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Design parameters of a non-air-conditioned cinema hall for thermal comfort under arid-zone climatic conditions

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Abstract

In this communication, a design of a cinema hall suitable for climatic conditions in an arid zone has been presented. The various cooling techniques, namely evaporative cooling, wind tower, ventilation/infiltration and natural cooling, have been incorporated in the design to achieve thermal comfort during the period of operation. The design parameters have been optimized on the basis of numerical computations after establishing an energy balance for each component of a cinema hall. It is observed that cooling treatment, i.e., a wind tower with a cooling pool on the roof provides reasonable thermal comfort inside the enclosure.

Keywords: passive cooling, solar energy, solar architecture.

Introduction

Human beings have a tolerance for a very narrow range of temperatures. Any changes of temperature in an upward or downward direction decelerate human activity, and bring a sense of discomfort. Additionally the human body is also sensitive to humidity, radiation and air movement. Man's quest for seeking protection against the vagaries of these factors has led to the construction of shelters incorporating solar architecture, with evaporative and natural cooling through roofs, walls and windows.

Solar passive systems offer simple and inexpensive means of space-conditioning in buildings. One passive cooling system in dry climates relies on evaporative cooling, which can be accomplished by a number of techniques such as an open roof pond, a thin water film vs. the flow of water over the surface. This concept of reducing heat flux is well known; for example, see ref. 1. Houghton *et al.* [2] reported the results of cooling produced by an open roof pond and spraying of water over the roof and found that these methods were effective in reducing the heat flux through all types of roofs. It was interesting to note [1, 3, 4] that the surrounding air is also cooled and, being heavier than hot air, slides down the walls of a building; much of the chilled air drifts into the building due to infiltration and ventilation and cools the internal environment.

Several workers [5–7] studied experimentally the performance of different cooling approaches, but no systematic analysis of these techniques is available in the literature so far. Some computer models for calculating the thermal load in the presence of a roof pond are available; however, the lack of effects of different parameters explicitly hindered their practical applicability. Sodha *et al.* [8, 9] analysed the problem of reduction of heat flux by (i) evaporation of a water film maintained over the roof, and (ii) the flow of water over the roof. Studies on natural cooling and heating of a greenhouse were undertaken by Mannam and Cheema [10].

In this paper, an effort has been made to formulate a mathematical model for the thermal load of a non-air-conditioned building, a cinema hall, which has a high occupancy per unit floor area. Suitable measures are suggested for balancing the thermal load to produce a sense of comfort among the occupants by application of design concepts, unproved landscaping of the surroundings, and processes of natural/radiant, evaporative cooling and the wind tower effect. The effects of a wind tower [11], evaporative cooling [1], and ventilation/infiltration, etc., have also been incorporated in the

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thermal analysis to produce a different design particularly.

Different cooling concepts

Design concepts essentially mean including or capturing the heat produced by the sun, which can be achieved by the orientation of the building in relation to the sun, and partly by either one or the combination of various techniques, such as shading, reflection, insulation, etc. Cooling of the building by passive systems can be provided through utilization of natural heat sinks or sources of natural cooling energies given in Table 1.

The term passive in relation to cooling means that the technique does not include the use of a fan or a pump when its application might enhance performance. This term emphasizes the utilization of natural heat transfer processes for heat and natural sinks enabling reflection of heat from the building [12].

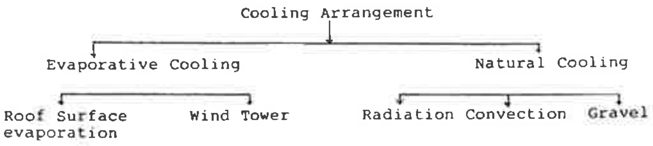
A brief description of various cooling techniques follows.

(a) Evaporative cooling [13, 14]

(i) Roof surface evaporation

Evaporation is a very potent source of cooling which can work during the day and at night. In summer, due to the high elevation of the sun, the intensity of radiation over a roof surface is significant. This is particularly true in a tropical climate. Hence reduction of the heat flux across a roof is a prime requirement in the thermal design of the building for hot or tropical climates. There are many well-known processes of improving thermal performance of roofs such as increasing roof thickness, inserting additional insulation, adding a false ceiling, shading the roof, and using surface reflective treatments. However, the most economical as well as effective method of reducing heat flux is by roof surface evaporation. This can be accomplished by maintaining an open roof pond or spraying the roof surface intermittently [2]. The evaporation is more effective if the water is sprinkled over a suitable water retentive material (e.g., gunny bags) spread over the roof surface to lessen heat capacity and thus providing a uniform wet surface [6]. Solar radiation falling on the water film is utilized in water evaporation and thus is prevented from entering the room below. In addition to the cooling of the roof, evaporation also causes cooling of air above the roof. As a result the air becomes heavier than hot air and slides down the walls of the building. Besides providing a comfortable environment, this cool air drifts into the living space due to infiltration and ventilation, replacing the room air, thereby aiding thermal comfort. This system is suitable for single-storey structures. It also provides a large water-air interface area for more evaporation. It has an additional advantage over the roof pond system; because of its large thermal mass, in addition to water evaporation, it stores substantial heat; this causes some heat to flow into the living space.

TABLE 1. Classification of cooling arrangements



(ii) Chimney/wind towers

Wind towers or "wind catchers" harness the prevailing summer wind to cool it down and circulate it through the building. The upper part of the wind tower is divided into air passages which terminate into openings on the top. These openings have wet gunny bags as shown in Fig. 1. Evaporative cooling occurs when the unsaturated air comes into contact with the bags, partially evaporates and the temperature of the air is lowered as its vapour content is increased. Also since it is a sloping roof, the tower is created at the apex. The sloped roof provides a larger surface area for heat transfer to ambient air. The wind velocity at the apex is higher, hence there is an increase in the convective heat transfer coefficient for the surface to outside. This type of roof is almost normal to the wind direction. The circulation of cooled air inside the enclosure can be affected either by natural circulation or forced circulation.

(b) Natural cooling

(i) Radiative cooling

Any material surface emits electromagnetic radiation of a wavelength inversely related to its temperature. The radiation emitted from the surface of the sun, referred to as short-wave radiation has a spectral range of 0.25–3 microns with peak radiation at about 0.5 microns. The longwave radiation emitted from the surface of the earth is in the spectral range of 5–30 microns with peak radiation about 10 microns. Constant exchange of radiant energy in the long-range spectrum takes place between buildings and the atmosphere: any element of the external envelope of the building which sees the sky emits longwave radiation towards it. This

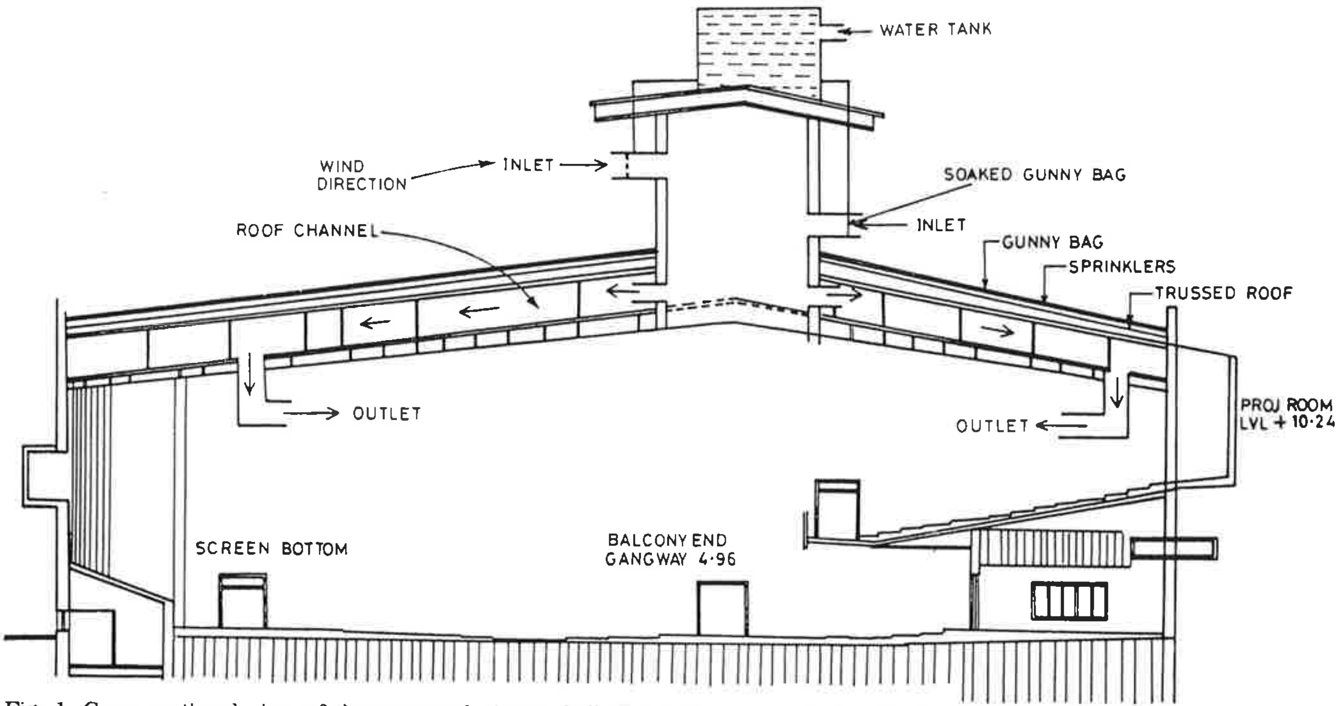


Fig. 1. Cross-sectional view of the proposed cinema hall showing cooling effect without earth air tunnel (all dimensions are in metres).

radiation is continuous over the whole spectral range. Roofs being the building elements with the highest exposure to the sky are the most effective components to be used as longwave radiation [12] and therefore most attempts to utilize radiative cooling techniques for the cooling of buildings focus on various technical solutions for roofs. Emission of longwave radiation takes place during the day, though an exposed roof may absorb solar energy that outweighs its longwave radiation, i.e., the net effect may be of heating rather than of cooling. Since most cooling is achieved at night, it is referred to as nocturnal radiation. In building heat transfer processes, heat is lost and gained by radiation and through convection and conduction as well as by radiation. For cooling buildings by radiation, the net radiant exchange between devices on the earth and the sky is of interest.

Deep space can be considered an infinite sink for radiant emission from the earth; atmospheric carbon dioxide and water vapour intervene in the radiation exchange by absorbing much of the longwave radiation. The sky radiates longwave radiation at a rate similar in magnitude but slightly less than the rate of the earth's radiation to the sky. Because the longwave absorption by the atmosphere is directly related to the water vapour content of the air, the effective temperature of the sky is a function of humidity and the dry-bulb temperature of the air near the ground. Therefore the effect of radiant cooling is significant and most applicable in dry arid regions.

(ii) Convection

In warm regions where night temperature in summer is below the comfort range (e.g., below 20 °C), it is possible to store the coolness of the night air by passing it through the building or through any storage such as gravel mass. This is because of the large surface area provided by ground mass for heat transfer. On the next day, outside air can be drawn through the ground mass before passing it into the living space.

(iii) Earth air tunnel/ground cooling

Ground cooling is possible with the help of an underground tunnel. The tunnel runs from the bottom of a tower to the basement of the building to be cooled. As the temperature of the ground is much less than the day ambient temperature, the ambient air, besides being cooled along its path down the tower, further cools down in the tunnel because of sensible cooling in the ground. This air can then be circulated in the living space according to need. The provision of an earth air tunnel integrated with the cinema is shown in Figs. 2 and 3 [15].

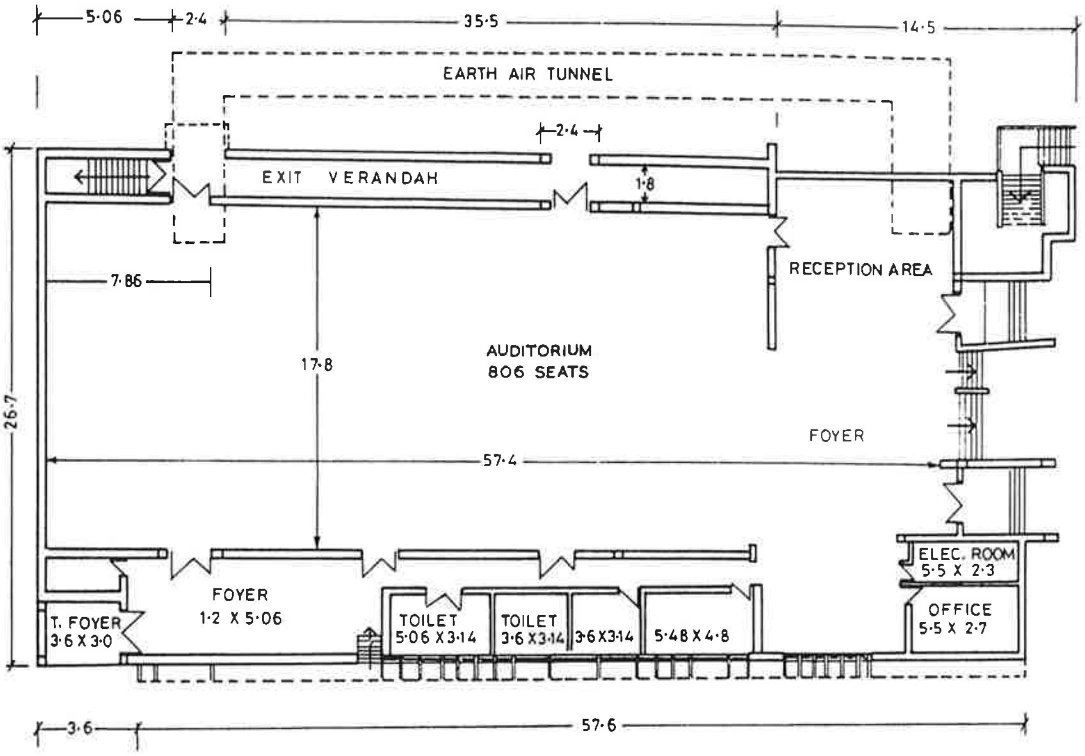


Fig. 2. Floor layout plan of the proposed cinema hall (all dimensions are in metres).

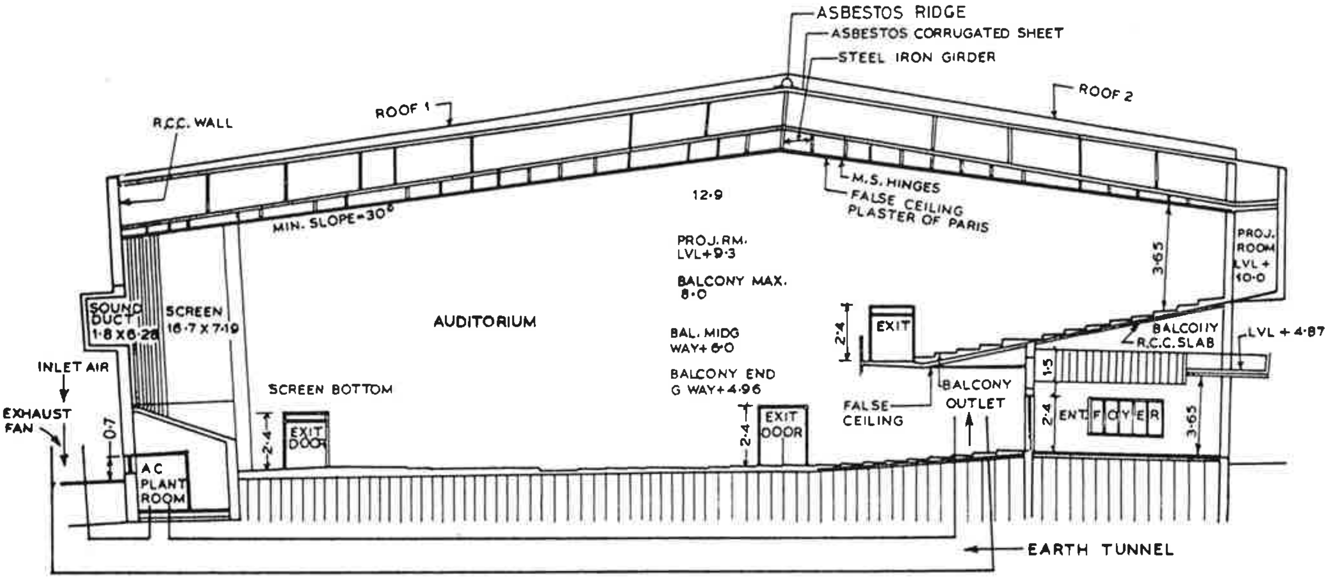


Fig. 3. Cross-sectional view of the proposed cinema hall with earth air tunnel (all dimensions are in metres).

(c) Orientation

An east-west orientation for the building has been selected for the building to present the reduced wall areas to the east and west and thereby to reduce the solar load on the building.

Foyers/verandas

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 extends out from the wall over an area of 3 m by

2 m. On the west side is the blank 200-cm-thick brick wall plastered (12 mm thick) on both sides. This side has no openings for doors and ventilators.

In order to optimize the thermal performance of the cinema hall on the basis of an energy balance for each component (walls, roof, air tunnel), the verandas can be considered as air cavity channels.

Walls

The north and south walls contribute very little to the heat load of the building; overhangs provided for these walls effectively reduce the solar load. Also the glazed area is at ventilator level. Furthermore, the inner walls of the cinema hall are covered with wood panelling, so that the gain/loss of thermal energy through these walls can be eliminated or can be considered in steady-state conditions.

Windows and doors

The location of the window and doors allow natural wind movement. Also, their positions allow the movement of people in and out under all conditions. Since the wind direction is from west to southwest, wherever possible windows and doors have been provided.

Auditorium

The effective area of the auditorium measures 35.3 m×17.8 m. It is an enclosed space with very little heat gain as it is surrounded by ancillary functional spaces such as the foyer and toilets, 5.0 m wide on the south side, an exit veranda 1.8 m wide, and a foyer 8.8 m wide on the east side. All the walls have been panelled with wood and glass wool, an insulating material.

Roof

The cross-sectional view of a room of the proposed cinema hall with a wind tower arrangement is shown in Fig. 1. The top of the roof is generally made up of asbestos sheet with proper wooden support from the bottom of the roof. This arrangement can be considered as an air cavity to circulate cooled air available through a wind tower, inside the cinema hall, particularly during nighttime. There is an inlet opening on both sides for cooled air through the wind tower. The opening of the inlet for cooled air depends on the direction of the wind outside the cinema hall. The asbestos roof is supported by wooden purlins with a wooden false ceiling as shown in Fig. 1.

Design concepts

The most important consideration in the building design has been creating comfortable conditions throughout the year without using any active systems, such as air conditioners or electric air heaters. The cinema hall at Chopansai Lane has been designed for a seating capacity of 806 people at two levels – at ground floor level and at balcony level.

The floor layout plan of the proposed cinema hall with floor dimensions 61×27 m^2 is shown in Fig. 2. The cross-sectional views of the cinema hall with and without the wind tower are shown in Figs. 1 and 3, respectively. It has the entrance foyer with an electrical room and an office adjoining. An exit veranda is on the north side with two openings. The foyer has a ventilator at a height of 2.9 m and an emergency staircase. On the west side is a 0.23-m-thick brick wall. Along the total length of the east wall there are no windows or ventilators. Along the south wall there is an overhang 0.609 m wide and a protruding projection room. There are toilets along a wall of 17.8 m, together with ventilators and windows, which are surrounded by a corridor 1.4 m wide. Further data on the building components are given in Table 2.

The main enclosure of the auditorium seats 806 people. In this zone, the heat gain is minimal as it is enclosed on all sides with ancillary activities.

Weather parameters

For most part of the year Jodhpur has a hot and dry climate. It is visited by monsoons in the month of August, and the total annual rainfall is about 360 mm. For two months a year, this town witnesses a mild winter.

The characteristics of arid climates are:

(i) high diurnal ranges of temperature and insolation level (Fig. 4);

(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 season and dehumidification during the monsoon. Winter heating is not an important design consideration as direct gains through south-facing walls will provide a good degree of comfort.

General formulation

In a building, heat conveyance takes place due to conduction, convection, radiation and a transfer of mass in the case of an evaporate cooling system. In this case, the thermal modelling of the proposed cinema hall is based on the following assumptions:

TABLE 2. Building data of proposed cinema hall

Component	Area (m^2)	Material	Subcomponent*	Area (m^2)	Material	Remarks
West wall	26.7×9.7 $=260.48$	Brick	VW_1	0.6×0.6 $=0.36$	Glazing	Wall insulated from inside
East wall	26.7×9.7 $=260.48$	Brick	DE_1	4.8×2.4 $=11.52$	Glazing	Wall insulated from inside
			DE_2	2.4×2.4 $=5.76$	Glazing	
			DE_3	2.4×2.4 $=5.76$	Wood	
			WE_1	1.0×1.5 $=1.5$	Glazing	
South wall	61.2×9.7 $=593.64$	Brick	VS_1	18 (0.6×0.6) $=6.48$	Glazing	Wall insulated from inside
North wall	61.2×9.7 $=593.64$	Brick	DN_1	2.4×2.4 $=5.76$	Wood	Wall insulated from inside
			DN_2	2.4×2.4 $=5.76$		
			Openings for the staircase	(i) 2×5.76 $=11.52$ (ii) 1.2×3.6 $=4.3$		
Roof 1	26.8×47.3 $=1268.8$					
Roof 2	26.8×23 $=619.0$					

*V, D and W represent ventilator, door and window respectively: E, W, N and S represent east, west, north and south.

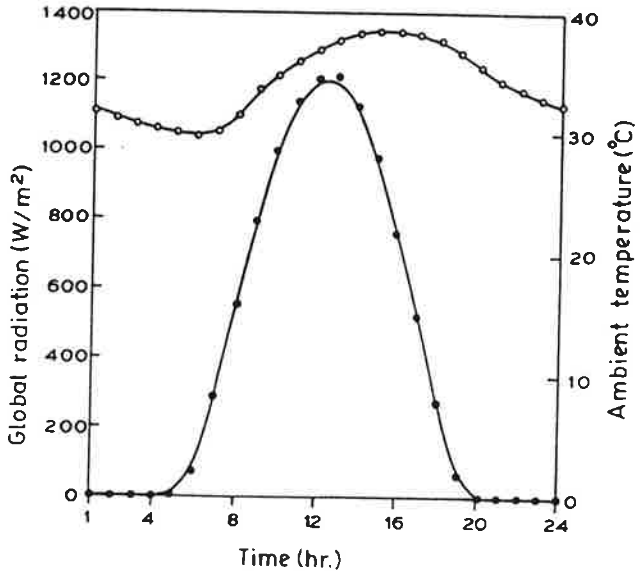


Fig. 4. Hourly variation of solar intensity and ambient air temperature. —●—●— global radiation, —○—○— ambient temperature.

(i) no stratification in room air temperature;

(ii) conduction losses/gains through the walls, doors and floors have been taken as under steady-state conditions;

(iii) thermal capacity of isothermal mass is negligible;

(iv) thermal capacity of roof material is negligible;

(v) quantity of metabolic heat produced is insignificant.

The basic energy balance in J/s (W) for different components (roof, walls, doors, floor, wind tower and enclosed air) of the proposed cinema hall can be written as in the following Sections.

Roof treatment

As mentioned earlier, the evaporative cooling technique is the best method to stop the incoming solar radiation through the roof. In this process, the solar radiation incident on the roof is transferred back to the external atmosphere in the form of evaporation which helps to reduce the room temperature inside the cinema hall. The energy balance of an elemental length dx of the roof, Fig. 5, can be written as [16]:

$$(\alpha_r I_R-\epsilon\Delta R)b\,\mathrm{d}x=\dot{m}_w C_w\frac{\mathrm{d}T_w}{\mathrm{d}x}\,\mathrm{d}x+(\dot{Q}_{cw}+\dot{Q}_{rw}+\dot{Q}_{ew})b\,\mathrm{d}x+U_R(T_w-T_R)b\,\mathrm{d}x \qquad (1)$$

where

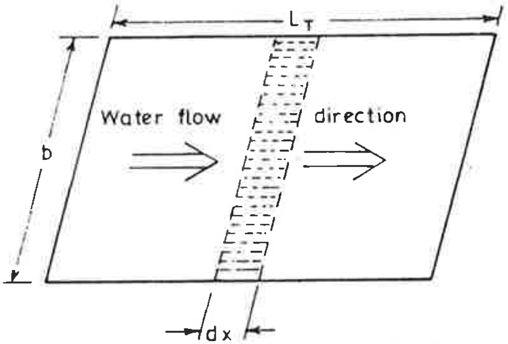


Fig. 5. Cross-sectional view of water flowing over the roof of the proposed cinema hall.

$$\dot{Q}_{\mathrm{cw}} = h_{\mathrm{cw}}(T_{\mathrm{w}} - T_{\mathrm{a}})$$

$$\dot{Q}_{\mathrm{ew}} = h_{\mathrm{ew}}(T_{\mathrm{w}} - T_{\mathrm{a}})$$

$$\dot{Q}_{\mathrm{rw}} = h_{\mathrm{rw}}(T_{\mathrm{w}} - T_{\mathrm{a}})$$

$$h_{\mathrm{cw}} = 0.884\left[T_{\mathrm{w}} - T_{\mathrm{a}} + \frac{(p_{\mathrm{w}} - \gamma p_{\mathrm{a}})(T_{\mathrm{w}} + 273)}{(268.9 \times 10^3) - p_{\mathrm{w}}}\right]^{1/3}$$

$$h_{\mathrm{ew}} = 0.016 \times h_{\mathrm{cw}}\left[\frac{p_{\mathrm{w}} - \gamma p_{\mathrm{a}}}{T_{\mathrm{w}} - T_{\mathrm{a}}}\right]$$

$$h_{\mathrm{rw}} = \frac{[(T_{\mathrm{w}} + 273)^4 - (T_{\mathrm{sky}})^4]\epsilon\sigma}{T_{\mathrm{w}} - T_{\mathrm{a}}}$$

$$T_{\mathrm{sky}} = (T_{\mathrm{a}} + 273) - 12 = T_{\mathrm{a}} + 261$$

$$U_{\mathrm{R}} = \left[\frac{1}{h_{\mathrm{i}}} + \frac{L_{\mathrm{ab}}}{K_{\mathrm{ab}}} + \frac{1}{C_{\mathrm{R}}} + \frac{L_{\mathrm{WR}}}{K_{\mathrm{WR}}}\right]^{-1}$$

Therefore

$$\frac{\mathrm{d}T_{\mathrm{w}}}{\mathrm{d}x} + \frac{(h_1 + U_{\mathrm{R}})b}{\dot{m}_{\mathrm{w}} C_{\mathrm{w}}} T_{\mathrm{w}} = \{\alpha_{\mathrm{r}} I_{\mathrm{R}} + U_{\mathrm{R}} T_{\mathrm{R}} + h_1 T_{\mathrm{a}}\} \frac{b}{\dot{m}_{\mathrm{w}} C_{\mathrm{w}}} \tag{2}$$

Equation (2) becomes,

$$\frac{\mathrm{d}T_{\mathrm{w}}}{\mathrm{d}x} + a_1 T_{\mathrm{w}} = f_1(t)$$

The solution of the above equation with the help of initial conditions, namely

$$T_{\mathrm{w}}|_{x=0} = T_{\mathrm{a}} - 1$$

$$= T_{\mathrm{wo}} \text{ (say)}$$

can be written as

$$T_{\mathrm{w}} = \left(\frac{f_1(t)}{a_1}\right)[1 - \exp(-a_1 x)] + T_{\mathrm{wo}} \exp(-a_1 x) \tag{2a}$$

where

$$a_1 = \frac{b(h_1 + U_{\mathrm{R}})}{\dot{m}_{\mathrm{w}} C_{\mathrm{w}}}$$

$$h_1 = h_{\mathrm{cw}} + h_{\mathrm{ew}} + h_{\mathrm{rw}}$$

and

$$f_1(t) = \frac{b}{\dot{m}_{\mathrm{w}} C_{\mathrm{w}}} \{\alpha_{\mathrm{R}} I_{\mathrm{R}} + U_{\mathrm{R}} T_{\mathrm{R}} + h_1 T_{\mathrm{a}}\}$$

Furthermore, the average water temperature over the roof length from $x=0$ to $x=L_{\mathrm{r}}$

$$\bar{T}_{\mathrm{w}} = \left(\frac{f_1(t)}{a_1}\right)\left[1 - \left(\frac{1 - \exp(-a_1 L_{\mathrm{r}})}{a_1 L_{\mathrm{r}}}\right)\right] + T_{\mathrm{wo}}\left(\frac{1 - \exp(-a_1 L_{\mathrm{r}})}{a_1 L_{\mathrm{r}}}\right) \tag{2b}$$

and

$$T_{\mathrm{wout}} = T_{\mathrm{w}}|_{x=L_{\mathrm{r}}} \tag{2c}$$

The net flux entering inside the room through the roof can be written as

$$\dot{Q}_{\mathrm{R}} = U_{\mathrm{R}}(\bar{T}_{\mathrm{w}} - T_{\mathrm{R}}) \tag{3}$$

where

$$U_{\mathrm{R}} = \left[\frac{1}{h_{\mathrm{o}}} + \Sigma \frac{L_{\mathrm{R}i}}{K_{\mathrm{R}i}} + \frac{1}{C_{\mathrm{R}i}} + \frac{1}{h_1}\right]^{-1}$$

$$h_1 = 5.7$$

$h_{\mathrm{o}} = 5.7 + 3.8\,V$; V is wind velocity [17].

Walls

The net heat gain/loss per square metre through a wall ($\dot{Q}_{\mathrm{w}}$) can be written as:

$$\dot{Q}_{\mathrm{w}} = U_{\mathrm{w}}(T_{\mathrm{SA}} - T_{\mathrm{R}}) \tag{4}$$

where

$$U_{\mathrm{w}} = \left[\sum_{i=1}^{n} \frac{L_i}{K_i} + \frac{1}{C_{\mathrm{wa}i}} + \frac{1}{h_i} + \frac{1}{h_{\mathrm{o}}}\right]^{-1}$$

is an overall heat transfer coefficient through a wall and

$T_{\mathrm{SA}} = \dfrac{\alpha I_{\mathrm{w}}}{h} + T_{\mathrm{a}} - \dfrac{\epsilon \Delta R}{h}$ is the solar temperature.

Outside the wall, $\epsilon\Delta R = 0$ for walls.

Ground

The net heat loss/gain per square metre through the floor of the cinema hall in steady-state conditions can be written as:

$$\dot{Q}_{\mathrm{G}} = U_{\mathrm{bg}}(T_{\mathrm{R}} - T_{\infty}) \tag{5}$$

where

$$T_\infty \simeq T_a$$

and

$$U_{bg} = \left[\frac{1}{h_i} + \Sigma \frac{L_{gi}}{K_{gi}}\right]^{-1}$$

Door

The net heat loss/gain per square metre through a door can be written as

$$\dot{Q}_D = U_D(T_R - T_a) \tag{6}$$

where

$$U_D = \left[\frac{1}{h_1} + \frac{L_D}{K_D} + \frac{1}{h_i}\right]^{-1}$$

Wind tower

The wind will pass through either one of two inlets, which will have wetted gunny bags depending upon the duration of day/night operation of the wind tower. At night, the temperature of the wind is generally in the comfortable range, hence there is no need to use the soaked gunny bags.

In order to write an energy balance of the wind passing through the wind tower and roof channel, one can use the Bernoulli's theorem as follows (Fig. 6):

$$A_{WT} V_w = 2 b_R d_R v_{RC} \tag{7a}$$

and

$$\dot{m}_{RC} C_a \frac{dT_{RC}}{dx} dx = [h_u(T_a - T_{RC}) + h_b(T_R - T_{RC})] b_R \, dx \tag{7b}$$

where

$$\dot{m}_{RC} = b_R d_R \rho_a v_{RC}$$

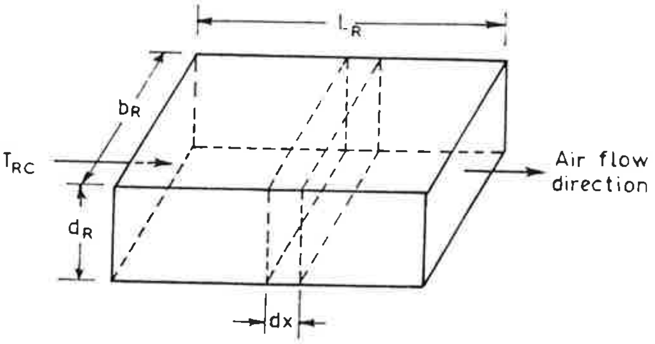


Fig. 6. Cross-sectional view of the roof channel integrated with wind tower ($A_{WT} V_w = 2 b_R d_R v_{RC}$).

$$h_u = \left[\frac{1}{h_{2''}} + \frac{L_{as}}{K_{as}} + \frac{1}{h_o}\right]^{-1}$$

$$h_b = \left[\frac{1}{h_{2'}} + \frac{L_b}{K_b} + \frac{1}{h_i}\right]^{-1}$$

The solution of eqn. (7b) with initial condition

$$T_{RC}|_{x=0} = T_{RCi} = (T_a - 2)$$

generally can be written as

$$T_{RC} = \frac{f_2}{a_2} [1 - \exp(-a_2 x)] + T_{RCi} - a_2 x \tag{8}$$

Now, the net thermal energy loss from the enclosed air of the cinema hall can be written as

$$\dot{Q}_{RC} = \dot{m}_{RC} C_a (T_R - T_{RC}|_{x=L_r}) = \dot{m}_{RC} C_a \left[\frac{h_u}{h_u + h_b}(T_R - T_a) + \left(\frac{h_u T_a + h_w T_R}{h_u + h_b} - T_{RCi}\right) \exp(-a_2 L_r)\right] \tag{9}$$

It is clear from the above equation that the value of Q_{RC} should be positive for cooling the enclosed air of the cinema hall. Furthermore, the conditions for cooling can be described as follows:

(i) the flow rate $\dot{m}_{RC}$ should be high;

(ii) $\exp(-a_2 L_r)$ should be at a maximum which implies that the flow rate should be at a maximum (in accordance with (i)), that the air channel should be perfectly insulated, and that the cooled air should be fed directly into the enclosure, i.e., $L_r = 0$.

Earth air tunnel

Referring to Fig. 7 the air at ambient temperature is fed through a tunnel which is at a lower temperature for a wet shaded surface (see Table 3). The velocity of air in the tunnel becomes lower due to a large cross-sectional area which is essential from a cooling/heating point of view. The cooled air is extracted through the outlet of the tunnel and directed inside the cinema hall to provide thermal comfort for occupants.

In order to write an energy balance equation for the earth air tunnel, the following assumptions have been made:

(i) the tunnel is of uniform cross-section;

(ii) surface temperatures of the earth air tunnel remain constant during the operation.

Considering an infinitesimal element of the tunnel, the heat balance equation can be written as [15]:

$$-\dot{m} C_a \frac{\partial T}{\partial y} \Delta y = b(\dot{Q}_c + \dot{Q}_e) \Delta y \tag{10}$$

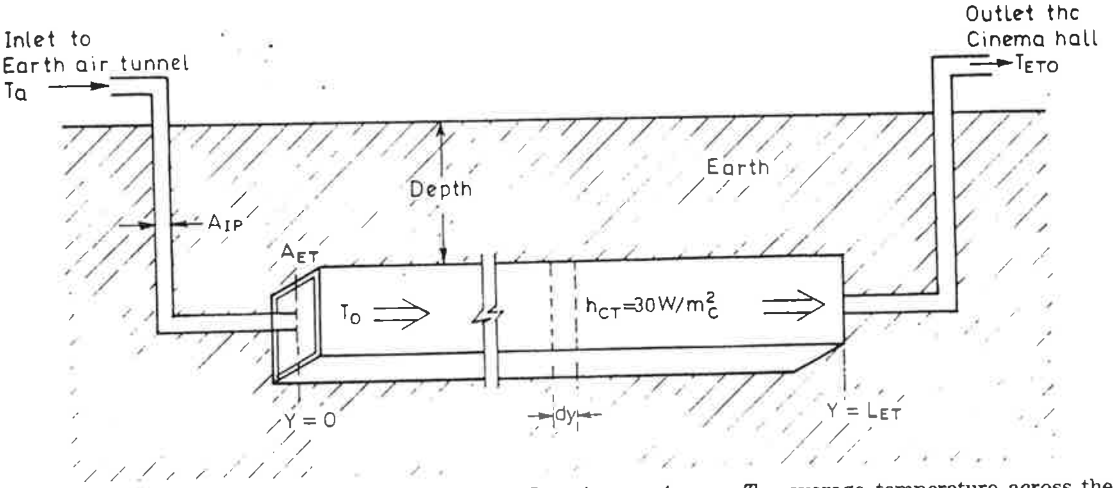


Fig. 7. View of earth air tunnel. At $Y=0$ and $Y=L_{ET}$, $A_{IP}v_{IP}=A_{ET}v_{ET}$; T_0 = average temperature across the tunnel surface.

where $\dot{Q}_c$ and $\dot{Q}_e$ correspond to convection and evaporation heat losses respectively from the hot air to unit surface area of the tunnel. In terms of measurable quantities

$$\dot{Q}_c = h_c(T_a - T_s) \tag{11}$$

If the tunnel is wet, vapour transfer also takes place, which may be evaluated as follows:

$$\dot{m}_w = h_D(W_s - W) \tag{12}$$

where W_s is the humidity ratio of the air in a saturated state and h_D is the mass transfer coefficient.

The enthalpy balance can be written as

$$W_S - W = \frac{C_a}{\mathscr{L}}(T_a - T_s) \tag{13}$$

Therefore,

$$\dot{m}_w = \frac{h_D C_a}{\mathscr{L}}(T_a - T_s) \tag{14}$$

and the amount of heat associated with water vapour is

$$\dot{Q}_e = h_D C_a(T_a - T_s) \tag{15}$$

The convective heat transfer coefficient h_c and the mass transfer coefficient h_D are related as [18]:

$$\frac{h_c}{h_D} = \frac{K}{D_m \rho_a}\left(\frac{D_m}{D}\right)^c \tag{16}$$

Substitution of eqns. (11) and (15) in eqn. (10) and integration with the initial condition that at $y=0$, $T=T_{amb}$ one obtains

$$\Delta T = (T_{amb} - T_s)\left[1 - \exp\left(\frac{-h_c + h_D C_a)bL}{\dot{m}_w C_a}\right)\right] \tag{17}$$

where the value of C_a is the sum of the specific heat of dry air and that of the water vapour associated with it.

Thus,

$$C_a = (1.005 + 1.884W) \times 10^3 \text{ J/kg °C} \tag{18}$$

The rate of cooled air transferred inside the cinema hall is given by

$$\dot{Q}_{ET} = -\dot{m}C_a\,\Delta T \tag{19}$$

Infiltration/ventilation effect

The infiltration of air from inside the cinema hall due to infiltration and ventilation to ambient air [19, 20] can be written as

$$\dot{Q}_{inf/vent} = V_o + V_I(T_R - T_a) \tag{20}$$

where

$$V_o = 2463M_i(N+N_o)\ \Delta R_H/C_a$$

$$V_I = M_i(N+N_o)(C_a + 1.88\Delta R_H)/C_a$$

Now the energy balance of air enclosed inside the cinema hall, including all parameters mentioned above, can be written as:

$$\dot{Q}_R A_{RF} + \sum_{i=E,W,N,S} \dot{Q}_w A_w + \dot{Q}_G A_G + \Sigma\dot{Q}_D A_D + \dot{Q}_{RC} + \dot{Q}_{ET} + \dot{Q}_{inf/vent} = M_a C_a \frac{dT_R}{dt} \tag{21}$$

The above equation can be solved for the inside room temperature of a cinema hall for a given initial condition. The same expression can be used to optimize the optimal use of various cooling techniques for achieving the thermal comfort in a cinema hall. Further each cooling technique can be also designed for given parameters of a cinema hall.

Equation (21) can be rewritten after substituting the various expressions for $\dot{Q}$ as follows:

$$\frac{dT_R}{dt}+aT_R=f(t) \tag{22}$$

The solution of eqn. (22) is

$$T_R=\frac{f(t)}{a}(1-\exp(-at))+T_{RO}\exp(-at)$$

where an expression for a and $f(t)$ can be obtained after algebraic manipulation and T_{RO} is room temperature at $t=0$.

The effect of isothermal mass has not been taken into account because of low isothermal mass in the cinema hall.

Numerical results and discussion

The following design and climatical parameters have been used to evaluate the inside room air temperature of the cinema hall (eqn. (22))

(1) Design parameters

The dimensions of the proposed cinema hall have been given in Table 2 and Figs. 2 and 3.

(a) Roof

$\alpha_R=0.4$, $\epsilon\Delta R=220$ W/m², $\dot{m}_w=0.03$ kg/s, $C_w=4190$ J/kg °C, $U_R=6.2$ W/m² °C, $r=0.6$, $\epsilon=0.8$, $\sigma=5.6\times10^{-8}$ W/m², $L_{R1}=47.3$ m, $L_{R2}=23$ m

(b) Walls

$\alpha=0.3$, $h_o=10$ W/m² °C, $\epsilon\Delta R=60$ W/m², $U_W=3.8$ W/m² °C

(c) Floor

$U_{bg}=1.8$ W/m² °C, $T_\infty=30$ °C

(d) Door

$U_D=0.5$ W/m² °C

(e) Wind tower

$V_w=6$ m/s, $A_{WT}=24\times1$ m², $d_R=0.25$ m, $b_R=26.8$ m, $C_a=1000$ J/kg °C, $h_b=2.5$ W/m² °C and $h_o=9.2$ W/m² °C

(f) Earth tunnel

The tunnel temperatures for different surface conditions are given in Table 3 [15] which is valid for Jodhpur climatic conditions. For a dry sunlit upper surface $T_s=30$ °C, and for a wet sunlit upper surface $T_s=19$ °C. $h_c=29.28$ W/m² °C, $h_D=0.03$ kg/s m², $C_a=1.038$ J/kg °C for $W=0.0176$ kg/kg of dry air. $L_{ET}=60$ m, $b_{ET}=2$ m, $d_{ET}=0.5$ m, $v_{IP}=2$ m/s, $A_{IP}=0.25$ m²

TABLE 3. Ground temperature at a depth of 4.0 m for various conditions of the upper surface [15]

Type of ground surface	Temperature at a depth of 4.0 m (°C)
Dry sunlit and glazed	51
Dry sunlit	30
Wet sunlit	19
Dry shaded	22
Wet shaded	17

Climatic parameters

The hourly variations of beam and diffuse radiation and ambient air temperature for a typical day at Jodhpur have been shown in Fig. 4. The radiation on the inclined roof and various walls has been computed by using the formula of Liu and Jordon.

The room air temperature has been computed for several days by assuming uniform climatic conditions. The results obtained for three consecutive days under steady-state conditions are shown in Fig. 8 for different cooling approaches namely:

(I) without any cooling technique;
(II) evaporative cooling technique;
(III) evaporative and wind tower techniques;
(IV) earth air tunnel.

As indicated in Fig. 6, an earth air tunnel is most effective (curve IV) in comparison with other methods. Furthermore, evaporative cooling (curve II) and a combination of evaporative and wind tower techniques (curve III) are also effective in order to reduce the room air temperature. In this case, the effect of ventilation has not been taken into account. It is further noted, on the basis of numerical computations, that ventilation during nighttime reduces the room temperature marginally.

Nomenclature

A_{ET}	cross-sectional area of earth air tunnel (m²)
A_{GF}	area of ground floor (m²)
A_{IP}	cross-sectional area of inlet pipe to earth air tunnel (m²)
A_{rl}	area of roof (m²)
A_{WT}	cross-sectional area of the wind tower (m²)

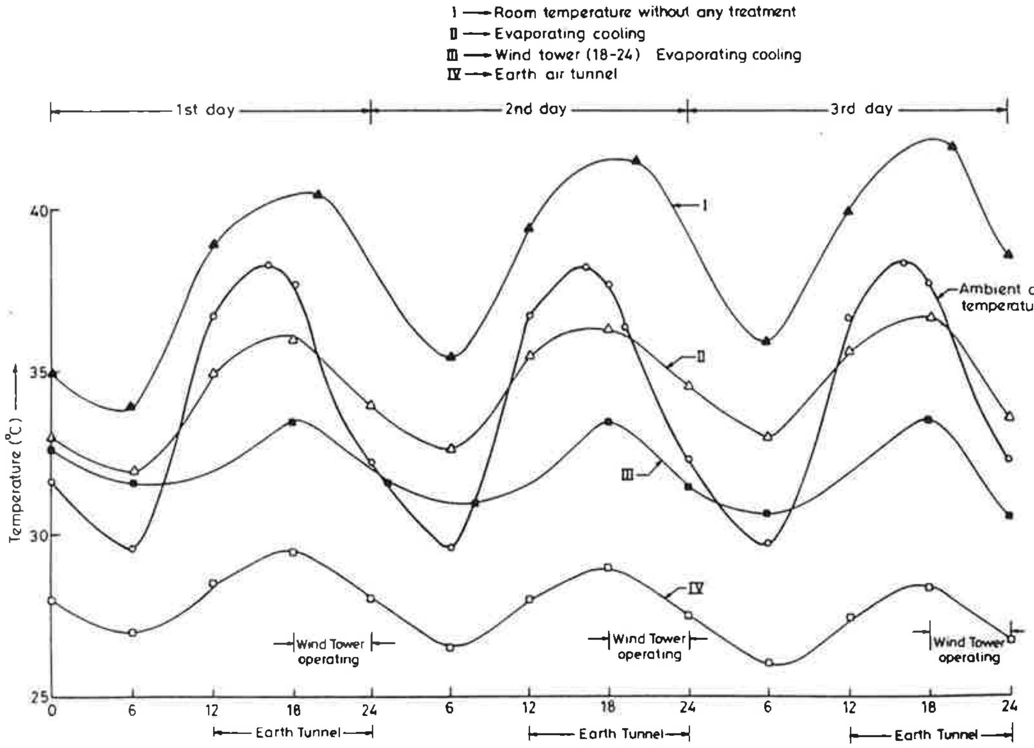


Fig. 8. Hourly variation of room temperature under different cooling treatment.

b	perimeter of the tunnel surface (m)
b_R	width of roof channel (m)
b_{ET}	width of earth tunnel (m)
C_a	specific heat of enclosed air (J/Kg °C)
C_r	air conductance of spacing in roof (W/m^2 °C)
C_w	specific heat of water (J/kg °C)
D	vapour diffusivity (m^2/s)
D_m	mass diffusivity (m^2/s)
d_R	depth of roof channel (m)
dx	elemental length along x direction (m)
d_{ET}	depth of earth air tunnel (m)
h_1	convective and radiative heat transfer coefficient for $V=0$ (W/m^2 °C)
$h_2'=h_2''$	convective heat transfer coefficient from flowing air to the contact roof and vice versa (W/m^2 °C)
h_c	convective heat transfer coefficient at inner surface of the tunnel (W/m^2 °C)
h_{cw}	convective heat transfer coefficient from water to ambient (W/m^2 °C)
h_{ew}	evaporative heat transfer coefficient from water to ambient (W/m^2 °C)
h_i	convective heat transfer coefficient from inner surface of walls/roof/doors to enclosed air (W/m^2 °C)
h_o	convective and radiative heat transfer coefficient at the outer surface (W/m^2 °C)
h_u	overall heat transfer coefficient from air of roof channel to ambient through top of channel cover (W/m^2 °C)
h_{rw}	radiative heat transfer coefficient from water to ambient (W/m^2 °C)
h_D	mass transfer coefficient (kg/s °C)
I_R	solar intensity on the roof (W/m^2)
I_w	solar intensity of wall (W/m^2)
K_{ab}	thermal conductivity of asbestos (W/m °C)
K_{as}	thermal conductivity of roof ceiling material (W/m °C)
K_{gi}	thermal conductivity of ground layer material (W/m °C)
K_i	thermal conductivity of walls/doors (W/m °C)
K_D	thermal conductivity of door material (W/m °C)
K_{Ri}	thermal conductivity of different roof components (W/m °C)
L_{as}	thickness of roof asbestos sheet (m)
L_{ET}	length of earth tunnel (m)
L_{gi}	thickness of ground layer (m)
L_i	thickness of wall (m)
L_{Ri}	thickness of different roof components (m)

L_{WR}	thickness of roof ceiling (m)
$\dot{m}$	mass flow rate of air (kg/m^2 s)
$\dot{m}_w$	rate of evaporation of water mass (kg/m^2 s)
$\dot{m}_{RC}$	mass flow rate of air in the roof channel (kg/s)
M_a	mass of enclosed air (kg)
N	number of air changes per hour from door ventilation
N_o	number of air changes per hour from window openings
p_a	partial pressure of saturated water vapour at ambient temperature (N/m^2)
p_w	partial pressure of saturated water vapour at water temperature (N/m^2)
$\dot{Q}$	average heat flux coming into the room through various components, (W/m^2)
$\dot{Q}_c$	net flux due to convection (W/m^2)
$\dot{Q}_{cw}$	heat transferred from water surface to ambient by convection (W/m^2)
$\dot{Q}_e$	heat flux due to evaporation (W/m^2)
$\dot{Q}_{ew}$	heat transferred from water surface to ambient by evaporation
$\dot{Q}_{rw}$	heat transferred from water surface by radiation (W/m^2)
$\dot{Q}_D$	energy transferred through door (W/m^2)
$\dot{Q}_G$	energy transferred from the ground surface (W/m^2)
$\dot{Q}_R$	rate of heat flux received from the roof (W/m^2)
T_a	tunnel air temperature (°C)
T_{ab}	roof temperature made up of asbestos (°C)
T_{amb}	tunnel inlet air temperature (°C)
T_s	tunnel surface temperature (°C)
T_{sky}	sky temperature (°C)
T_w	temperature of water (°C)
T_{wt}	temperature of wind tunnel (°C)
T_{wout}	outlet roof water temperature (°C)
T_a	ambient air temperature (°C)
T_R	room air temperature (°C)
T_{Rci}	inlet roof channel temperature (°C)
T_{RC}	roof channel temperature (°C)
T_{RO}	room temperature at $t=0$ (°C)
T_{WO}	roof water temperature at $t=0$ (°C)
U_R	overall heat transfer coefficient for the roof (W/m^2)
U_{bg}	overall heat transfer coefficient from the room to inside ground, (W/m^2 °C)
U_D	overall heat transfer coefficient through door (W/m^2 °C)
V_{RC}	velocity through roof channel (m/s)
V_w	velocity of flowing air (m s^{-1})
v_{IP}	velocity of air through inlet pipe to earth air tunnel (Fig. 5c) (m/s)
v_{ET}	velocity of air through earth air tunnel (Fig. 7) (m/s)
W	humidity ratio
W_s	saturated humidity ratio
Y	position coordinate (m)
α	absorptivity of the surface
α_0	thermal diffusivity of air
α_r	absorptivity of the roof surface
γ	relative humidity
ΔR_H	difference in internal and external readings of relative humidity
ΔT	change in tunnel air temperature (°C)
ϵ	emissivity
$\epsilon\Delta R$	longwave radiation exchange between surface and sky
ρ_a	density of air (kg m^{-3})
σ	Stefan–Boltzmann constant
$\mathscr{L}$	latent heat of vaporization (J/kg)

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