ENERGY CONSERVATION IN A CINEMA HALL UNDER HOT AND DRY CONDITION

A. K. SINGH,1 G. N. TIWARI,1† N. LUGANI1 and H. P. GARG2

1Development Alternatives, B-32, TARA Crescent, Qutab Institutional Area, New Mehrauli Road and
Centre for Energy Studies, Indian Institute of Technology, Delhi, Hauz Khas, New Delhi 110 016, India

(Received 16 November 1994; received for publication 12 July 1995)

Abstract—In this communication, energy conservation in a cinema hall due to evaporative cooling, wind
tower and earth air tunnel has been evaluated. The effects of occupancy, infiltration and lighting have
been taken into account. The load on the air-conditioner is reduced significantly by the earth air tunnel
along with evaporative cooling.

Energy conservation Cooling concepts Energy efficient building

NOMENCLATURE

\[ A_{WT} = \text{Cross-sectional area of wind tower (m}^2) \]
\[ b_r = \text{Width of roof channel (m)} \]
\[ b_E = \text{Width of earth air tunnel (m)} \]
\[ C_e = \text{Specific heat of enclosed air (J/kg °C)} \]
\[ C_w = \text{Specific heat of water (J/kg °C)} \]
\[ d_E = \text{Depth of earth tunnel (m)} \]
\[ d_r = \text{Depth of roof channel (m)} \]
\[ h_{v=0} = \text{Convective and radiative heat transfer coefficient for } v = 0 \text{ (W/m}^2\text{°C)} \]
\[ h_c = \text{Convective heat transfer coefficient (W/m}^2\text{°C)} \]
\[ h_{ic} = \text{Convective heat transfer coefficient from inner surface of walls/roof and doors to enclosed air (W/m}^2\text{°C)} \]
\[ h_{ct} = \text{Convective and radiative heat transfer coefficient from air to roof channel to ambient through top of channel cover (W/m}^2\text{°C)} \]
\[ h_r = \text{Radiative heat transfer coefficient (W/m}^2\text{°C)} \]
\[ h_m = \text{Mass transfer coefficient (kg/s m}^2\text{)} \]
\[ K_a = \text{Thermal conductivity of asbestos (W/m}^2\text{°C)} \]
\[ K_p = \text{Thermal conductivity of plaster (W/m}^2\text{°C)} \]
\[ K_g = \text{Thermal conductivity of ground layer material (W/m}^2\text{°C)} \]
\[ K_d = \text{Thermal conductivity of door material (W/m}^2\text{°C)} \]
\[ K_c = \text{Thermal conductivity of concrete (W/m}^2\text{°C)} \]
\[ K_b = \text{Thermal conductivity of board (used for partition) (W/m}^2\text{°C)} \]
\[ L_p = \text{Thickness of plaster (used for roof and wall) (m)} \]
\[ L_{pl} = \text{Thickness of roof asbestos sheet (m)} \]
\[ L_c = \text{Length of earth tunnel (m)} \]
\[ m_a = \text{Mass flow rate of air (kg/s)} \]
\[ m_{ch} = \text{Mass flow rate of air in roof channel (kg/s)} \]
\[ T_R = \text{Room temperature (°C)} \]
\[ T_a = \text{Ambient air temperature (°C)} \]
\[ T_{rc} = \text{Roof channel temperature (°C)} \]
\[ T_{sw} = \text{Solar temperature without treatment (°C)} \]
\[ T_{ew} = \text{Temperature with wall exposed (°C)} \]
\[ U_d = \text{Overall heat transfer coefficient through door (W/m}^2\text{°C)} \]
\[ U_r = \text{Overall heat transfer coefficient of roof (W/m}^2\text{°C)} \]
\[ U_c = \text{Overall heat transfer coefficient of wall (W/m}^2\text{°C)} \]
\[ U_w = \text{Overall heat transfer coefficient of partition wall (W/m}^2\text{°C)} \]

†To whom all correspondence should be addressed.
**INTRODUCTION**

Much of the energy in the built environment is used for space conditioning, and this consumption can be reduced by energy conservation [1] for most conventional buildings.

The thermal design of the building for efficient heating/cooling embraces a large number of factors that affect the energy balance and, hence, the energy consumption. Since the role of various design and climatological parameters in predicting the thermal environment is too intricate to be assessed independently, it is convenient to develop a thermal model which includes all the different factors over the performance.

Most the literature available on thermal modeling are restricted to air-conditioned buildings [2-4]. However, for a non-air-conditioned building, the inside air temperature is variable and is controlled by many factors, such as air-ventilation and infiltration, size of windows, furnishings and basement ground heat conduction.

Novel concepts of passive cooling systems based on water evaporation over the roof offer simple attempts [5-10]. It is seen that, even for effective roof cooling systems with no ventilation, the average room air temperature remains greater than the ambient air temperature during the night hours [11]. Ventilation control is used to commensurate with comfort conditions.

In this communication, a cinema hall, situated at Chopasani Road, Jodhpur, India, has been considered. The analysis of the building has been made in terms of energy conservation due to various passive cooling concepts, namely; wind tower, earth air tunnel and evaporative cooling. The energy consumed by the building when it has been air-conditioned under normal conditions has also been considered.

**DESIGN OF CINEMA HALL**

The cross-sectional view of the cinema hall with wind tower is shown in Fig. 1 [12]. The floor layout plan with the earth air tunnel of the cinema hall is given in Fig. 2 and has floor dimensions 57.6 m x 26.7 m. It is a two-storey building with a balcony for viewers.

There is an entrance foyer and an electrical room of 5.5 m x 0.7 m. There are thirteen ventilators at a height of 2.9 m. There is an exit verandah, 1.8 m wide and 35.36 m long, and a staircase, 5.06 m long, on the north side.

There are two openings, each 2.4 m wide. There is an emergency staircase, 10 m wide, starting from the outside. On the east wall, there are no windows or ventilators. The east side has extended foyers and a recessed entrance with an overhang of 1.75 m which reduces the solar load on this wall. The projection room projects out at a height of 3 m x 2 m. In order to optimize the thermal performance of the cinema hall, each component, the walls, roofs and verandah, can be considered as an air-cavity channel.

The north, south and east walls contribute very little to the heat load of the conditioned space. The overhang provided for these walls reduces the solar load. The location of the windows and doors is decided with a view to allowing a natural wind load.

The roof is made of asbestos sheet, supported on beams. This arrangement can be considered as an air cavity to circulate the cooled air available through a wind tower, particularly during the night time, inside the cinema hall. The openings for the inlet in the wind tower for the cooled air to flow to the cinema hall depend on the direction of the wind outside the cinema hall.

\[
\begin{align*}
U_{th} & = \text{Overall heat transfer coefficient from room to inside ground (W/m}^2\text{°C)} \\
v & = \text{Velocity of air (m/s)} \\
v_{rc} & = \text{Velocity of air in roof channel (m/s)} \\
w & = \text{Humidity ratio} \\
\rho_a & = \text{Density of air (kg m}^{-3}\text{)} \\
\varepsilon & = \text{Emissivity} \\
\delta_R & = \text{Thermal diffusivity of air} \\
\alpha_r & = \text{Absorptivity of roof surface} \\
\gamma & = \text{Relative humidity}
\end{align*}
\]
Fig. 1. Cross-sectional view of cinema hall.
Fig. 2. Floor layout plan of cinema hall.

All dimensions are in meters.
WEATHER PARAMETERS

For most of the year, Jodhpur has a hot and dry climate. It is visited by monsoons in the month of August. The total rainfall in the year is about 360 mm. For two months in a year, the town experiences a mild winter. The characteristics of the climate are:

(i) High diurnal ranges of temperature and insolation level.
(ii) Fairly good consistent wind, mostly dry throughout the year.
(iii) Very low annual rainfall and, hence, low relative humidity.

The overall climatic parameters indicate that the main comfort demand will be for cooling during the hot seasons and dehumidification during the monsoons. Winter heating is not a very important design constraint as the direct gain through the south-facing wall will provide a good degree of comfort.

GENERAL FORMULATIONS

In a building, heat conveyance takes place due to conduction, convection, radiation and transfer of mass.

The following assumptions have been made in the energy conservation analysis for the cinema hall:

(i) There is no stratification in room temperature.
(ii) Conduction loss/gain through walls, doors and floors have been taken under steady-state conditions.
(iii) The thermal capacity of the thermal mass is negligible.
(iv) The thermal capacity of the roof material produced is insignificant and the quantity of metabolic heat produced is insignificant.

Based on the basic energy balances, in terms of watts, for the different components, namely walls, doors, floors, wind tower and enclosed air of the cinema hall, numerical computations have been carried out.

DIFFERENT COOLING CONCEPTS

Natural cooling techniques can reduce the peak cooling power demand of a building and thus reduce the size of air-conditioning equipment needed and the period for which it is generally required. Passive cooling concepts encompass a large number of natural heat rejection mechanisms, including ventilation, infiltration, evaporation, infra-red transfer to the sky and earth contact cooling.

<table>
<thead>
<tr>
<th>Item</th>
<th>Area (m²)</th>
<th>Volume (m³)</th>
<th>Temperature (°C)</th>
<th>U value (W/m²°C)</th>
<th>Thermal gain/loss (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roof (without treatment)</td>
<td>1800</td>
<td>—</td>
<td>—</td>
<td>53.48 - 27 = 26.48</td>
<td></td>
</tr>
<tr>
<td>Roof (with treatment)</td>
<td>1800</td>
<td>—</td>
<td>168 253.9</td>
<td>55.9 - 27 = 6.9</td>
<td></td>
</tr>
<tr>
<td>West wall</td>
<td>344.3</td>
<td>—</td>
<td>43.75 - 27 = 16.75</td>
<td>3.5</td>
<td>20 184.6</td>
</tr>
<tr>
<td>North wall</td>
<td>11 743.34</td>
<td>—</td>
<td>41.75 - 27 = 14.75</td>
<td>1.86</td>
<td>20 385.3</td>
</tr>
<tr>
<td>East wall</td>
<td>344.3</td>
<td>—</td>
<td>41.75 - 27 = 14.75</td>
<td>3.5</td>
<td>17 774.5</td>
</tr>
<tr>
<td>South wall</td>
<td>11 743.04</td>
<td>—</td>
<td>41.75 - 27 = 14.75</td>
<td>1.86</td>
<td>20 385.3</td>
</tr>
<tr>
<td>Doors</td>
<td>45</td>
<td>—</td>
<td>41.75 - 27 = 14.75</td>
<td>0.5</td>
<td>331.9</td>
</tr>
<tr>
<td>Floor</td>
<td>1537.92</td>
<td>—</td>
<td>33.75 - 27 = 6.75</td>
<td>4.42</td>
<td>45 883.8</td>
</tr>
<tr>
<td>Ventilation</td>
<td>—</td>
<td>—</td>
<td>6.75</td>
<td>0.28</td>
<td>227.3</td>
</tr>
<tr>
<td>Infiltration</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>57 220</td>
</tr>
<tr>
<td>Occupancy (a) 806 (No.)</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>75</td>
<td>60 450</td>
</tr>
<tr>
<td>Occupancy (b) 806 (No.)</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>55 (—44 330)</td>
<td>1875</td>
</tr>
<tr>
<td>Light (a) 1500 W</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>1.25</td>
<td>1250</td>
</tr>
<tr>
<td>Light (b) 1000 W</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>1250</td>
</tr>
<tr>
<td>Appliances</td>
<td>15 770 W</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>15 880</td>
</tr>
</tbody>
</table>
The first step is to reduce any unnecessary thermal load. There are usually two loads in the building: (i) external load due to climate, and (ii) internal load due to people, light, appliances, etc. The thermal load enters the building in three ways:

(i) Penetration of direct beam sunlight.
(ii) Conduction of heat through roof and walls.
(iii) Infiltration of outside air.

Evaporative cooling

Evaporation of water takes place by the conversion of sensible heat into latent heat, and a large amount of heat can be removed by this method [11, 13]. Since evaporation occurs at the liquid interface, it is best to create as much surface area as possible between the water and dry air.

Reduction of the heat flux across the roof assumes prime interest in the thermal design of buildings for hot and dry climates. It is more effective when water is sprinkled over gunny bags (water retentive material) spread over the roof surface, due to their small heat capacity. It provides a uniform wet surface. Solar radiation falling on the water film is utilized for heating and evaporating the water and preventing the heat from entering the roof. In addition to cooling the roof, evaporation also causes cooling of the air above the roof.

Wind tower

A wind tower harnesses the prevailing summer wind to cool and circulate air through the building. The tower is created at the apex of the sloping roof. The upper part of the wind tower is divided into air passages that terminate in openings on the top. These openings have wet gunny bags, as shown in Fig. 1. Because of this, evaporative cooling occurs when the unsaturated air comes into contact with the gunny bags. The circulation of air inside the building can be carried out by forced or natural circulation.

Earth air tunnel

An air tunnel constructed inside the ground exploits the earth storage potential to be effectively used for cooling the building. As the temperature of the ground in summer is much less than the ambient air temperature, the ambient air is cooled along its path. This air can then be circulated in the living space. The provision of an earth air tunnel is shown in Fig. 2. The velocity of air in the tunnel becomes lower due to its large cross-sectional area.

Infiltration and ventilation

Besides providing a comfortable environment, the cool air then drifts into the living space due to infiltration and ventilation, thereby aiding thermal comfort. The above cooling methods can reduce the load on the air-conditioner which is the most conventional method of achieving thermal comfort inside the building. Air-conditioning is meant to control temperature and humidity simultaneously. Air-conditioning, in the present communication, has been considered for summers. In summer, the outside air and humidity are both high. The room, therefore, gains heat as well as moisture. The supply of air to the confined space comprises both fresh air and recirculated air. This is done to maintain a comfortable temperature inside the confined space after taking the thermal loads due to walls, roofs, occupants, floor and ventilators into account.

EQUATIONS USED FOR CALCULATION

Energy saving inside the cinema hall due to various cooling techniques is presented in this section. The rate of heat gain/loss through the roof, walls, doors and floor can be evaluated by using the following equations.

Roof

The thermal energy per square metre passing through the roof is given by

\[ Q_R = U_R (T_{set} - T_R). \]
Solair temperature $T_{sr}$, with water film, can be calculated as follows:

$$T_{sr} = (1/H')(\alpha_w I_r + H_1 T_a - R_0 R_s (1 - \gamma)),$$

where $H' = h_s + h_r + R_0 R_s$, $H_1 = h_s + h_r + \gamma R_0 R_s$, $h_c = 2.8 + 3v$ (excluding radiation losses), $h_0 = h_s + h_r$, $h_0 = 5.7 + 3.8v$ (including radiation losses) and $R_0 = 0.013h_c$.

For $v = 2.5$ m/s, $T_a = 33.75$ °C, $h_0 = 10.3 \text{W/m}^2 \text{°C}$, $\alpha_w = 0.6$, $I_r = 600 \text{ W/m}^2$, $\gamma = 0.55$, $R_s = 325.17 \text{N/m}^2$ °C (summer), $R_s = -5154.89 \text{N/m}^2$ (summer). Hence $T_{srr} = 33.9$ °C.

Solair temperature, without water film, under normal conditions, can be calculated as follows:

$$T_{sr} = \frac{\alpha_w I_w}{h_0} + \frac{\epsilon \Delta R}{h_0},$$

where $T_s = \frac{1}{2}(T_{s(max)} + T_{s(min)})$, $T_{s(max)} = 37.5$ °C, $T_{s(min)} = 30.0$ °C, $h_0 = 5.7 + 3.8v$, $I_w = 600.0 \text{ W/m}^2$, $\alpha_w = 0.6$, $v = 2.5$ m/s, $\epsilon \Delta R = 60.0 \text{ W/m}^2$. Hence $T_{sr} = 53.48$ °C.

The overall heat transfer coefficient can be calculated as follows:

$$U_R = \left( \frac{1}{h_s} + \frac{1}{K_{sh}} + \frac{1}{h_r} + \frac{1}{K_{rl}} + \frac{1}{K_{con}} \right)^{-1},$$

$$= \left( \frac{1}{7} + 0.01 + 1 + 0.01 + 0.075 \right)^{-1}.$$

Hence $U_R = 3.53 \text{ W/m}^2 \text{°C}$.

Thermal loss/gain (without roof treatment) = 78619.43 W, thermal loss/gain (with evaporative cooling) = 22930.38 W.

**Walls**

The net heat gain/loss through walls in all directions is given by

$$Q_w = U_w(T_{sw} - T_a).$$

Solair temperature without shading (i.e. with walls completely exposed to sky) is given by

$$T_{sw} = \frac{\alpha_w I_w}{h_0} + \frac{\epsilon \Delta R}{h_0},$$

where $I_w = 400 \text{ W/m}^2$, $\alpha_w = 0.4$, $h_0 = 10 \text{ W/m}^2$ °C, $\epsilon \Delta R = 60.0 \text{ W/m}^2$. Hence $T_{sw} = 43.75$ °C.

Solair temperature with shading (i.e. unexposed to sky) is given by

$$T_{sw} = \frac{\alpha_w I_w}{h_0} + T_s,$$

where $I_w = 200 \text{ W/m}^2$, $\alpha_w = 0.4$, $h_0 = 10 \text{ W/m}^2$ °C, $\epsilon \Delta R = 60.0 \text{ W/m}^2$. Hence $T_{sw} = 41.75$ °C.

The overall heat transfer coefficient of the walls can be calculated as follows:

$$U_w = \left( \frac{L_{br}}{K_{br}} + \frac{L_{con}}{K_{con}} + \frac{1}{h_s} + \frac{1}{h_r} + \frac{L_{pl}}{K_{pl}} \right)^{-1},$$

$$= \left( \frac{0.1}{1.32} + \frac{0.2}{9} + \frac{1}{23} + \frac{0.0125}{8.65} \right)^{-1}.$$

Hence $U_w = 3.5 \text{ W/m}^2 \text{°C}$.

Further, the overall heat transfer coefficient of the partition walls can be calculated as follows:

$$U_{wp} = \left( \frac{L_{br}}{K_{br}} + \frac{L_{pl}}{K_{pl}} + \frac{1}{h_s} + \frac{1}{h_r} \right)^{-1}.$$

So $U_{wp} = 1.86 \text{ W/m}^2 \text{°C}$.

The thermal gain/loss through various walls is given by $A_e Q_w$(east side) = 13255.5 W, $A_e Q_w$(south side) = 15202.59 W, $A_e Q_w$(north side) = 15202.59 W, $A_e Q_w$(west side) = 19280.8 W.
Door

The net heat gain/loss per square metre through the door is given by

\[ Q_D = U_D (T_R - T_a) \]

The overall heat transfer coefficient through the door can be written as

\[ U_D = \left( \frac{1}{h_1 + \frac{L_D}{K_D} + \frac{1}{h_0}} \right)^{-1} \]

where \( h_0 = 10.0 \text{ W/m}^2 \text{°C} \), \( L_D = 0.12 \text{ cm} \), \( K_D = 0.3 \text{ W/m} \text{°C} \), \( h_1 = 7 \text{ W/m}^2 \text{°C} \). Therefore, \( U_D = 0.5 \text{ W/m}^2 \text{°C} \).

The net gain through doors is given by \( A_D Q_D = 311.85 \text{ W} \).

Floors

The net heat gain/loss per square metre through the floor is given by

\[ Q_G = U_{bg} (T_R - T_f) \]

where \( T_{\infty} \approx T_a \) and

\[ U_{bg} = \left( \frac{1}{h_1 + \frac{L_{bg}}{K_{bg}}} \right)^{-1} \]

Here, \( L_{bg} = 0.15 \text{ cm} \), \( K_{bg} = 1.8 \text{ W/m}^2 \text{°C} \), \( h_1 = 7 \text{ W/m}^2 \text{°C} \), \( T_{\infty} \approx T_a = 33.75 \text{°C} \).

Therefore, the overall heat transfer coefficient is given by \( U_{bg} = 4.42 \text{ W/m}^2 \text{°C} \).

The rate of heat loss/gain through the floor has been calculated and is given by \( A_{bg} Q_{bg} = 8304.768 \text{ W} \).

Infiltration and ventilation

The infiltration of air inside the cinema hall from the ambient air is given by

\[ Q_{\text{infiltration/ventilation}} = V_0 + V_1 (T_a - T_R) \]

Here, \( V_0 = 27157.658 \text{ W} \), \( V_1 = 34.98 \text{ W/°C} \), \( T_a = 33.75 \text{°C} \), \( T_R = 27.0 \text{°C} \). So, the rate of heat loss/gain through infiltration/ventilation is given by \( Q_{\text{infiltration/ventilation}} = 27393.77 \text{ W} \).

Occupancy load

The net gain/loss due to occupancy which is attributed to the sensible heat load (see Ref. [14]) is given by

Sensible load = No. of people \times SHL = 60450 \text{ W},

where No. of people = 806, and SHL = sensible heat load = 75 W/person.

The net gain/loss due to occupancy which is attributed to latent heat load (see Ref. [14]) is given by

Latent load = No. of people \times LHL = 44330 \text{ W},

where LHL = latent head load = 55 W/person.

Lights and power appliances

The net heat gain due to lights is 22750 \text{ W}. The appliance load has been taken as 15880 \text{ W}. The net heat due to lights and power appliances \( Q_E = 38630 \text{ W} \).

Wind tower

The net thermal energy loss from the enclosed air of the cinema hall is given by

\[ Q_{RC} = \dot{m}_{RC} C_s (T_R - T_{RC}) \]
where, $\dot{m}_{RC} = b_w d_w \rho_s v_{RC}$, $v_{RC} = 6 \text{ m/s}$, $A_w = 24 \times 1 \text{ m}^2$, $d_w = 0.25 \text{ m}$, $b_w = 26.8 \text{ m}$, $\rho_s = 1.2 \text{ kg/m}^3$, $C_s = 1000 \text{ J/kg} \cdot \text{C}$, $T_R = 27.0 \text{ C} \text{ (assumed)}$, $T_{RC} = 26.4 \text{ C}$. Thus, $Q_{RC} = 28944 \text{ W}$. It means that:

(i) $Q_{RC}$ should be positive for cooling the enclosed air of the cinema hall,
(ii) the flow rate $\dot{m}_{RC}$ should be maximum in accordance with keeping the air channel perfectly insulated and the cooled air fed directly into the enclosure.

**Earth air tunnel**

It has been assumed that the earth air tunnel is of uniform size, and its surface temperature remains constant during operation. The rate of cooled air transferred inside the cinema hall is given by

$$Q_{ET} = \dot{m} \Delta T C_s,$$

where

$$\Delta T = (T_h - T_a) \left[1 - \exp \left(\frac{-h_c + h_d C_s}{m_a C_s} b_{ET} L_{ET}\right)\right] = 14.75 \text{ C.}$$

Here, $C_s$ is the sum of the specific heat of dry air and water vapour content. Thus, $C_s = (1.005 + 1.884 W) \times 10^3 \text{ J/kg} \cdot \text{C}$. Also, the tunnel temperature for wet sunlit surface is $T_h = 19 \text{ C}$, $h_c = 29.28 \text{ W/m}^2 \cdot \text{K}$, $h_d = 0.03 \text{ kg/s} \cdot \text{m}^2$, $W = 0.0176 \text{ kg/kg of dry air}$, $L_{ET} = 60 \text{ m}$, $b_{ET} = 2 \text{ m}$, $d_{ET} = 0.5 \text{ m}$, $m_a = 5.28 \times 10^{-4} \text{ kg/s}$. So, $Q_{ET} = 8.1 \text{ W}$.

**NUMERICAL RESULTS AND DISCUSSION**

By using the above calculations, the thermal energy passing through the different components of the cinema hall with and without roof cooling, have been obtained and are given in Table 1. On the basis of this table and numerical computations, the comparison of energy saved in the cinema hall due to evaporative cooling, earth air tunnel, wind tower and room without any treatment has been completed.

Based on the above studies, the following conclusions can be drawn:

(i) The earth air tunnel is the most efficient way to provide thermal comfort in the cinema hall.
(ii) The reduction of heat flux through the roof is the most economical technique.
(iii) The heat flux through the door, floor, light and infiltration is insignificant due to their minimum overall heat transfer coefficients.

**REFERENCES**