A Comparison of Passive Cooling Techniques

G. N. TIWARI*, M. UPADHYAY*, S. N. RAI*

A comparison of passive cooling techniques of a non-airconditioned apartment for Delhi climatic conditions has been presented. The various cooling techniques namely, evaporative cooling, movable canvas, roof gardens, shading effect and air cavity in walls etc. have been incorporated in the thermal analysis. Numerical computations were carried out for Delhi climatic conditions and it is inferred that

(i) the evaporative cooling is the best option to reduce the incoming heat flux through the roof if the water is easily available, and
(ii) the air cavity also reduces the incoming flux entering through walls.

NOMENCLATURE

- $A_s$: surface area of isothermal mass (m$^2$)
- $b$: breadth (m)
- $C_T$: specific heat of air (J/kg · °C)
- $C_r$: thermal air conductivity of air-gap (W/m · °C)
- $C_i$: specific heat of conducting material in $i$th layer of the roof/walls (J/kg · °C)
- $C_w$: specific heat of water (J/kg · °C)
- $d$: depth of water film (m)
- $f_s$: shading factor for windows
- $h_s$: heat transfer coefficient from the enclosed air to the underground surface (W/m$^2$ · °C)
- $h_c$: convective heat transfer coefficient from the exposed surface of the roof/walls with and without water film (W/m$^2$ · °C)
- $h_h$: heat transfer coefficient for the doors (W/m$^2$ · °C)
- $h_c$: convective heat transfer coefficient from the roof surface to moving water (W/m$^2$ · °C)
- $h_r$: heat transfer coefficient from bare surface of the roof/walls to ambient (W/m$^2$ · °C)
- $h_i$: heat transfer coefficient from inside surface of the roof/wall to an enclosed room air (W/m$^2$ · °C)
- $h_c$: convective heat transfer coefficient from the room air to isothermal mass and vice versa (W/m$^2$ · °C)
- $h_r$: radiative heat transfer coefficient from the exposed surface of the roof/walls with and without water film (W/m$^2$ · °C)
- $i$: solar intensity on the roof and walls (W/m$^2$)
- $k$: thermal conductivity (W/m · K)
- $L$: characteristic length of the roof (m)
- $M_a$: mass of air inside room (kg)
- $M_w$: mass of water over the roof (kg)
- $m_w$: mass flow rate of water over the roof (kg/sec)
- $n$: integers
- $P(T)$: partial pressure of the saturated vapor at temperature $T$ (Pa)
- $Q$: rate of heat flux gain/loss to an enclosed room (W/m$^2$)
- $T_w$: ground temperature at large depth (°C)
- $T_a$: ambient air temperature (°C)
- $T_r$: room temperature (°C)
- $T_{hmax}$: maximum room air temperature (°C)
- $T_{hmin}$: minimum room air temperature (°C)
- $T_{w}$: solar temperature (°C)
- $T_{wall}$: water temperature over the roof (°C)
- $T_{L}$: thermal load levelling
- $U(i)$: overall heat transfer coefficient from the roof surface in the case of movable insulator (W/m$^2$ · °C)
- $u$: water velocity (m/sec)
- $r$: wind velocity (m/sec)
- $X$: position coordinate along the thickness of the roof (m)
- $Y$: position coordinate along flow direction (m)

Greek symbols

- $\alpha$: fraction of solar radiation absorbed by the surface
- $\gamma$: relative humidity
- $\Delta R$: difference between the longwave radiation incident on the surface from sky and surrounding, and the radiation emitted by a black body at ambient temperature (W/m$^2$)
- $\Delta \gamma$: difference in relative humidity between enclosed air and outside air
- $\varepsilon$: emissivity
- $\eta$: number of air change with infiltration (h$^{-1}$)
- $\eta_i$: number of air change with ventilation (h$^{-1}$)
- $\rho$: density (kg/m$^3$)
- $\sigma$: Stefan's constant = 5.67 × 10$^{-8}$ (W/m$^2$ · K$^4$)
- $\omega$: 2π/period (sec$^{-1}$).

Subscripts

- $a$: ambient air
- $b$: floor/ground
- $d$: door
- $g$: glass window
- $i$: east, west, north and south wall
- $l$: isothermal mass
- $j$: $j$th layer in the roof
- $R$: room
- $v$: ventilation
- $w$: water
- $ww$: wall

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INTRODUCTION

A BUILDING cooled and heated by the use of solar energy is generally referred to as a solar house. The classification of solar house has been given in Table 1. The cooling and heating of a building can be done either by a passive or an active method. Sodha et al. [1] and Kaushik et al. [2] have described the various passive techniques for cooling and heating which can be integrated with the walls and roof of a building. For heating a building, the well-known concepts namely 'Trombe Wall', [3] 'The Water Wall', [4] 'The Transwall', [5] and 'A Solarium', [6] etc. are used. The relative thermal performance of these concepts for a south wall has been studied by Tiwari et al. [7]. Later, the effect of these concepts for a south wall was integrated with non-air-conditioned houses and the studies have been carried out by Tiwari [8] for cold climatic conditions.

In order to cool the building, there are various cooling concepts namely water film, [9] roof pond, [10] roof garden, movable insulation, and plantation of vegetables over the roof, [11] and air cavity in wall [12] etc. which can also be integrated to provide thermal comfort inside the building. The detailed relative thermal performances of these concepts have been studied by Singh [12]. The use of an earth air tunnel for the same purpose is also a most promising technique, [13] which can be considered as an active mode of operation. Srivastava et al. [14] have also designed a building for thermal comfort under the semi-arid climate of India by considering the chimney effect.

In this communication, comparative study of a non-air-conditioned two room apartment has been presented by incorporating the various cooling techniques through walls/roof including ventilation and infiltration, [15].

The energy balance equations for the different components of the house have been separately written. The steady state solutions for room air temperature has been derived to evaluate the thermal comfort index inside room.

DESIGN OF SOLAR HOUSE

The floor plan of a two room apartment has been shown in Fig. 1(a). The partition inside the house has been done by wooden wall. The windows and doors were provided in the east and the west direction as cross-ventilation is required. The windows are also provided in the bath room as well as in the kitchen for a better light during the day. The elevation of the plane at X = Y has been depicted in Fig. 1(b). In this case, the inclination of the roof is toward north facing so that the incident solar radiation on the roof will be minimized. The cross-sectional view of the roof and walls with different cooling concept have been shown in Figs 2 and 3 respectively. In this case, a thermal comfort can be achieved by reducing the incoming flux inside the room through the walls and the roof. The dimensions of the roof/walls, windows and doors are given in Table 2. The air cavity in the wall will act as an insulation which can minimize heat transfer by conduction. The roof and the walls are constructed of concrete, mud-plasika* and bricks which can also be used for load levelling and for a phase lag between maximum temperature inside and outside the room.

THERMAL ANALYSIS

In order to write the energy balance equation for the different components of the proposed two room apartment, the following assumptions have been made:

there is no stratification in air temperature inside the enclosed room:

<table>
<thead>
<tr>
<th>Serial number</th>
<th>Component</th>
<th>Areas (in²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>South wall</td>
<td>10 x 4 = 40</td>
</tr>
<tr>
<td>2</td>
<td>North wall</td>
<td>10 x 3 = 30</td>
</tr>
<tr>
<td>3</td>
<td>East wall</td>
<td>15.3</td>
</tr>
<tr>
<td>4</td>
<td>West wall</td>
<td>15.3</td>
</tr>
<tr>
<td>5</td>
<td>Door (East and West)</td>
<td>1.9 x 0.9 = 1.7</td>
</tr>
<tr>
<td>6</td>
<td>Window (East and West)</td>
<td>2 x 2 = 4</td>
</tr>
<tr>
<td>7</td>
<td>Floor</td>
<td>10 x 6 = 60</td>
</tr>
<tr>
<td>8</td>
<td>Roof</td>
<td>61</td>
</tr>
</tbody>
</table>

* Refers to a mixture of soil, dried grass and water.
A Comparison of Passive Cooling Techniques

Fig. 1. (a) Floor layout plan of two room apartment non-air conditioned, showing location of living rooms, kitchen and bathroom, respectively. (b) Cross-sectional view at X-Y of Fig. 1(a) showing location of window and the door respectively.

The house is in steady state condition; one dimensional heat propagation due to conduction has been considered; there is continuity in temperature and the flux at interface; the heat lost to the floor has been considered in a steady state condition, and the numerical computations have been carried out for clear climatic conditions, etc.

The solar radiation, after reflection from the exposed surface of the roof and the walls, is absorbed by the roof and the wall. The absorbed solar radiation is transferred inside the room by conduction. In order to find the rate of heat conduction inside the room, the following one dimensional heat conduction equation is solved:

\[
\frac{K_j}{\rho_j C_v} \frac{\partial^2 T_j}{\partial x^2} = \frac{\partial T_j}{\partial t}. \tag{1}
\]

In a steady-state condition, the solution of equation (1) can be expressed as

\[
T_j(x, t) = T_{j0}(x) + \sum_{n=1}^{\infty} T_{jn} \exp (in\omega t). \tag{2a}
\]

After substituting equation (2a) in equation (1) and equating time independent and dependent parts of both sides of above equation and after algebraic simplification one gets,

\[
T_j(x, t) = A_j x + B_j + \sum_{n=1}^{\infty} [C_n \exp (\beta_n x) + D_n \exp (-\beta_n x)] \exp (in\omega t) \tag{2b}
\]

where

\[
\beta_n = \left( \frac{n\omega \rho C_v}{2K_j} \right)^{1/2} (1 + i)
\]

\(A_j, B_j, C_n\) and \(D_n\) are constants and can be determined by using the energy balance equations for each case by separating real and imaginary part, here \(j\) refers to the roof for the \(j\)th layer.

**ROOF**

Normal roof (Fig. 2(a))

The energy balance equation at \(x = 0\) (Fig. 2(a)) for the surface exposed to the solar radiation and external environment is

\[
-k \left. \frac{\partial T_1}{\partial x} \right|_{x=0} = \alpha R(t) - (h_s + h_p) (T_1|_{x=0} - T_s) - \Delta \Delta R
\]

\[
= h_s (T_s - T_1|_{x=0}) \tag{3}
\]
where \( h_n = h_s + h_u \), \( h_s \), \( h_u \) denotes the heat transfer coefficient by convection and radiation from surface to outside environment and \( \varepsilon \Delta R \) denotes the amount of net long wavelength radiation exchange with the sky, and

\[
T_w = \frac{q(t)}{h_0} + T_u - \frac{\varepsilon \Delta R}{h_n}
\]

is known as solar temperature.

**Water film** (Figs 2(b) and 2(c))

The reduction of the heat flux entering into the room through the roof by utilizing the evaporation of the water over the roof surfaces is a highly effective approach; this can be achieved by an open roof pond or thin film or flow of water or by a roof garden. A roof garden is essentially an evaporative cooling system except that it requires a layer of soil on the roof for grass and other vegetation to grow.

A general formulation of the water evaporative cooling has been presented; the water film, open roof pond, moving water and roof garden are special cases of this analysis. [9].

The energy balance equation for the flowing water layer over the roof of thickness \( a \) (Fig. 2(d)) is given by

\[
\left( \frac{b ho_s C_v}{\partial t} + \frac{m_u C_u}{\partial y} \frac{\partial T_u}{\partial y} \right) dy = \left[ q(t) - \dot{q}_i - \dot{q}_v - h_n(T_u - T_w) \right] dy \cdot b \]

**Movable canvas**

Fig. 2. Cross-sectional view of the roof with different treatment. (a) Normal roof consists of layers of concrete, mud phuska and brick. (b) Water film/sprinkl/gunny bag (special case of (d)). (c) Roof garden over the normal roof. (d) Cross-section of moving water film over the normal roof. (e) Movable canvas during sunshine hours.

where

\[
h_n = \frac{K_u}{L_u} \left[ 0.14 (Gr \cdot Pr)^{1/3} + 0.664 (Pr)^{1/3} (Re)^{1/2} \right],
\]

\[
\dot{q}_i = h_i (T_u - T_w),
\]

\[
\dot{q}_v = h_v (T_u - T_v),
\]

\[
\dot{q}_v = 0.013 h_u [P(T_w) - P(T_u) - r],
\]

\[
h_v = C_v [(T_u + 273.15) - (T_u + 261.15) \ln(T_u - T_w)].
\]

\[
\Delta v = 0 - h_v,
\]

where \( L_u \) is the characteristic length of the roof.

In a normal operating temperature range, the saturation vapour pressures at water and ambient air temperature can be expressed as, Nayak et al. [11],

\[
P(T) = R_1 T + R_2
\]

where \( R_1 \) and \( R_2 \) are the two constants which can be obtained from the steam table by using the least square curve fitting. Further equation (5) can be rewritten as

\[
M_u C_v \frac{\partial T}{\partial t} + m_u C_u \frac{\partial T_u}{\partial y} = -bH(T_u - T_w) + b h_n (T_u - T_w)
\]

where
where $b_x$, $b_y$, $U_x$ and $U_y$ are constants and can be evaluated by using the Fourier analysis techniques, [12].

**CONTINUITY OF TEMPERATURE AND FLUX AT INTERFACES**

At the interfaces $x = x_i$ and $x = x_{i+1}$, the temperature and heat flux must be continuous, i.e.

\[ T(x, t)_{x=x_i} = T(x, t)_{x=x_{i+1}}, \quad (11) \]

\[-K_i \frac{\partial T}{\partial x} \bigg|_{x=x_i} = K_{i+1} \frac{\partial T}{\partial x} \bigg|_{x=x_{i+1}}, \quad (12)\]

where $j$ and $j+1$ refer to the interface between $j$th and $(j+1)$th layer of the roof and the walls.

**The surfaces in contact with room air**

At the surface which is in contact with the inside room air temperature, the rate of heat flux entering the room can be written as

\[ Q_x = -K_i \frac{\partial T}{\partial x} \bigg|_{x=x_i-n, x_i} = h_i(T_{i,x_i-n, x_i} - T_a) \quad (13) \]

**Walls**

In the present case, two types of walls namely solid and cavity walls have been considered for the evaluation of an enclosed room air temperature. The energy balance for the exposed surface and the surface which is in contact with room air can be written as

**Solid wall.** (Fig. 3(a) )

\[-K_i \frac{\partial T}{\partial x} \bigg|_{x=0} = a_i I(t) - h_i(T_{i,x=0} - T_a) \quad (14) \]

and

\[ Q_{ww} = K_i \frac{\partial T}{\partial x} \bigg|_{x=x_i-n, x_i} = h_i(T_{i,x_i-n} - T_a) \quad (15) \]

**Cavity wall.** (Fig. 3(b) ) In this case, there will be an additional energy balance equation in comparison with solid wall which can be written as

\[ \begin{aligned}
\end{aligned} \]

**Fig. 3.** Schematic representation of proposed configuration of walls (a) solid wall and (b) air cavity wall.
whereas $C_i$ is the air conductance of cavity provided in the walls $(i)$ refers to east, west, north and south wall, $f_i$ is a term signifying sunshading, i.e. $f_i = 1$ no shading and $f_i = 0$ means 100% shading. $I(i)$ is the radiation on $i$th wall and can be evaluated by Liu and Jordon formula, Duffie and Beckman [16] and Fig. 4.

**(Glass windows)**

The rate of heat flux entering inside the room through a glass window can be written as

$$\dot{Q}_a = (I(t)f_w - U_a(T_r - T_a))$$

during sunshine hours

$$= U_a(T_r - T_a)$$

during off sunshine hours, (17)

whereas $f_w$ is a factor which determines that a curtain has been used or not. In the case of curtain, $f_w = 0.15$ otherwise $f_w = 1$.

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Fig. 4. (a) Hourly variation of beam and diffuse radiation on the horizontal surface for a typical summer day in Delhi (16 May 1981). (b) Hourly variation of ambient air temperature and the heat transfer coefficient in the case of movable canvas.
Doors
The rate of heat transferred through the door material from inside the room to outside or vice-versa is given by

\[ Q_d = h_d(T_d - T_a) \]  \hspace{1cm} (18)

Floor of the house
In this case, the heat conducted through the floor of the house is determined in a steady state condition. If the floor is constructed with various layers of different material for water proofing, then the rate of heat transferred to ground can be estimated as

\[ Q_s = h_s(T_s - T_a) \]  \hspace{1cm} (19)

where \( T_s \) is the temperature inside ground and

\[ h_s = \left[ \frac{1}{h_f} + \sum \frac{L_m}{K_m} \right]^{-1}. \]

Isothermal mass
In a residential house, the amount of furniture, public utility, and kitchen material, etc. depends upon the number of occupants which introduces the concept of isothermal mass. In this case, a fraction of energy is stored by isothermal mass and the fluctuations in temperature inside the room can be minimized. This provides a reasonable thermal comfort index throughout a complete cycle.

The energy balances can be written for isothermal mass as

\[ Q_i = h_i A_i (T_i - T_a) = M_i C_i \frac{dT_i}{dt}. \]  \hspace{1cm} (20)

Ventilation/infiltration
The rates of thermal energy carried away from inside room of the house due to ventilation and infiltration are determined by the following expression, Shaviv and Shaviv [15],

\[ Q_v = V_v + V_i (T_a - T_d) \]  \hspace{1cm} (21)

where

\[ V_v = 2463 M_a (\eta + \eta_s) \frac{\Delta y}{C_a} \]

and

\[ V_i = M_i (\eta + \eta_s) \left\{ \frac{C_w + 1.88 \Delta y}{C_w} \right\} \]

\( \eta_s = 0 \) without infiltration, i.e. the room enclosure is air leak proof;
\( \eta > 0 \) with infiltration, i.e. there is a leakage of room air regularly;
\( \eta = 0 \) without ventilation, i.e. the doors/windows are closed for blockage of room air to go out;
\( \eta > 0 \) with ventilation, i.e. the room air is moving out through doors and windows whenever it is required to achieve thermal comfort.

In the case of requirement of ventilation, the window should be opened for cross-ventilation and the excess thermal energy available inside room of the house will be carried away by the wind which will pass through the room.

Now, the energy balance equation for an enclosed room air temperature can be written as:

\[ \frac{dT_R}{dt} = \sum M_i C_i \frac{dT_i}{dt} \]

\[ + [ \text{the rate of heat lost to the floor, isothermal mass} ] \]

\[ + [ \text{the rate of heat carried away due to ventilation/infiltration} ] \]  \hspace{1cm} (22)

Since the rate of heat flux entering the room is periodic in nature due to periodical behaviour of solar intensity and ambient air temperature and hence the room air temperature can also be written as:

\[ T_R = T_{in} + \sum_{n=1}^r T_{in} \exp (in\omega t) \]  \hspace{1cm} (23)

where \( T_{in} \) and \( T_{in} \) can be obtained from the time independent and time dependent parts of equation (22).

Equation (22) has been first solved by neglecting the effect of isothermal mass and it was observed that the heat capacity of enclosed air can be neglected in comparison to the heat capacity of isothermal mass. For simplification, an isothermal mass has been considered as equivalent to water mass due to its large heat capacity.

**THERMAL LOAD LEVELLING**

The thermal load levelling (TLL) for a non-air-conditioned room is defined as

\[ TLL = \frac{T_{max} - T_{min}}{T_{max} + T_{min}} \]  \hspace{1cm} (24)

The value of TLL should be minimum for best load levelling along with reduced \( T_{max} \) and \( T_{min} \) and the calculated values of TLL for different cases are given in Tables 3(a), (b) and (c).

**NUMERICAL COMPUTATIONS**

In order to have numerical computations for an enclosed room air temperature, equation (22) has been used. The numerical computations have been carried out for the following cases:

(i) Normal roof with and without cavity wall.
(ii) Roof with water flow with air cavity wall.
(iii) Roof with shading with air cavity.
(iv) Roof with movable canvas with air cavity.

A separate computer program was developed for time dependent and independent part for cases (i-iii) which gives a matrix of the order of 13 x 13. In the case (iv), a matrix of the order of 26 x 26 was solved by considering the number of harmonics \( n = 6 \). Further, the thermal load levelling (TLL) has also been computed by using the maximum and minimum temperature of the enclosed room air temperature.

The following physical properties of roof/walls component and heat transfer coefficients have been used for evaluating enclosed room air temperature.
Table 3(a). The thermal load levelling (TLL) for normal roof

<table>
<thead>
<tr>
<th>Serial number</th>
<th>Different combinations of wall</th>
<th>$T_{\text{max}}$ (°C)</th>
<th>$T_{\text{min}}$ (°C)</th>
<th>Thermal load levelling (TLL)</th>
<th>$\Delta T = T_{\text{max}} - T_{\text{min}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Wall with air gap (solid wall = 0.11 m and air gap = 0.05 m)</td>
<td>23.41</td>
<td>35.90</td>
<td>0.211</td>
<td>12.49</td>
</tr>
<tr>
<td>2</td>
<td>Wall with air gap (solid wall = 0.23 m and air gap = 0.05 m)</td>
<td>23.4</td>
<td>35.06</td>
<td>0.198</td>
<td>11.66</td>
</tr>
<tr>
<td>3</td>
<td>Solid wall, 0.11 m</td>
<td>24.24</td>
<td>37.90</td>
<td>0.220</td>
<td>13.66</td>
</tr>
<tr>
<td>4</td>
<td>Solid wall, 0.23 m</td>
<td>23.84</td>
<td>36.90</td>
<td>0.215</td>
<td>13.06</td>
</tr>
<tr>
<td>5</td>
<td>Solid wall, 0.35 m</td>
<td>23.76</td>
<td>35.56</td>
<td>0.199</td>
<td>11.80</td>
</tr>
<tr>
<td>6</td>
<td>Ambient air</td>
<td>27.41</td>
<td>44.60</td>
<td>17.19</td>
<td></td>
</tr>
</tbody>
</table>

Table 3(b). Thermal load levelling (TLL) for different roof temperature

<table>
<thead>
<tr>
<th>Serial number</th>
<th>Different roof treatments</th>
<th>$T_{\text{max}}$ (°C)</th>
<th>$T_{\text{min}}$ (°C)</th>
<th>Thermal load levelling (TLL)</th>
<th>$\Delta T = T_{\text{max}} - T_{\text{min}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>30% shaded roof</td>
<td>23.15</td>
<td>35.71</td>
<td>0.213</td>
<td>12.56</td>
</tr>
<tr>
<td>2</td>
<td>60% shaded roof</td>
<td>22.90</td>
<td>35.52</td>
<td>0.210</td>
<td>12.62</td>
</tr>
<tr>
<td>3</td>
<td>90% shaded roof</td>
<td>22.65</td>
<td>35.34</td>
<td>0.219</td>
<td>12.69</td>
</tr>
<tr>
<td>4</td>
<td>Without movable canvas</td>
<td>24.16</td>
<td>36.64</td>
<td>0.205</td>
<td>12.48</td>
</tr>
<tr>
<td>5</td>
<td>With movable canvas</td>
<td>23.45</td>
<td>36.17</td>
<td>0.214</td>
<td>12.72</td>
</tr>
<tr>
<td>6</td>
<td>Water spray</td>
<td>22.44</td>
<td>35.13</td>
<td>0.220</td>
<td>12.69</td>
</tr>
<tr>
<td>7</td>
<td>Water film</td>
<td>22.13</td>
<td>34.85</td>
<td>0.223</td>
<td>12.72</td>
</tr>
<tr>
<td>8</td>
<td>Gunny bags</td>
<td>21.81</td>
<td>34.59</td>
<td>0.226</td>
<td>12.78</td>
</tr>
<tr>
<td>9</td>
<td>Roof garden $\gamma = 0.1$</td>
<td>22.35</td>
<td>35.10</td>
<td>0.222</td>
<td>12.75</td>
</tr>
<tr>
<td>10</td>
<td>Roof garden $\gamma = 0.2$</td>
<td>22.08</td>
<td>34.87</td>
<td>0.225</td>
<td>12.79</td>
</tr>
<tr>
<td>11</td>
<td>Roof garden $\gamma = 0.5$</td>
<td>21.81</td>
<td>34.60</td>
<td>0.227</td>
<td>12.79</td>
</tr>
<tr>
<td>12</td>
<td>No shading $\gamma = 0.3$</td>
<td>22.11</td>
<td>34.89</td>
<td>0.224</td>
<td>12.76</td>
</tr>
<tr>
<td>13</td>
<td>Shaded roof (30%) with water spray</td>
<td>22.03</td>
<td>34.83</td>
<td>0.225</td>
<td>12.80</td>
</tr>
<tr>
<td>14</td>
<td>60% shading with water film</td>
<td>21.95</td>
<td>34.75</td>
<td>0.226</td>
<td>12.80</td>
</tr>
<tr>
<td>15</td>
<td>90% shading with gunny bags</td>
<td>21.85</td>
<td>34.67</td>
<td>0.227</td>
<td>12.82</td>
</tr>
</tbody>
</table>

Table 3(c). Effect of isothermal mass on thermal load levelling (TLL)

<table>
<thead>
<tr>
<th>Serial number</th>
<th>Different isothermal mass (kg)</th>
<th>$T_{\text{max}}$ (°C)</th>
<th>$T_{\text{min}}$ (°C)</th>
<th>Thermal load levelling (TLL)</th>
<th>$\Delta T = T_{\text{max}} - T_{\text{min}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>250 kg</td>
<td>20.65</td>
<td>33.01</td>
<td>0.230</td>
<td>12.36</td>
</tr>
<tr>
<td>2</td>
<td>500 kg</td>
<td>20.71</td>
<td>32.90</td>
<td>0.226</td>
<td>12.19</td>
</tr>
<tr>
<td>3</td>
<td>1000 kg</td>
<td>21.05</td>
<td>32.72</td>
<td>0.217</td>
<td>11.67</td>
</tr>
</tbody>
</table>

**DIFFERENT PARAMETERS USED FOR CALCULATIONS**

**Physical properties of roof/walls material, Singh [12]**

<table>
<thead>
<tr>
<th></th>
<th>Concrete</th>
<th>Mud phuskha</th>
<th>Brick tiles</th>
<th>Water</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal conductivity</td>
<td>0.72</td>
<td>0.52</td>
<td>0.72</td>
<td>–</td>
</tr>
<tr>
<td>Density (kg/m³)</td>
<td>1858.0</td>
<td>2050.6</td>
<td>1922.4</td>
<td>1000.0</td>
</tr>
<tr>
<td>Specific heat (J/kg K)</td>
<td>655.2</td>
<td>1840.0</td>
<td>837.4</td>
<td>4190.0</td>
</tr>
<tr>
<td>Thickness (m)</td>
<td>0.15</td>
<td>0.10</td>
<td>0.05</td>
<td>0.005</td>
</tr>
</tbody>
</table>

**Normal roof with/without shading**

\[ h_s = 22.78 \text{ W/m}^2 \text{°C} \]
\[ h_a = 5.7 \text{ to } 8.0 \text{ W/m}^2 \text{°C} \] (heat flow downwards)

\[ \epsilon = 0.9 \]
\[ \Delta R = 61.11 \text{ W/m}^2 \]

**Roof with movable canvas**

\[ U = 22.78 \text{ W/m}^2 \text{°C} \] (when canvas is not used)
\[ = 3.16 \text{ W/m}^2 \text{°C} \] (when canvas is used)

\[ h_s = 5.7 \text{ to } 8.0 \text{ W/m}^2 \text{°C} \] (heat flow downwards)
\[ \Delta R = 61.11 \text{ W/m}^2 \text{°C} \]
\[ \epsilon = 0.9 \]

**Roof with water film/roof garden**

\[ h_c = 10.0 \text{ m} \]
\[ h_c = 283.98 \text{ W/m}^2 \text{°C} \]
\[ l_c = 6.0 \text{ m} \]
\[ r (relative humidity) = 0.1, 0.3, 0.5 \]
\[ R_1 = 325.17 \text{ N/m}^2 \text{°C} \]
\[ R_2 = -5154.89 \text{ N/m}^2 \]
\[ \epsilon = 3.5 \text{ m/s} \]
\[ \sigma_w = 0.0 \]
\[ \sigma_f = 0.54 \] (for water film case)
\[ = 0.6 \] (for roof garden case)
Walls
Thickness of wall:
0.11 m, 0.23 m, 0.35 m
air gap = 0.05 m.
The value of air conductance corresponding to 0.05 has been used for calculations and it is same for all thickness of walls.

Climatic data
The hourly variation of beam and diffuse radiation for a typical hot day of Delhi has been shown in Fig. 4(a). Figure 4(b) has been used to calculate solar radiations on different walls and inclined roof by using the Liu and Jordan formula, [16]. The hourly variation of intensity and $U$ value (in case of movable insulation) have been shown in Fig. 4(b). The coefficients of equation (10) have been evaluated by using this value of $U$ from Fig. 4(b).

The hourly variation of room air temperature with different roof treatment and with cavity wall has been shown in Fig. 5. It is observed that there is sharp decrease in maximum and minimum room air temperature due to evaporation processes over the roof with gunny bags/water film. Further, there is a sharp increase in room air temperature between 0800-1000 hours. It is due to the fact that the solar intensity is maximum on the east wall during this period and is trapped inside. The room temperature also decreases due to thermal losses through windows, in the absence of solar radiation on the east and west walls.

The effect of wall thickness with and without air cavity, roof shading effect, movable canvas, roof garden, shading effect with water film on thermal load levelling (PLL) for a non-air-conditioned room have been given in Tables 3(a) and 3(b) respectively. It is inferred from these tables that:

- the thermal load levelling is maximum for the solid walls and the normal roof (serial number 3 of Table 3(a)) and is lowered either in the case of air cavity walls or in the case of greater thickness of the solid walls;
- the fluctuation of room air temperature ($T$, i.e. last column of Table 3(b)) for different roof treatments has also been reduced in comparison to room air temperature fluctuation (serial no. 3 of Table 3(a)) with the solid walls and the normal roof;
- the thermal load levelling in the case of any roof treatment is not significantly affected;
- there is significant reduction in maximum ($T_{max}$) and minimum ($T_{min}$) room air temperature in the case of roof treatment with gunny bags (serial no. 8 of Table 3(b)); and;
- the ratio of inside temperature swing to outside temperature swing for gunny bag is about 0.75 which is required condition for roof cooling.

Further effect of isothermal mass on room air temperature and thermal load levelling (PLL) has been shown in Fig. 6 and Table 3(e) respectively. One can

![Fig. 5. Hourly variation of room temperature with different roof treatments namely: I solid wall with normal roof; II air cavity wall with canvas; and III air cavity wall with gunny bags.](image-url)
observe that the thermal load levelling (TLL) is significantly decreased along with the reduction in the fluctuation (T) due to increase in isothermal mass.

Further, the effect of ventilation has also been carried out through numerical computation and it was observed that there is an increase in room temperature because of higher ambient air temperature. Hence, the ventilation is only required if outside ambient air temperature is lower than room air temperature as expected.

**CONCLUSIONS**

On the basis of numerical computations, the following conclusions have been drawn:

(i) the evaporative cooling is the best technique for minimising heat flux through roof which can be obtained through roof garden, and

(ii) the ventilation through window should be allowed only during night period, if required.

**REFERENCES**