table>

Table 6 Unsteady thermal response characteristics of cinder concrete

<table>
<thead>
<tr>
<th>CC Configuration</th>
<th>U (W/m²K)</th>
<th>f</th>
<th>ϕ (h)</th>
<th>Y (W/m²K)</th>
<th>ω (h)</th>
<th>F</th>
<th>Ψ (h)</th>
<th>χ (J/m²K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C-a</td>
<td>2.674</td>
<td>0.819</td>
<td>0.303</td>
<td>3.844</td>
<td>1.466</td>
<td>0.568</td>
<td>1.279</td>
<td>51909</td>
</tr>
<tr>
<td>C-b</td>
<td>2.459</td>
<td>0.991</td>
<td>0.668</td>
<td>2.589</td>
<td>0.837</td>
<td>0.675</td>
<td>0.414</td>
<td>21506</td>
</tr>
<tr>
<td>C-c</td>
<td>1.694</td>
<td>0.977</td>
<td>1.217</td>
<td>2.053</td>
<td>1.691</td>
<td>0.767</td>
<td>0.570</td>
<td>26790</td>
</tr>
<tr>
<td>C-d</td>
<td>1.297</td>
<td>0.949</td>
<td>1.932</td>
<td>1.959</td>
<td>2.376</td>
<td>0.807</td>
<td>0.706</td>
<td>31734</td>
</tr>
<tr>
<td>C-e</td>
<td>1.049</td>
<td>0.899</td>
<td>2.798</td>
<td>2.023</td>
<td>2.770</td>
<td>0.822</td>
<td>0.816</td>
<td>35815</td>
</tr>
<tr>
<td>C-f</td>
<td>0.879</td>
<td>0.827</td>
<td>3.778</td>
<td>2.120</td>
<td>2.927</td>
<td>0.824</td>
<td>0.893</td>
<td>38655</td>
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</tbody>
</table>

Table 7 Unsteady thermal response characteristics of cellular concrete blocks

<table>
<thead>
<tr>
<th>CCB Configuration</th>
<th>U (W/m²K)</th>
<th>f</th>
<th>ϕ (h)</th>
<th>Y (W/m²K)</th>
<th>ω (h)</th>
<th>F</th>
<th>Ψ (h)</th>
<th>χ (J/m²K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C-a</td>
<td>1.093</td>
<td>0.745</td>
<td>4.503</td>
<td>2.313</td>
<td>2.248</td>
<td>0.768</td>
<td>0.835</td>
<td>35740</td>
</tr>
<tr>
<td>C-b</td>
<td>1.914</td>
<td>0.995</td>
<td>0.553</td>
<td>1.986</td>
<td>0.747</td>
<td>0.748</td>
<td>0.256</td>
<td>12947</td>
</tr>
<tr>
<td>C-c</td>
<td>1.342</td>
<td>0.986</td>
<td>0.989</td>
<td>1.537</td>
<td>1.486</td>
<td>0.818</td>
<td>0.354</td>
<td>16397</td>
</tr>
<tr>
<td>C-d</td>
<td>1.037</td>
<td>0.968</td>
<td>1.558</td>
<td>1.406</td>
<td>2.167</td>
<td>0.851</td>
<td>0.441</td>
<td>19702</td>
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<td>C-e</td>
<td>0.843</td>
<td>0.935</td>
<td>2.253</td>
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<td>2.647</td>
<td>0.867</td>
<td>0.517</td>
<td>22634</td>
</tr>
<tr>
<td>C-f</td>
<td>0.710</td>
<td>0.885</td>
<td>3.053</td>
<td>1.464</td>
<td>2.906</td>
<td>0.872</td>
<td>0.576</td>
<td>24987</td>
</tr>
</tbody>
</table>

**RESULTS AND DISCUSSIONS**

Decrement factor and time lag of solid bricks

Decrement factor decreases and decrement time lag increases with the increase in the thickness of the solid bricks. Figure 3 (a) and (b) show the decrement factor and it’s time lag as a function of thickness. Lower the decrement factor the higher is the wall effectiveness at suppressing temperature swings. The time lag of decrement factor should be as high as possible. From the results it is observed that concrete block (CB) up to 0.1m offers lower decrement factor, whereas cellular concrete block (CCB) offers lower decrement factor for all its thicknesses over 0.1m among five brick materials studied. The cellular concrete blocks (CCB) give the highest time lag values at all the thicknesses of the bricks among five studied brick materials.

Admittance and Transmittance of solid bricks

High thermal admittance values are advantageous from a thermal mass perspective, whereas low thermal transmittance values are desirable for low energy transfer through walls. Thermal transmittance is steady state property and thermal admittance is a dynamic property of brick material. Figure 4 shows admittance and the transmittance of solid bricks as a function of thickness. From the results, it is noted that concrete block (CB) has the highest thermal mass due to higher thermal admittance values and cinder concrete (CC) has the lowest thermal mass due to lower thermal admittance values at all the brick thicknesses among five brick materials studied.
Cellular concrete block (CCB) has the lowest thermal transmittance values at all brick thicknesses among five brick materials investigated therefore they serve as the best insulation materials.

Admittance and Transmittance of hollow bricks
Figure 5 shows the admittance and transmittance of hollow bricks of five different brick materials. From the results, it is observed that thermal transmittance decreases with the increase in the number of air gaps in the brick. For reduced cooling loads in the buildings, admittance should be as high as possible and thermal transmittance should be as low as possible. Brick with five air gaps (C-f) offers the maximum thermal admittance values at minimum thermal transmittance among all studied configurations with five brick materials. Among all the studied hollow brick configurations (From C-b to C-f), concrete block bricks (CB) with five air gaps (C-f) offer highest admittance values (3.06 W/m²K) therefore concrete block bricks can store maximum energy (58885 J/m²K) among all studied configurations with five brick materials. Cellular concrete blocks (CCB) offer lowest thermal transmittance for all the configurations among five brick materials studied hence, they are good insulators. It is observed that solid bricks have high thermal admittance with high thermal transmittance values, whereas hollow bricks have good admittance values at reduced thermal transmittance values.

Surface factor and it’s time lag of hollow bricks
Figure 6 shows the surface factor and it’s time lag of hollow bricks of five different brick materials. Surface factor should be as low as possible and surface factor time lag should be as high as possible. Responsiveness of the bricks to the short wave radiation decreases with the increase in the number of air gaps in the bricks. From the results, it is observed that bricks with five air gaps (C-f) have higher surface factor time lags compared to the other hollow brick configurations. Concrete blocks (CB) with five air gaps offer highest surface factor time lags (1.37) among all the studied hollow brick configurations (C-b to C-f). Hence, they are slow responsive to short wave radiation than any other studied hollow brick configurations with five brick materials.

Decrement factor and it’s time lag of hollow bricks
Figure 7 (a) and 7 (b) show the decrement factor and it’s time lag of hollow bricks of five different brick materials respectively. Hollow effect is significant on decrement factor and time lag values. The decrement factor decreases and time lag value increase with the increase in the number of air gaps in the bricks. Bricks with four air gaps offer the lowest decrement factor and the highest time lag values among all the studied hollow bricks. From the results, it is observed that concrete block (CB) with five air gaps offer the least decrement factor (0.64) and highest time lag (5.84) values among all the studied configurations with five brick materials. Hence increasing the number of air gaps in the bricks is the best from lower decrement factor and higher time lag perspective.

Areal thermal heat capacity of hollow bricks
Figure 8 shows the areal thermal heat capacity of the hollow bricks. This gives the clear picture of the amount of energy stored in the brick during daytime. The same amount of energy will be released during night time. From the results, it is noticed that areal thermal heat capacity increases with the increase in the number of air gaps in the bricks. Concrete block is observed to be efficient for storing maximum energy among all the configurations of five brick materials studied, whereas cellular concrete blocks are observed to be poor in storage among all the configurations studied with five brick materials. Concrete block (CB) with five air gaps (C-f) stores maximum energy (58885 J/m²K) among all the hollow brick configurations studied with five brick materials.

Figure 3 (a) Decrement factor of solid brick as a function of thickness (b) Time lag of solid brick as a function of thickness
Figure 4 Admittance and transmittance of solid brick as a function of thickness

Figure 5 Admittance and transmittance of hollow bricks

Figure 6 Surface factor and it’s time lag of hollow brick

Figure 7 (a) Decrement factor of hollow bricks (b) Time lag of hollow bricks
CONCLUSIONS

- Thermal admittance, decrement time lag, surface factor time lag and areal thermal heat capacity of the bricks increase with the increase in the number of air gaps within the brick due to improved thermal mass and thermal insulation. These enhanced unsteady state properties make the hollow bricks more energy efficient than the solid bricks.
- Thermal transmittance and decrement factor of the hollow bricks decrease with the increase in the number of air gaps in the bricks. This behavior of the bricks helps in reducing cooling loads of the buildings.
- Concrete block (CB) with five air gaps offers the highest admittance (5.84) at minimum thermal transmittance, lowest decrement factor (0.64), highest time lag (5.84h), highest areal thermal heat capacity (58885 J/m²K) and highest surface factor time lag (1.37h) values among twenty five hollow brick configurations with five brick materials. Hence, these hollow bricks are recommended for energy efficient building construction among five brick materials.
- Increase in the air gaps in the bricks increases the thermal insulation (decreases the thermal transmittance) and increases the thermal mass. These are essential parameters for energy efficient hollow bricks.

The results of the study help in designing energy efficient hollow bricks for building construction.

NOMENCLATURE

- $C_p$ = Specific heat capacity (J/kgK)
- $f$ = Decrement factor (Dimension less)
- $F$ = Surface factor (Dimension less)
- $k$ = Thermal Conductivity (W/mK)
- $U$ = Thermal transmittance (W/m²K)
- $Y$ = Thermal admittance (W/m²K)
- $\alpha$ = Thermal diffusivity (m²/s)
- $\rho$ = Density (kg/m³)
- $\phi$ = Decrement time lag (h)
- $\chi$ = Areal thermal heat capacity (J/m²K)
- $\psi$ = Surface factor time lag (h)
- $\omega$ = Admittance time lead (h)

REFERENCES


