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AN IMPROVED DESIGN OF WIND TOWERS FOR NATURAL VENTILATION AND PASSIVE COOLING†

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Abstract—A design is proposed to improve the performance of wind towers (or Baud-Geers) for natural ventilation and passive cooling. Under similar climatological and design conditions, the new design is capable of delivering air to the building at higher flow rates. It can also cool the air evaporatively to lower temperatures. Higher airflow rates and the evaporative cooling capability of the new Baud-Geer design can be fully utilized at night in summer to cool the building mass to lower temperatures.

Momentum, mass and energy analyses are carried out for the proposed design. The results are presented in graphical forms which may be used as guidelines for employing the design for specific applications in the hot, arid areas of the world. An example is worked out to show the use of the results.

1. INTRODUCTION

Wind towers or wind catchers, or Baud-Geers (as they are called in Persian), have been used in Iran and the neighboring countries for natural ventilation and passive cooling for centuries[1–4]. Briefly, a Baud-Geer is a tower designed to "catch" the wind at higher elevations and direct it into the living space. In locations where wind is predominantly in one direction the tower head has only one opening facing that direction. In areas with variable wind directions the tower head has openings in all directions. Figure 1 shows the cross section of a typical Baud-Geer which has four openings on top to accommodate wind in all directions. The airflow passages in the tower may have equal or different (as in Fig. 1) areas.

The air entering the tower at opening 1, or the windward opening with positive wind pressure coefficient, leaves through any opening (connected to point 1) which has a pressure coefficient smaller than that at point 1. That is, part of the air which has entered the tower is lost through other tower openings (which have negative pressure coefficients) and the rest enters the house. The portion entering the house may be partially cooled by the structure, if the latter has stored a sufficient amount of ambient air coolness the night before. When the air flows over moist surfaces (for example, when air is flowing from point, 2 to 3 in Fig. 1) it is further cooled evaporatively. During the night, when air is flowing through the tower and the house, the ambient air coolness is also stored in the building mass. With heavy structures this energy storage plays an important role in providing thermal comfort during the following day. Baud-Geers, designed and operated with the full utilization of the technology which was available centuries ago, have the following disadvantages that can be overcome with the present technology:

1. Dust, insects and sometimes small birds, can enter the building.
2. A portion of the air admitted in the tower is lost through other tower openings and never enters the building. When the tower has only one opening facing the wind all the air entering the tower enters the house.
3. The amount of coolness which can be stored in the tower mass is generally limited (due to small mass and low specific heat of the energy-storing material), and may not be enough to meet the cooling needs of the building during a hot summer day. Or, the exposed surface area of the energy storing material may not be sufficient to allow a high rate of heat transfer.
4. Even in buildings with basements, where the air is made to flow over moist surfaces, the evaporative cooling potential of the air is not fully utilized. In hot, arid climates evaporative cooling is a very effective process for providing thermal comfort. In fact, because of this effectiveness, and due to their relatively low initial and operating costs, electrically driven evaporative or desert coolers have now become very popular in Iran, even in cities which have traditionally employed Baud-Geers.
5. Baud-Geers do not find any application in areas with very low wind speeds.

The major advantage of the Baud-Geers is that they are passive systems, requiring no energy for their operation. In those areas of the developing countries where electricity is either unavailable or unreliable Baud-Geers can be relied upon more than the evaporative coolers to provide ventilation and passive cooling.

The purpose of this investigation was to explore

† The research was carried out when the author was a visiting professor (on leave of absence from Shiraz University, Shiraz, Iran) at the Department of Mechanical Engineering, University of Waterloo, Waterloo, Ontario, Canada.

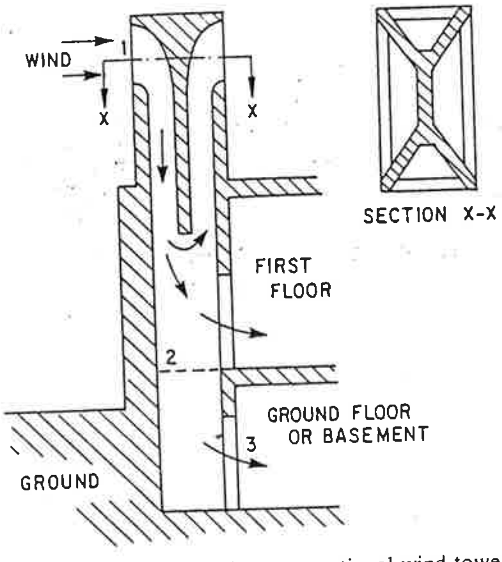

Fig. 1. Airflow pattern in a conventional wind tower.

a design which is believed to improve the performance of the wind towers, and to eliminate or minimize some of the disadvantages mentioned above. Furthermore, the implementation of the design does not require sophisticated technology, and can readily be employed in most of the developing countries.

In humid areas, where air motion with respect to the skin plays an important role in maintaining thermal comfort, the proposed design can still be used to maintain high air flow rates through the building. For example, people seated at rest and wearing light-weight clothing, feel thermally comfortable under the following conditions of air dry-bulb temperature, relative humidity and speed[5]:

$$T_{db} = 27.2°\text{C}, \quad \phi = 20\% \quad \text{and} \quad V = 0.2\,\text{m/s};$$

or

$$T_{db} = 28.2°\text{C}, \quad \phi = 60\% \quad \text{and} \quad V = 1.5\,\text{m/s},$$

where the mean radiant temperature (T_{mr}) of the surrounding surfaces is assumed to be equal to the room air temperature. When T_{mr} is lower the same comfort can be accomplished at a higher air temperature.

In this article, after presenting the design, a theoretical analysis is carried out to evaluate the performance of the system under various environmental conditions. The results of this analysis will help architects or designers to select the size and dimensions of a Baud-Geer to provide natural ventilation and passive cooling in a specific location. Finally, an example is worked out to demonstrate the design procedure.

2. THE PROPOSED DESIGN

The proposed design attempts to eliminate or to minimize the disadvantages of the conventional Baud-Geers. The design, as shown in Fig. 2, consists of three distinct improvements. They are

(a) A tower head which accepts wind blowing in any direction, and prevents the air from leaving the other tower openings.
(b) An energy storing system or column with a substantial increase in the heat transfer area.
(c) Full utilization of the potential of evaporative cooling of air by wetting the wall areas of the column.

These concepts are further discussed in the following sections.

2.1 *Design of the tower head*

In areas with variable wind directions the tower head may be designed with one-way dampers. Figure 2 shows a possible design. When the wind pressure coefficient at a tower opening is positive the damper at that opening is open, while the other dampers are closed. The dampers may be such as shown in the figure, or they may be of durable curtain material hung behind the screens. The screens are of large openings which result in small pressure losses and are considered to prevent birds and larger insects from entering the tower.

An alternate design which reduces the costs appreciably is to eliminate the curved nature of the entrance region at the cost of allowing additional pressure drop in this section. The screens and dampers (or curtains) are the same as the previous design, but the tower head has no specially designed entrance section to reduce the pressure losses (see Fig. 2).

Another design of the tower head is to make it to swivel into the wind, admitting air into the tower when wind is blowing in any direction.

2.2 *Design of thermal energy storage section of the Baud-Geer*

The convective heat transfer coefficient of air blowing over energy storing material is generally low. Thus, for a given quantity of heat to be transferred to the material, the surface area must be large. Large surface areas must be selected without excessive pressure losses of air as it flows over them. Figure 2 shows the cross section of a possible design. The energy storage material is baked (but unglazed) clay, made in the form of long conduits. The conduits may have circular, rectangular, or as in Fig. 2, square cross sections. A wall thickness of about 10 mm or less may be considered for the conduits. For a wind tower cross section (normal to the airflow) of 1 m^2 and square conduits of 10 cm outside dimensions and 1 cm wall thickness, the total heat transfer area, mass and the thermal capacitance of 50 conduits which can be placed in the tower are, respectively, 36 m^2, 306 kg and 256 kJ/C per 1 m height of the tower. That is, in 1 m^3 of the wind tower, employing clay conduits as the energy storing material, the mass of the material is 306 kg and the system has a heat transfer area of

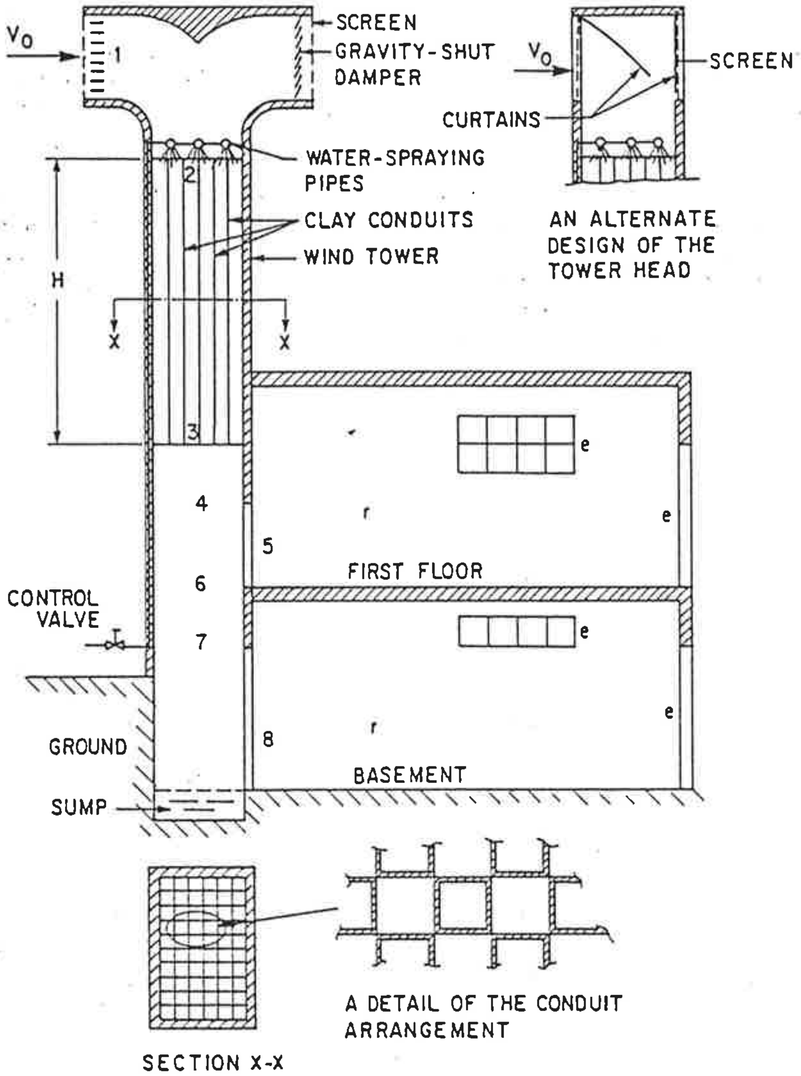

Fig. 2. A cross-section of the proposed design of the wind tower or Baud-Geer.

36 m^2. Compared with the conventional designs, this is an increase of about five to ten times in the heat transfer area and not much change in the total mass of the thermal energy storing material. That is, while the mass of the storage material is basically the same as in the conventional Baud-Geers, the proposed design provides a substantial increase in the heat transfer area.

Another advantage of the proposed design with small conduit wall thickness is that the temperature gradient within the material normal to the wall surface is very small. The response time to temperature changes is small, and the material can be heated or cooled very rapidly. Furthermore, with large heat transfer area the temperature difference between the air and the walls of the conduits is also small. Although the conduits with a desired specification may not be readily available in many countries, it is, however, believed that they can be produced by brick factories without much difficulty or excessive costs.

2.3 *Evaporative cooling of air by wetting of the clay conduits*

The unglazed clay conduits proposed for thermal energy storage can be wetted uniformly by spraying (or pouring) water over them at the top of the column. Water, uniformly sprayed over the conduits, will not run off the walls quickly; rather, it will keep the clay conduits uniformly moist as it flows down. The excess water leaving the column is collected in a sump located at the bottom of the tower. This water may be reused or drained off.

In addition to directing more air into the building and storing and retrieving coolness more effectively, the proposed design can utilize the potential of evaporative cooling, and can deliver air to the building at much lower temperatures. It has an additional advantage of removing some of the fine dust particles from the air, thus delivering cleaner air to the space. Entrance of dust into the living space in desert regions is a major problem, and definitely one of the disadvantages of employing Baud-

Geers for ventilation and passive cooling, as compared with other cooling systems.

To remove some of the larger dust particles from the air before entering the living space, the air velocity can be reduced by increasing the flow area. For example, the air entering the first floor (in Fig. 2) can be made to flow through the basement (by closing door 5) and admitting air into the first floor through floor registers connecting the two spaces. With low air velocity, most of the larger dust particles will be collected on the floor. In this design the door number 5 may be eliminated and the evaporation column can be extended down to point 6 (instead of point 3, such as shown in Fig. 2).

3. THEORETICAL ANALYSIS

In this section fluid flow, heat transfer, energy storage, mass transfer and evaporative cooling analyses are presented for the design shown in Fig. 2. The analyses are carried out numerically for four ambient air conditions, three wind velocities and variable heights of the energy-storing and evaporation column. The analyses are given for a Baud-Geer with 1 m^2 (2 m $\times$ 0.5 m) cross sectional area to supply evaporatively cooled air to a residential or commercial space.

3.1 *Selection of environmental and other design conditions*

The following conditions are selected for our numerical analyses:

(a) Air at atmospheric pressure.

(b) Air at dry-bulb and the corresponding wet-bulb temperatures of

(1) T_{db} = 45°C, T_{wb} = 22°C, corresponding with ϕ_0 = 12%

(2) T_{db} = 40°C, T_{wb} = 20°C, corresponding with ϕ_0 = 15%

(3) T_{db} = 35°C, T_{wb} = 18°C, corresponding with ϕ_0 = 18%

(4) T_{db} = 25°C, T_{wb} = 15°C, corresponding with ϕ_0 = 34%.

(c) Wind blowing in any direction at speeds of:

(1) V_0 = 5 m/s

(2) V_0 = 10 m/s

(3) V_0 = 15 m/s.

These conditions are selected primarily to represent the climate in the hot, arid areas of the world. Conditions 1, 2 and 3 in section (b) represent the daytime temperatures on a hot summer day, while condition 4 represents that during the night. Table 1 gives the dry-bulb and wet-bulb temperatures and the daily range recommended for cooling load calculations for a selected number of cities[5].

One may design a Baud-Geer to perform well under these recommended design conditions, or design the Baud-Geer using the mean daily maximum value of the dry-bulb temperature and its corresponding wet-bulb temperature. The mean daily maximum temperatures may be lower than the recommended design temperatures by about 3–7°C. Designing for the latter conditions, the size of Baud-Geer will be smaller, but one has to endure the thermal discomfort which may be caused when the ambient air temperatures exceed these values.

3.2 *Fluid flow analysis*

The driving potential for the air flow through the Baud-Geer is the pressure difference between the inlet section of the tower and the door or window through which the air leaves the building. This pressure difference may be expressed as

$$\Delta p_a = (C_{p1} - C_{pe}) \tfrac{1}{2} \rho V_0^2, \quad (1)$$

where C_{p1} and C_{pe} are the wind pressure coefficients at the tower head and exit section of the building (see Fig. 2), V_0 the wind velocity and ρ is the air density. For the direction of wind shown in Fig. 2, C_{p1} is always positive and C_{pe} is negative. These coefficients are determined through experimental studies of Baud-Geer models in wind tunnels[6, 7]. Values of C_{p1} = 0.85, C_{pe} = −0.17, or

$$\Delta C_p = C_{p1} - C_{pe} \cong 1 \quad (2)$$

may be selected for our analysis. When wind is blowing in directions other than that shown in Fig. 2, C_{p1} and C_{pe} may change. Depending on the location of the exit e, the design of the house (or the building) and the wind shadowing effect of adjacent structures with respect to the house, C_{pe} will change and may even become positive at some of the exits. In designing a building one can select the best orientation for the house with respect to the dominant wind direction. Or, one may even create wind shadowing effects by adjacent structures, trees, etc. so that C_{pe} is always negative[6, 7].

The total pressure drop through the tower is

$$\Delta p_t = \Delta p_1 + \Delta p_{12} + \Delta p_{23} + \Delta p_{34} + \Delta p_{46} + \Delta p_{67} + \Delta p_{78} + \Delta p_{8e} + \Delta p_e, \quad (3)$$

where we have considered the longest path for the airflow and the subscripts refer to the points shown in Fig. 2. Assuming a constant density for the air as it flows through the tower, the continuity equation becomes

$$V_1A_1 = V_2A_2 = V_4A_4 = V_5A_5 + V_6A_6 \quad (4)$$

and

$$V_5A_5 = V_rA_r = V_eA_e, \quad (5)$$

where A refers to the area and subscript r refers to the room. To simplify our analysis we assume that

$$A_1 = A_4 = A_6 = A_7$$

$$A_5 = A_8 = A_e = 2A_1$$

$$A_r = 15\,A_1.$$

Table 1. Design conditions for several cities for estimation of cooling load[5].

Country	City	Dry - Bulb Temperature °C	Wet - Bulb Temperature °C	Daily Range* °C
Afghanistan	Kabul	37	19	18
Australia	Alice Springs	40	24	15
Greece	Athens	35.5	22	10
Iran	Mashad	37	20	16
	Tehran	39	24	15
Iraq	Baghdad	45.5	23	19
Jordan	Amman	36	21	14
Mexico	Guadalajara	34	20	16
Saudi Arabia	Riyadh	43	25	18
Syria	Damascus	39	22	20
Turkey	Ankara	34.5	20	15.5
U.S.A.	Phoenix, AZ	43	22	15
	Prescot, AZ	35.5	16	17
	Tucson, AZ	40	19	14.5
	Yuma, AZ	44	22	15
	Palm Springs, CA	44.5	22	19.5
USSR	Tashkand	35	22	16

*The daily range is the difference between the mean daily maximum and the mean daily minimum temperatures in the warmest month.

Then, neglecting the pressure drops in the passages where the air velocities are small, or taking

$$\Delta p_{34} = \Delta p_{46} = \Delta p_{67} = \Delta p_{8e} \cong 0,$$

eqn (3) becomes

$$\Delta p_t = \Delta p_1 + \Delta p_{12} + \Delta p_{23} + \Delta p_{78} + \Delta p_e \quad (6)$$

or

$$\Delta p_t = C_t \tfrac{1}{2} \rho V_1^2 + \Delta p_{23}, \quad (7)$$

where C_t is a loss coefficients[5], accounting for the pressure losses through all the sections (except for 2–3) shown in Fig. 2. For the design considered in this study, C_t was calculated to be about 4. We assume a value of $C_t = 5$ to account for additional or miscellaneous pressure losses. Then, we have

$$\Delta p_t = \tfrac{5}{2} \rho V_1^2 + \Delta p_{23}. \quad (8)$$

For any wind velocity V_0, a flow is maintained in the tower and the building so that

$$\Delta p_a = \Delta p_t. \quad (9)$$

Or, combining with eqns (1), (2) and (8) we have

$$\tfrac{1}{2}\rho V_0^2 = \tfrac{5}{2} \rho V_1^2 + \Delta p_{23}. \quad (10)$$

Equation (10) was solved by iteration for V_0 = 5, 10 and 15 m/s, and for the heights of the column corresponding with H = 2, 4, 6, 8, and 10 m. The pressure drop through the column, or Δp_{23}, was determined by using the friction chart provided for galvanized steel and a correction factor recommended for the rough column surfaces. An absolute surface roughness factor of $\epsilon = 3$ mm (as compared with $\epsilon = 0.15$ mm for galvanized steel) was chosen. This value is recommended for rough concrete ducts[5]. Figure 3 shows the velocity V_1 (at the entrance to the tower) and V_2 (in the energy storage or evaporation column) for different wind speeds and for different heights of the column. The analysis presented here can be repeated for the surfaces with roughness factors other than $\epsilon = 3$ mm. Then, curves such as shown in Fig. 3 may be obtained for any material employed as the evaporation column.

3.3 *Heat transfer and energy storage analysis*

The average convection heat transfer coefficient for air flowing through a smooth duct or pipe may

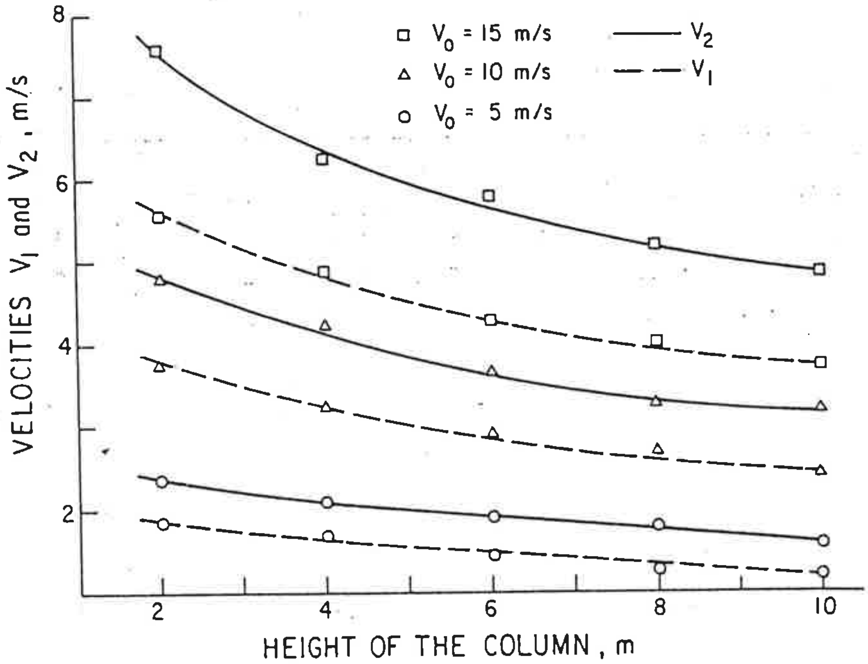

Fig. 3. Air velocities V1 and V2 as functions of the column height and wind velocity.

be obtained from[5, 8]

$$h_s = 0.023\ (k_a/d_e)\ (\mathrm{Re})^{0.8}\ (\mathrm{Pr})^{0.4}, \tag{11}$$

where k_a and Pr are the thermal conductivity and Prandtl number of the air, d_e the equivalent diameter of the conduit and Re is the Reynolds number. For rough surfaces one may use the following relation[9–11]:

$$\frac{h}{h_s} = \left(\frac{f}{f_s}\right)^n, \tag{12}$$

where n is a constant which depends on the nature of the surface roughness, and f and f_s are the friction factors for the rough and smooth ducts. For sand-grain roughness $n = 0.68$ may be used. Selecting $n = 0.68$ to represent the roughness of the baked unglazed clay conduits considered in this analysis, and combining eqns (11) and (12), we obtain

$$h = 0.023\ (k_a/d_e)\ (\mathrm{Re})^{0.8}\ (\mathrm{Pr})^{0.4}\ (f/f_s)^{0.68}. \tag{13}$$

It was shown in section 2.2 that for a wind velocity of $V_0 = 5$ m/s and a column height of 5 m the average air velocity in the conduits with $d_e = 10$ cm is about $V_2 = 2$ m/s (see Fig. 3). For an air temperature of 40°C, where $k_a = 0.0272$ W/mC, Pr = 0.7, we obtain Re = 11800, $f/f_s = 2$, and $h = 15.72$ W/m^{2}C.

Conduction of heat through the conduit walls is of transient nature in that in a daily cycle heat flows into the material during the day and out of it during the night. To determine the nature of heat flow in the conduit walls, we examine the Biot modulus, Bi = $ht/2k_c$, where t is the wall thickness and k_c is the thermal conductivity of the wall. For $t = 1$ cm, $k_c = 0.671$ W/mC (the value recommended for masonry bricks), and $h = 15.72$ W/m^{2}C, we have Bi = 0.117. With such a low Bi the temperature gradient in the wall in the direction normal to the wall surface is very small and can be neglected[8].

To study the storage of thermal energy in the conduit walls, we divide the column into n small sections and assume that the wall temperatures in each of these sections and at any given time is constant. For a section i and at time element j we have

$$\dot{Q}_{i,j} = (\dot{m}_a c_{pa})_j (T_{i,j} - T_{i+1,j}), \tag{14}$$

$$\dot{Q}_{i,j} = h\ a[T_{i,j} + T_{i+1,j})/2 - T'_{i,j}], \tag{15}$$

$$\dot{Q}_{i,j} = \rho_c c_c a \frac{t}{2} (T'_{i,j+1} - T'_{i,j})/\theta, \tag{16}$$

where $\dot{Q}_{i,j}$ is the rate of heat transfer to the wall, $\dot{m}_a$ the mass flow rate and c_{pa} the constant pressure specific heat of air, T the air temperature, T' the wall temperature, a the heat transfer surface area of the section, ρ_c and c_c the density and specific heat of the wall material, t the wall thickness and θ is a small time step. Subscripts i and j refer to location and time, respectively.

For a selected column height and for a given wind velocity and ambient air temperature, the velocities of air flowing through the tower and through the column, the mass flow rate and the heat transfer coefficient were determined. Equations (14) to (16) were then solved simultaneously to determine the air temperature (as it passes through the conduits

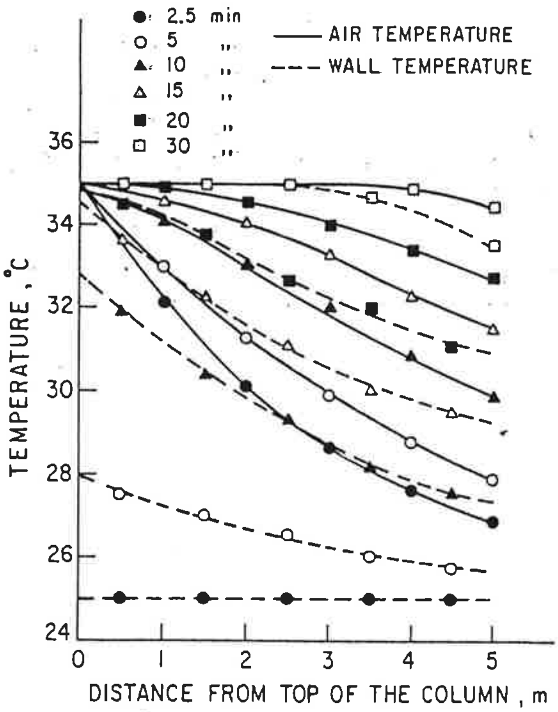

Fig. 4. Variation of air and wall temperatures in the non-wetted column for a wind velocity of 5 m/s.

or the column) and the wall temperature at any location and time. Figure 4 shows the results of the calculations for $H = 5$ m and $V_0 = 5$ m/s. In these calculations, $V_2 = 2$ m/s and $h = 15.72$ W/m^2 were obtained, and it was assumed that the wall temperature, initially, and for the first 2.5 min, is at 25°C, and the ambient air temperature is at 35°C. This corresponds to an operation which assumes the entire column is cooled to 25°C the night before, but the daytime operation of Baud-Geer starts only at a time when the ambient air temperature and wind velocity are 35°C and 5 m/s, respectively. The calculations were also based on a time step of θ = 2.5 min and dividing the column into five sections, each 1 m high.

It is clear from Fig. 4 that, while at the beginning of the air cooling process (or retrieval of the stored coolness), the temperature difference between the air and the wall is about 10°C, this difference drops to about 1°C after only about 20 min of operation, and that the wall temperature increases very rapidly. This means that the coolness stored in the conduit walls is retrieved very quickly as air circulation through the Baud-Geer is first permitted (by opening of doors 5 or 8 in Fig. 2 and the doors or windows in the building to allow airflow out of the building). After this period, the wall temperature follows the variation in air temperature very closely and the changes of air temperature, as the air flows through the tower, become very small. This phenomenon may be explained as follows: For the design considered in this study the total amount of coolness which can be stored in the clay conduit walls is small, while the airflow rate and the heat transfer area are large. For a height of 5 m for the column, and with a daily range of about 15°C, the maximum amount of coolness which may be stored is about 19,200 kJ. Assuming an average airflow rate of 1.5 m^3/s for about 8 h of Baud-Geer usage during the day, the air can be cooled as an average by about 0.4°C. Such a small temperature drop is not significant to provide thermal comfort in the building. This points to the fact that with a very small thermal capacitance of the energy storage material employed in this design, the stored coolness can make a very small contribution to the maintenance of thermal comfort in the building during the hot summer days. In such a case the role of evaporative cooling becomes more important. This is shown in the next section.

3.4 *Mass transfer and evaporative cooling analysis*

We assume that the surface area of the clay conduits is uniformly moist. For the turbulent flow of air in the conduits and for air and water vapor at low mass flow rates, the Lewis relation gives[5]:

$$h_m = h/c_{pa}, \tag{17}$$

where h and h_m are the heat and mass transfer coefficients, and c_{pa} is the constant pressure specific heat of air. The rate of water evaporated into the air is given by

$$\dot{m}_v = h_m A_m (W' - W), \tag{18}$$

where A_m is the mass transfer area, W' is the humidity ratio of the air as if it were saturated at the wall temperature and W is the humidity ratio at free stream conditions. As air flows through the conduits, water evaporates into the air stream adiabatically, and the moisture content or humidity ratio of the air increases. Dividing the height of the column into small sections (as it was done in the heat transfer analysis), and assuming a constant moisture content within each section, we can determine the moisture content at the next section from

$$W_{i+1} = W_i + \dot{m}_v/\dot{m}_a, \tag{19}$$

where i denotes the section number.

The dry-bulb temperature and humidity ratio of air leaving the evaporative cooling column were determined by assuming each section to be 1 m high, and to be at a constant wall temperature equal to the ambient air wet-bulb temperature. The following conditions were considered for the analysis:

(a) H = 2, 4, 6, 8 or 10 m,
(b) V_0 = 5 and 15 m/s,
(c) Dry-bulb and the corresponding wet-bulb temperatures: 45°C and 22°C; 40°C and 20°C; 35°C and 18°C; 25°C and 15°C,
(d) The evaporation effectiveness of the column: 60%.

The evaporation effectiveness of 60% was considered to account for the non-perfect wetting of the conduit walls. It simply assumes that about 60% of the conduit wall area is available for mass transfer. No heat gain from the surroundings was considered by the evaporation column.

The following procedure was followed for the analysis: We first selected a column height H. Then, for a given wind velocity and the ambient air conditions, we determine V_2 (from Fig. 3), $\dot{m}_a$, h_m, and then solved eqns (18) and (19), as was explained before. The conditions (dry-bulb temperature and humidity ratio) of air leaving the column of height H were then determined. The process was repeated for all other variables indicated before. Figure 5 shows the results of the computations. The case of ambient air condition of T_{db} = 25°C and T_{wb} = 15°C was considered to explore the evaporative cooling potential of the column at night. Figure 5 shows that even with a moderate height of 5 m, the air leaving the evaporative cooling column at night is very cold. Air at such a low temperature can be used to cool the building structure at night. This process is of a great significance in the passive cooling of buildings in the hot, arid regions.

Conditions of air (that is, the dry-bulb temperature, relative humidity and velocity) leaving a column with a selected height H are given in Figs. 6 and 7 for wind velocities of 5 and 15 m/s. It can be seen from Fig. 6 that when, for example, H = 5 m, and when the ambient air is at T_0 = 40°C (dry-bulb temperature), ϕ_0 = 15% and wind velocity is V_0 = 5 m/s, the air leaving the column is at T_3 = 25°C, ϕ_3 = 65% and V_3 = 1.5 m/s. When the wind velocity changes to V_0 = 15 m/s (with other conditions remaining the same) we have (from Fig. 7) T_3 = 26.5°C, ϕ_3 = 56% and V_3 = 4.5 m/s. At night, assuming T_0 = 25°C, ϕ_0 = 34% and V_0 = 5 m/s, the air leaving the Baud-Geer will be at T_3 = 17.5°C (see Fig. 5), ϕ_3 = 78.5% and V_3 = 1.5 m/s.

4. MAINTAINING THERMAL COMFORT IN THE BUILDING

Thermal comfort depends on several factors, the most important of which are[5]

1. The metabolic rate.
2. The insulating effect of clothing.
3. The air temperature.
4. The air relative humidty.
5. The air velocity with respect to the skin.
6. The mean radiant temperature of the surrounding surfaces.

While the first two parameters are generally determined by the occupants, it is the other four parameters which may be controlled to provide thermal comfort.

Design of a Baud-Geer and the building to be cooled by it should be considered together. This is important from the point of view of providing a desirable airflow through the building and also in storing the ambient air coolness within the building structure at night. With higher air velocity in the space and lower wall temperatures (which is a result of the stored coolness in the structure), thermal comfort can be maintained at higher air temperatures and relative humidities.

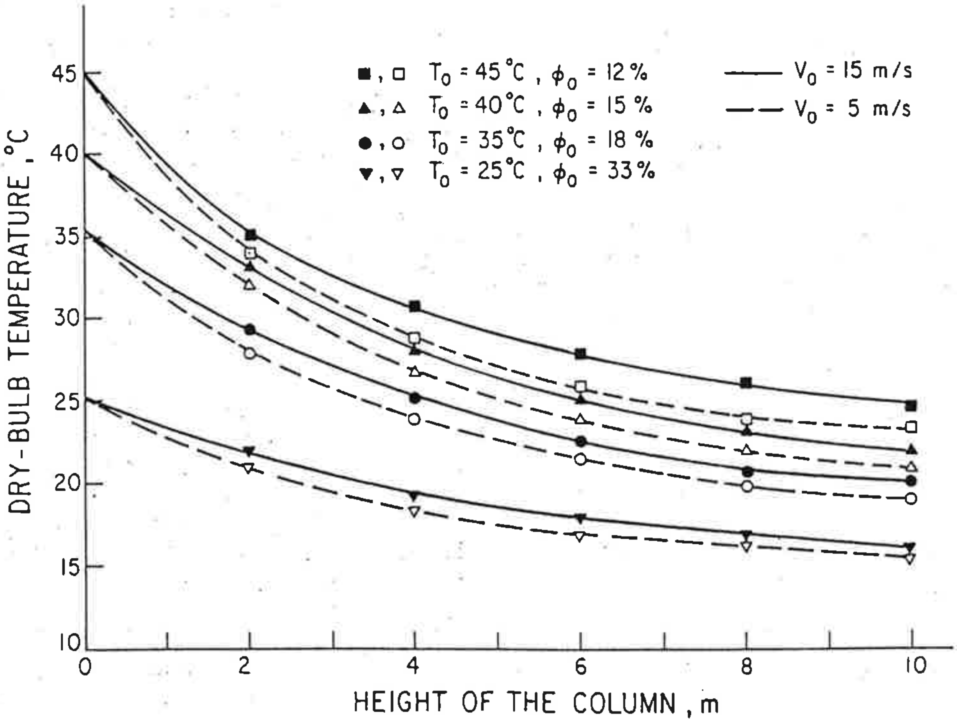

Fig. 5. Dry-bulb temperature of air leaving the evaporative cooling column.

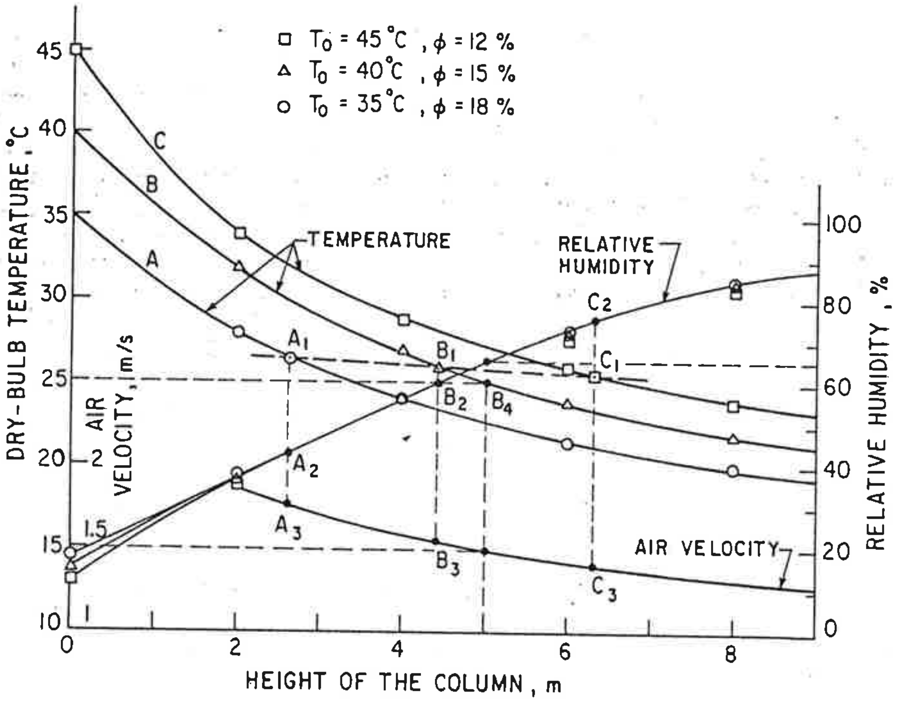

Fig. 6. Condition of air leaving the evaporative cooling column for a wind velocity of 5 m/s.

To find out if the design proposed here can indeed provide thermal comfort for a building, we make the following assumptions:

(a) Sedentary level of physical activity, corresponding with a metabolic rate of 1 Met.

(b) Light clothing, corresponding with an insulating effect of 0.5 clo.

(c) Mean radiant temperature equal to the air temperature.

(d) An air velocity in the space about 1/15 (ratio of A_3 to A_r in Fig. 2) of the air velocity in Baud-Geer.

With these assumptions we can now determine if the air leaving a Baud-Geer and entering the space

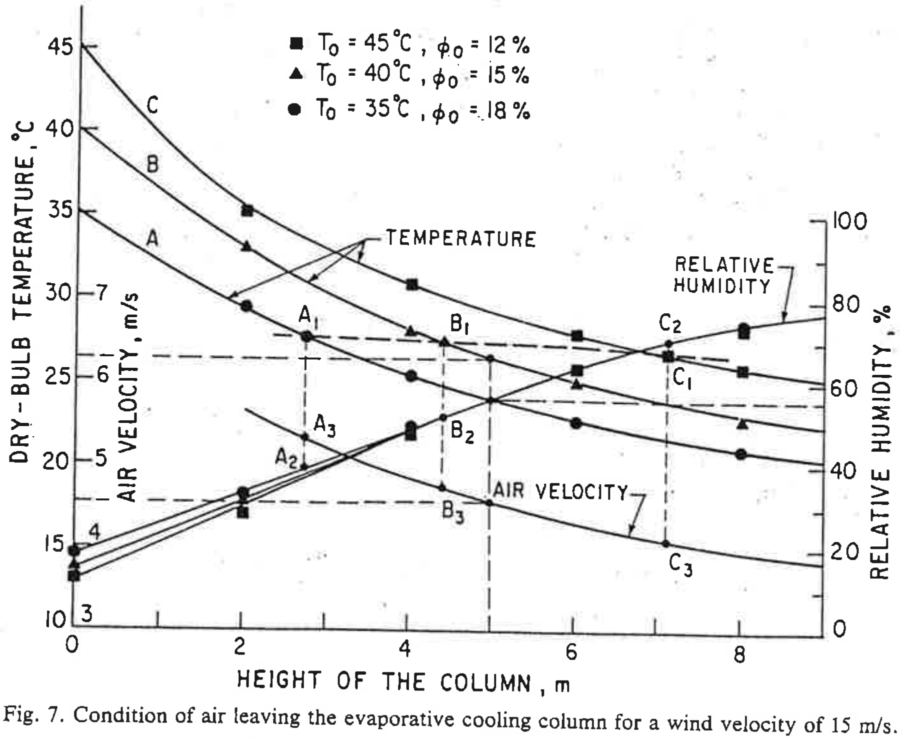

Fig. 7. Condition of air leaving the evaporative cooling column for a wind velocity of 15 m/s.

can maintain thermal comfort in the building. Using thermal comfort charts[5], and referring to Figs. 6 and 7, we find (by trial and error) points A_1, B_1 and C_1 on curves A, B and C so that the air leaving the Baud-Geer and reaching the occupants at these conditions can maintain thermal comfort. The heights of the evaporative cooling column corresponding with points A_1, B_1 or C_1 represent the minimum values. Heights lower than these cannot deliver air to the space at suitable thermal conditions. That is, for a given ambient air condition and wind velocity the evaporative cooling column should have a height at least equal to that represented by line A_1 B_1 C_1. (Use linear interpolation for conditions which are within the ranges considered in Figs. 6 and 7.) Of course, the air supplied to the space should be cooler so that when it reaches an occupant (after having picked up some of the space heat gains), it is still at a thermally comfortable level.

To show how the height of the evaporation column and the size of the Baud-Geer may be determined to provide thermal comfort in a building we treat the following example.

Example: It is desirable to provide thermal comfort in a residential building employing the ventilation and passive cooling design proposed here. The building, 10 × 10 × 3 m in dimensions, is located in Tucson, Arizona, and has a peak cooling demand of $\dot{Q}$ = 10 kW, with a sensible heat factor of about 0.65. The air reaching the occupants may be assumed to have been heated (through the building heat gains), as an average, by about 1/2 of the cooling load, and that it has a velocity of about 0.1 m/s. Determine the dimensions of the Baud-Geer, the height of its evaporative cooling column and the condition of the air reaching the occupants. Assume a wind velocity of V_0 = 5 m/s for Tucson.

Solution: First we have to determine the amount of air which has to be delivered by the Baud-Geer. With the building dimensions and the relative air velocity in the building specified, we select an air flow rate of about 3 m^3/s to be supplied by the Baud-Geer. We further assume that the curve labelled B in Fig. 6 (for T_{db} = 40°C, ϕ_0 = 15%, T_{wb} = 20°C and V_0 = 5 m/s) can represent the design conditions for Tucson. Unknowns are the cross-sectional area (A_4) of the Baud-Geer and the height H which can deliver the needed quantity of air at desirable conditions. The point representing the condition of air leaving the tower has to be to the right of B_1 (see Fig. 6). By a trial and error procedure, point B_4 is found which is at T_4 = 25°C and ϕ_4 = 65%. From the psychrometric chart[5] we obtain enthalpy and density of this air to be about h_4 = 58.0 kJ/kg C and ρ_4 = 1.156 kg/m^3. The condition of air reaching the occupants can be determined from

$$\tfrac{1}{2}\dot{Q} = \rho_4 \dot{V}_4 (h_r - h_4), \tag{20}$$

and the psychrometric chart, with a sensible heat factor of 0.65. From eqn (20) we find h_r = 59.44 kJ/kg C, and from the psychrometric chart we find T_r = 25.95°C and ϕ_r = 64%, where the subscript r refers to the condition of air in the room before reaching the occupants. With T_r, ϕ_r and V_r = 0.1 m/s we note that the condition of thermal comfort (under the assumptions stated earlier) is satisfied[5]. The height of the evaporative cooling column is (from Fig. 6) about 5 m, and the velocity of air leaving the wind tower (from Figs. 3 or 6) is about 1.5 m/s. This leads to a cross-sectional area of 2 m^2 for the Baud-Geer. For a better air distribution in the building, we select two wind towers, each with a cross-sectional area of about 1 m^2.

5. SYSTEM CONTROL

Baud-Geers may be designed to meet the peak cooling demands (as in the above example). For partial loads one has the following options:

(a) Control the evaporative cooling by reducing the wetted area of the conduit walls by controlling the rate of water sprayed on the conduit walls.
(b) Control the airflow through the Baud-Geer.

The first option may be carried out by controlling the amount of water which is sprayed on top of the column, while the second one is accomplished by partially closing the openings admitting air into (from Baud-Geer), or out of the building. In winter, or any time when no cooling is needed, the openings between the Baud-Geer and the building have to be completely shut.

6. CONCLUSIONS

As compared with conventional wind towers and for given climatological conditions, the proposed design supplies air to the building at higher flow rates and with less dust. Furthermore, the air delivered to the building is cooled evaporatively to lower temperatures. Without evaporative cooling, the cooling effect of the tower (due to the storage of night air coolness) is very small. The theoretical analysis carried out in this study may be used as a guideline for designing natural ventilation and passive cooling systems in the hot, arid areas of the world.

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REFERENCES

1. M. N. Bahadori, "Thermal performance of old buildings in central Iran employing air towers," Passive Solar Heating and Cooling Conference, Los Alamos Scientific Laboratory, New Mexico, Report No. LA-6637-C, pp. 157–159, May 1976.
2. M. N. Bahadori, Passive cooling systems in Iranian architecture. *Sci. Am.* 238(2), 144–154 (1978).

3. M. N. Bahadori, "Natural Cooling in Hot Arid Regions," in *Solar Energy Application in Buildings* pp. 195–225 (Edited by A. A. M. Sayigh), Academic Press, New York (1979).
4. M. N. Bahadori, "Passive and hybrid convective cooling systems," International Passive and Hybrid Cooling Conference, American Section of the International Solar Energy Society, Miami Beach, Florida, pp. 715–727, Nov. 1981.
5. "ASHRAE Handbook, 1981, Fundamentals," American Society of Heating, Refrigerating and Air Conditioning Engineers, Inc., Atlanta, Georgia, 1981.
6. M. N. Bahadori, "Pressure coefficients to evaluate air flow pattern in wind towers," International Passive and Hybrid Cooling Conference, American Section of the International Solar Energy Society, Miami Beach, Florida, pp. 206–210, Nov. 1981.
7. C. Karakatsanis, M. N. Bahadori and B. J. Vickery, Evaluation of pressure coefficients and estimation of airflow in buildings employing wind towers. Submitted for publication.
8. F. Kreith, *Principles of Heat Transfer*, 3rd Edn., Intext Educational Publishers, New York (1973).
9. G. A. Kemeney and J. A. Cyphers, Heat transfer and pressure drop in an annular gap with surface spoilers. *J. Heat Transfer* **83**, 189–198 (1961).
10. D. F. Dipprey and R. H. Sabersky, Heat and momentum transfer in smooth and rough tubes at various Prandtl numbers. *Int. J. Heat and Mass Transfer* **6**, 329–353 (1963).
11. V. Kolar, Heat transfer in turbulent flow of fluids through smooth and rough pipes. *Int. J. Heat and Mass Transfer* **8**, 639–653 (1965).