Performance studies of a passively cooled mahal

G.N. Tiwari a, N. Lugani a, A.K. Singh b, H.P. Garg a

* Centre for Energy Studies, Indian Institute of Technology Delhi, Hauz Khas, New Delhi 110016, India
b Development Alternatives, B-32 Tara Crescent, Qutab Institutional Area, New Mehrauli Road, New Delhi 110016, India

Received 1 March 1994; accepted 15 June 1994

Abstract

The design and performance of an ancient passively cooled mahal (building) have been presented. The mahal was generally used for pilgrims during their visit to the city of Banaras. Energy balance equations for different components, namely walls and roof, of a mahal have been used to evaluate the performance of the mahal in terms of an enclosed-room air temperature. It is observed that a reasonable thermal comfort temperature is achieved by ventilation using natural cold air through the windows.

Keywords: Passive building; Natural cooling; Design; Solar house

1. Introduction

In order to achieve thermal comfort in the environment inside a building, various cooling and heating concepts have been classified as (i) passive concepts, and (ii) active concepts.

In the passive concept, cooling and heating devices are integrated into the building. If the cooled/heated air is forced to pass inside the building to achieve thermal comfort from external conditions, then it is referred to as an active concept.

Various passive cooling techniques are available in the literature [1,2]. Some of these techniques are as follows:

(i) evaporative cooling [3,4];
(ii) shading effect [5];
(iii) mud/stone walls [6,7];
(iv) ventilation/infiltration [8].

In this paper, an old building known as Raja mahal, used for religious services, has been studied to see the effect of various cooling concepts considered before construction. The Raja mahal is situated near the banks (ghat) of the River Ganges in Banaras (a city in the state of Uttar Pradesh in India, Fig. 1), now known as Varanasi. Most of the passive cooling concepts were preserved during renovation of the building. The performance of the building has been studied using the basic energy balance for each component of the building including the effect of natural cooling/ventilation and evaporative cooling. Some innovative concepts such as an existing underground tunnel can be integrated for further cooling purposes.

From numerical computations, it has been inferred that:
(i) there is an improvement in thermal comfort by using natural ventilation through the windows;
(ii) thermal comfort can be further increased by having evaporative cooling.

2. Historical background of Banaras

Banaras, an urban area in India (Fig. 1), originated as a site of pilgrimage, and became a centre for the transformation of silk and a leading market in the north Indian financial network.

The founding date of the original city of Banaras is uncertain and the debate between archaeologists and traditional historians concerning the emplacement of Banaras remains open. Jain historical sources mention the visit of (King) Ashoka in 240 BC, Buddha in the 6th century and the birth of Paravsanath in Banaras in the 8th century. Traditional historians argue that the traditional Banaras region has remained unchanged since the founding of the city [9].

As with other ancient Indian cities, Banaras developed through an urban sequence as follows:
(i) the distinctive urban fabric, situated in the part of the city which was at one time called Pakka and nowadays Cauk;
(ii) the urban development spread along the river, composed of representative buildings of the states of Hindu princes;
(iii) the surrounding districts emerged.

The built-up city is segregated by the ghat (vast beaches of stones), pavements and landings ensuring passage towards the water of the River Ganges. They were erected during the construction of the palaces and the bank buildings. They ensure transitional spaces which were developed continuously along the left shore of the River Ganges and accommodate numerous activities of Banarasi culture. They ensure free access to pilgrims and to the public [10].

Permitting frontal access to the water, the ghats are extended by pavements which permit access to the building situated on the upper edge. The projecting facade (front elevation of the building) on the supporting wall, appears to be imposed and prevents the building from flooding during the monsoon season.

3. Details of Raja mahal

3.1. General description

The building under study is known as Raja mahal which consists of a terrace on which there is a refectory (where pilgrims are served food) reserved exclusively for the Brahmans (a caste in Hindu religion), temples and a residential building.

Access to the refectory is by way of a stairway leading from the ghat and passing under the Naubat (the place where the priest plays the trumpet). The refectory is a two-storey building with a terrace roof. On each floor there is a kitchen, a store room and a large hypostyle hall (hall with a large number of columns). Each floor is lit by a central square courtyard. In 1980 the building was restored, using traditional techniques, by the Indian National Trust for art cultural heritage.

3.2. Building plan

The square building faces the River Ganges on the east side (Fig. 2(a) and (d)) and is 19 m away from the river. The main hypostyle is 18.29 m × 18.49 m. It has two bays 9.14 m wide on all sides (as shown by dotted lines in Fig. 2(a) and (b)). Each side has 9 columns of 0.7 m × 0.5 m. The central four columns are closely spaced. Along the main hall towards the south there are three rooms measuring 3.0 m × 5.8 m, 3.0 m × 5.8 m and 8.7 m × 4.3 m. These rooms are used for grain storage on the ground floor and as a kitchen, on the first floor (Fig. 2(b)) to serve food to the Brahmans. On the north side there is a small temple.

The central courtyard always had a large cylindrical vessel in which water was stored from the River Ganges. There is no well in the building unlike other buildings along the ghat.

The window openings are on the east side of the building towards the river bank. The windows are provided only on the first floor (Fig. 2(b)) of the Raja mahal at a sill level of 2.5 m above floor level. The size of the windows is 0.6 m × 0.6 m. The window sections are inset in a 1.0 m thick stone wall. They are thirteen in number placed at the refectory level on the first floor (Fig. 2(b)). The entrance to the first floor is by the stairway, 2.1 m wide, which leads to the hypostyle hall.

The frame of wooden beams and purlins (wooden members to support the roof) supports the roof of 0.3 m thickness of lime mortar. The wooden beam sections have now been replaced by 'I' sections of steel, over which a concrete roof of 0.4 m of cement mortar in a 1:2:4 cement-mortar mix has been laid. The building is at a plinth level of 11.6 m from the water level (Fig. 2(c)). The plinth is assumed to be resting on a foundation filled with stone boulders compactly laid together with mortar. The hypostyle hall on the first floor leads to the terrace at the ground-floor hall. The terrace overlooks the River Ganges.

4. Natural cooling concepts

The effects of air temperature, solar radiation, humidity, wind and sky clearness upon the building determine the internal thermal environment. These out-
(continued)
door conditions are constantly changing and, at any
given time, their effects on a specific building element
depend upon the location and orientation of that ele-
ment. Solar radiation is the main cause of overheating
of buildings. Therefore, reduction of solar radiation,
interception, absorption and inward transmission by
the building envelope are the first principles for natural
cooling [5,7]. The solar radiation received by the building
elements is dependent on their orientations.

The variation of solar intensity on the horizontal and
east surface wall is shown in Fig. 3. Direction of air
and wind in general is in the south-west to north-east
direction. The wind velocity in summer varies between
2 and 2.5 m/s. The main component of solar radiation
is on the roof and the wall facing the south-east direction.
Other walls are overshadowed by adjacent buildings
along the street. Other exposed surfaces border the
alley (narrow street). The most favourable orientation
is therefore south-east.

Structural shading devices, such as horizontally and
vertically inclined louvres, movable screens, deciduous
trees and plants, can all be used to control direct solar
radiation. The effectiveness of sunshades is poor, there-
fore windows should be provided only in those positions
where effective protection against the sun can be en-
sured. Protection [1,6] against diffused and reflected
radiation cannot be provided by any simple method.
Shading is the easiest to provide on the south wall
where a horizontal projection at an appropriate height
will exclude summer sun while permitting sunlight in
the buildings in winter. The east and west walls can
be protected by a combination of horizontal and vertical
louvres, but fixed shading devices of this kind cannot
be designed to allow sunlight in winter. In the case of
Raja mahal, small windows on the first floor have been
provided. These windows have a small area towards
the inside, compared to the area towards the outside.
They are inset in the thick stone wall thereby reducing
the heat transmission to the interior in summer and
the decrease of heat loss in winter. These windows do
not interfere with nighttime radiative cooling [11]. On
the east and west sides, surface shading can be provided
as an integral part of the building element. External shading devices used on a building surface should not interfere with nighttime radiative cooling. This is particularly important for the roof surface which is exposed to the cool night sky. A solid cover of concrete or galvanized iron sheets will shade the roof from solar radiation but it will not permit the roof to cool down by radiation to the night sky. An alternative method is to provide a cover of deciduous plants or creepers. Because of leaf evaporation, the temperature of such a cover will be lower than air temperature, thus allowing effective radiant cooling and shading at the same time.

The reduction of interior solar heat gain in summer is provided by the shading of courtyard walls. The layout plan of the building is compact with very few openings other than the door. The heat loss in summer is enhanced by ventilation of the veranda, by evaporative cooling and sprinkling of water.

5. Thermal analysis

To formulate the energy balance equation for different components of the mahal under study, the following assumptions have been made:
- one-dimensional heat flow has been considered through the walls and roof;
- there is no temperature gradient within the enclosure;
- the wind velocity through windows has been considered to be a constant;
- there is a uniform water layer over the roof;
- the mahal is in a steady-state condition;
- the water and roof temperatures are almost the same owing to the thin layers;
- the heat flows through the partition roof and the ground floor have been considered to be in a steady-state condition.

Following Kaushik et al. [4] and Sodha et al. [2], energy balance equations for different components of the mahal are given in the following paragraphs.

(a) Roof of the mahal
The rates of heat flux per square metre passing through the roof surface at \( x = 0 \) with (gunny bags) and without roof treatment are given by:

(i) roof with gunny bags

\[
-K_1 \frac{\partial T_1}{\partial x} \bigg|_{x=0} = \alpha_1(t) - h_c(T_1|_{x=0} - T_a) - h_e(T_1|_{x=0} - T_a) - h_r(T_1|_{x=0} - T_a) - e \Delta R
\]

(ii) roof without gunny bags

\[
-K_1 \frac{\partial T_1}{\partial x} \bigg|_{x=0} = \alpha_1(t) - h(T_1|_{x=0} - T_a) - e \Delta R
\]

where

\[
h_c = 2.8 + 3V
\]

\[
h_e = 0.016h_t \left( \frac{p_w - p_a}{T_w - T_a} \right)
\]

\[
h_r = e \alpha/(T_w + 273)^4 - (T_{sky} + 273)^4)/(T_w - T_s)
\]

\[
h = 5.7 + 3.8V
\]

\[
T_{sky} = (T_a - 12)
\]

The rate of heat flux per square metre entering an inside enclosure through the roof is given by:

\[
-K_1 \frac{\partial T_1}{\partial x} \bigg|_{x=L_K} = h_1[T_1|_{x=L_K} - T_{K1}]
\]

(b) Exposed wall
The rates of heat flux per square metre through an exposed wall at \( x = 0 \) and \( x = L_w \) via conduction are given by:

(i) exposed wall surface

\[
-K_2 \frac{\partial T_2}{\partial x} \bigg|_{x=0} = \alpha_2(t) - h(T_2|_{x=0} - T_a)
\]

(ii) first-floor enclosure

\[
-K_2 \frac{\partial T_2}{\partial x} \bigg|_{x=L_w} = h_2[T_2|_{x=L_w} - T_{R2}]
\]

(iii) ground-floor enclosure

\[
-K_2 \frac{\partial T_2}{\partial x} \bigg|_{x=L_w} = h_2[T_2|_{x=L_w} - T_{R2}]
\]
Unexposed wall (facing to lane)

The rates of heat flux per square metre, gain and loss, through unexposed walls are given by:

(i) first floor enclosure

\[-K_1 \frac{\partial T_1}{\partial x} \bigg|_{x=L_w} = h \left[ T_{3,1} - T_{L_w} - T_{R1} \right] \]  

(5b)

(ii) ground floor enclosure

\[-K_1 \frac{\partial T_3}{\partial x} \bigg|_{x=L_w} = h \left[ T_{3,1} - L_{L_w} - T_{R2} \right] \]  

(5c)

(d) First floor ceiling

The rate of heat flux per square metre from enclosure 1 to enclosure 2 and vice-versa is given by

\[ Q_{12} = U_{12} (T_{R1} - T_{R2}) \]  

(6)

where

\[ U_{12} = \left( \frac{1}{R_1} + \frac{L_{L_w}}{K_1} + \frac{1}{h_1} \right)^{-1} \]

(e) Ground floor

The rate of heat flux per square metre lost to the ground is given by

\[ \dot{Q}_b = U_b (T_{R2} - T_\infty) \]  

(7)

where

\[ U_b = \left( \frac{1}{R_2} + \frac{L_8}{K_x} \right)^{-1} \]

and \( T_\infty \) is the temperature within the ground at large distances and it can be considered as the average temperature within the ground at a distance of about one metre.

The temperature distribution in the roof and walls can be obtained by solving the following one-dimensional heat conduction equation:

\[ K_i \frac{\partial^2 T}{\partial \xi^2} = \rho_i C_i \frac{\partial T}{\partial \xi} \]  

(8)

The solution of Eq. (8) \((T_i)\), in a periodic condition can be written as [12]:

\[ T_i = A_i x + B_i + \sum_{n=1}^{\infty} \left[ C_{in} \exp(\beta_{in} x) + D_{in} \exp(-\beta_{in} x) \right] \exp(i\omega t) \]  

(9)

where

\[ \beta_{in} = \pm \alpha_{in} (1 + i) \]

\[ \alpha_{in} = \sqrt{\omega \rho_i C_i / 2K_i} \]

and \( A_i, B_i, C_{in} \) and \( D_{in} \) are constants, which can be obtained by using the above boundary conditions, Eqs. (1)–(7), where \( j = 1, 2, \) and 3 refer to roof, exposed and unexposed walls, respectively.

Now the energy balance equations for enclosure 1 (first floor) and enclosure 2 (ground floor) can be written as:

\[ A_R h_1 [T_{1L} - T_{R1}] + A_{w1} h_1 [T_{2L} - T_{R1}] - T_{R1}] + A_{w2} h_2 [T_{2L} - T_{R2}] - T_{R2}] = M_{R1} C_{R1} \frac{dT_{R1}}{dt} + h_{11} A_{11} (T_{R1} - T_{11}) + V_0 \]

\[ + V_1 (T_{R1} - T_s) + U_W A_R (T_{R1} - T_{R2}) \]  

(10)

and

\[ U_R A_R (T_{R1} - T_{R2}) + A_{w2} h_1 [T_{2L} - T_{R2}] - T_{R2}] = M_{R2} C_{R2} \frac{dT_{R2}}{dt} \]

\[ + h_{12} A_{12} (T_{R2} - T_{12}) + U_b (T_{R2} - T) \]  

(11)

where the expressions for \( V_0 \) and \( V_1 \) can be obtained as given by Shaviv and Shaviv [8].

Further, the energy balance equations for isothermal mass for enclosures 1 and 2 are given by:

\[ h_{11} A_{11} (T_{R1} - T_{11}) = M_{11} C_{11} \frac{dT_{11}}{dt} \]  

(12)

and

\[ h_{12} A_{12} (T_{R2} - T_{12}) = M_{12} C_{12} \frac{dT_{12}}{dt} \]  

(13)

Since solar intensity \((I_s(t))\) and ambient air temperature \((T_a(t))\) are periodic in nature, they can be expressed in Fourier series [13]:

\[ I_s(t) = I_{0s} + \sum_{n=1}^{\infty} I_{ns} \exp(i\omega t - \sigma_n) \]  

(14a)

and

\[ T_a(t) = T_{0a} + \sum_{n=1}^{\infty} T_{na} \exp(i\omega t - \sigma_n) \]  

(14b)

It is observed that up to six harmonics of these series give close representation of hourly variation of solar intensity and ambient air temperature and hence only six harmonics have been considered for numerical computations. Furthermore, the enclosed room \((T_{Rj})\) and isothermal mass air temperature \((T_{nj})\) have also been expressed as follows:

\[ T_{Rj} = T_{Rj0} + \sum_{n=1}^{6} T_{Rjn} \exp(i\omega t - \sigma_n) \]  

(15a)

and

\[ T_{nj} = T_{nj0} + \sum_{n=1}^{6} T_{njn} \exp(i\omega t - \sigma_n) \]  

(15b)
Table 1
Properties of materials

<table>
<thead>
<tr>
<th>Material</th>
<th>Temp. (K)</th>
<th>Thermal conductivity K (W/m °C)</th>
<th>Density ρ (kg/m³)</th>
<th>Specific heat C (kJ/kg °C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Limestone</td>
<td>100-300</td>
<td>1.26-1.33</td>
<td>2500</td>
<td>0.90</td>
</tr>
<tr>
<td>Sandstone</td>
<td>40</td>
<td>1.83</td>
<td>2160</td>
<td>0.71</td>
</tr>
<tr>
<td>Wood</td>
<td>30</td>
<td>0.055</td>
<td>1440</td>
<td>0.84</td>
</tr>
<tr>
<td>Cement and mortar</td>
<td>1200</td>
<td>1.90</td>
<td>1500</td>
<td></td>
</tr>
<tr>
<td>Lime mortar</td>
<td>20</td>
<td>0.48</td>
<td>1440</td>
<td>0.84</td>
</tr>
<tr>
<td>Steel</td>
<td>7833</td>
<td>0.46</td>
<td>54</td>
<td>1.474</td>
</tr>
</tbody>
</table>

Fig. 4. Effect of ventilation on room air temperature.

With the help of Eqs. (14) and (15), Eqs. (1)-(13) give two matrices each for the time-independent and time-dependent parts. These matrices have been solved by the inverse matrix method by computational work to determine various constants including constants of enclosures 1 and 2, respectively. The results obtained are illustrated in Figs. 4 and 5.

6. Numerical results and discussion

In order to solve the matrix equation, the following design and climatic parameters have been used:

- \( \alpha = 0.3 \), \( V = 2 \) m/s, \( \varepsilon \Delta R = 60 \) W/m², \( h_e = 8.8 \) W/m² °C, \( h = 13.3 \) W/m² °C, \( h_1 = 5.7 \) W/m² °C, \( h_2 = 5.7 \) W/m² °C, \( T = 25 \) °C, \( L_{R1} = L_{R2} = 0.5 \) m. The properties of the materials are given in Table 1. The dimensions of the mahal are given in Fig. 2(a) and (b). The hourly variations of beam and diffuse radiation are given in Fig. 3.

The hourly variation of room temperatures of enclosure 1 (first floor) and enclosure 2 (ground floor) are shown in Fig. 4. From this Figure, it is clear that the room temperature of the ground floor which is used for storage purposes is significantly lower than the room temperature of the first floor, owing to the fact that the exposed surface area of the first floor is higher than the exposed surface area of the ground floor. The effect of ventilation has also been taken into account and it is observed that ventilation has more effect during sunless hours owing to lower wind temperatures. The wind temperature is also lowered by evaporation from the water surface.

The effects of roof thickness and wetted gunny bags on room air temperatures are shown in Fig. 5. It can be concluded that there is a phase shift of 12 hours...
for 0.40 m roof thickness and also there is a further reduction in room air temperature owing to the large thermal capacity of the room material. There is also a significant reduction in room air temperature owing to evaporation over the roof surface. Most of the solar radiation is cut-off from the roof surface by the presence of gunny bags.

7. Conclusions

On the basis of numerical performance and the study of the building, it is concluded that:

(i) There is a reasonable natural thermal comfort inside various rooms of a Raja mahal owing to the higher plinth level from the water level of the River Ganges which is generally not the case for contemporary building.

(ii) An arrangement for evaporative cooling should be incorporated in the existing structure from a thermal comfort point of view. Here plenty of water is available in the river even in summer. Water is not available for evaporative cooling in most of India in summer. Hence there is no need for re-structure of the existing energy-efficient building from an economical point of view.

Nomenclature

\[ A_{w2} \] surface area of exposed wall for 1st floor (m²)
\[ A_{w3} \] surface area of unexposed wall for 1st floor and ground floor (m²)
\[ C_j \] specific heat of jth roof material (J/kg °C)
\[ C_{11} \] specific heat of 1st isothermal mass (J/kg °C)
\[ C_{12} \] specific heat of 2nd isothermal mass (J/kg °C)
\[ C_{R1} \] specific heat of room air of enclosure 1 (J/kg °C)
\[ C_{R2} \] specific heat of room air of enclosure 2 (J/kg °C)
\[ h \] convective and radiative heat transfer coefficient from the roof to ambient (W/m² °C)
\[ h_c \] convective heat transfer coefficient from roof to ambient (W/m² °C)
\[ h_e \] evaporative heat transfer coefficient for wetted roof (W/m² °C)
\[ h_i \] convective heat transfer coefficient from inner surface of roof/walls to enclosed room (W/m² °C)
\[ h_r \] radiative heat transfer coefficient from roof to sky (W/m² °C)
\[ h_{11} \] convective heat transfer coefficient from enclosed room 1 to isothermal mass 1 (W/m² °C)
\[ h_{12} \] convective heat transfer coefficient from enclosed room 2 to isothermal mass 2 (W/m² °C)
\[ h_1 \] convective heat transfer coefficient from enclosed room 1 to first floor ceiling (W/m² °C)
\[ I_1 \] solar intensity on the roof (W/m²)
\[ I_2 \] solar intensity on exposed wall (W/m²)
Greek letters

$\alpha$ absorptivity
$\varepsilon$ emissivity
$\sigma$ Stefan–Boltzmann constant; $5.67051 \times 10^{-8} \frac{\text{W} \cdot \text{m}^{-2} \cdot \text{K}^{-4}}{}$
$\sigma_n$ phase change
$\rho_i$ density of roof/wall material ($\text{kg/m}^3$)
$\Delta R$ long-wave radiation exchange between roof surface and sky

References