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Renewable Energy 33 (2008) 2273–2281
RENEWABLE ENERGY
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Experimental investigation of new designs of wind towers

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Received 16 January 2007; accepted 18 December 2007
Available online 14 February 2008

Abstract

Two new designs of wind towers were tested side by side with a conventional wind tower in the city of Yazd, Iran. All the towers were of identical dimensions. The two new designs were one with wetted column, consisting of wetted curtains hung in the tower column, and the other one with wetted surfaces, consisting of wetted evaporative cooling pads mounted at its entrance. The air temperature leaving the wind towers with evaporative cooling provisions were much lower than the air temperature leaving the conventional design, and its relative humidity much higher. The air-flow rate was reduced slightly in these new towers. It was found that the wind tower with wetted column performs better with high wind speeds whereas the tower with wetted surfaces performs better with low wind speeds. It is recommended that these new designs of wind towers should be manufactured in different sizes and incorporated in the designs of new buildings. They can replace the evaporative coolers currently employed in Iran, and other hot arid regions, with considerable saving in electrical energy consumption.

Keywords: Wind towers; Passive evaporative cooling

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 of buildings for centuries [1–3]. 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. Fig. 1 shows the cross section of a typical Baud-Geer, which has four openings on top to accommodate the 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 through evaporation of water.

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.

Wind towers, 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 [4]:

1. Dust, insects, and sometimes, small birds can enter the building.

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doi:10.1016/j.renene.2007.12.018

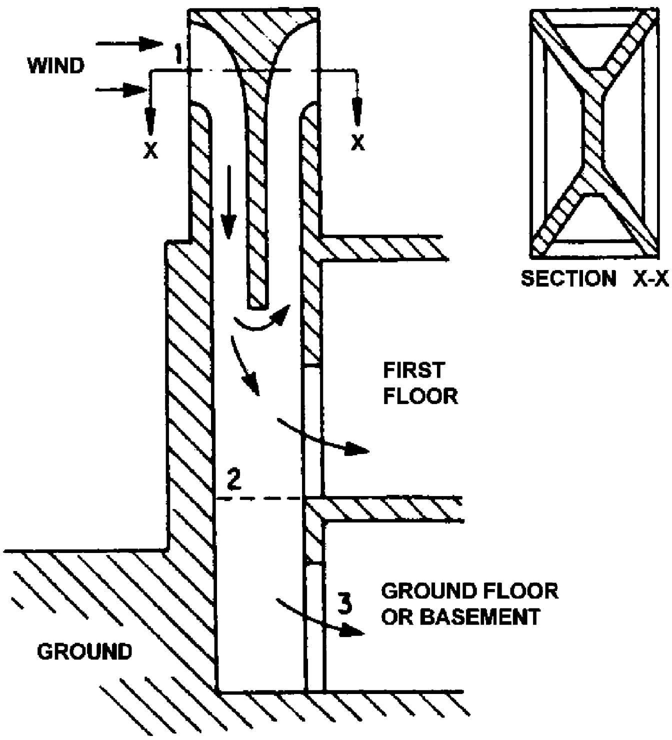


Fig. 1. Airflow pattern in a conventional wind tower.

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 summer. 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 or wind towers do not find any application in areas with very low wind speeds.

The major advantage of the wind towers 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 experimentally the performance of two new designs of wind towers, and compare the results with those of a conventional design, and with a numerical analysis performed for all three designs.

Fig. 1 shows a cross section of a typical design of a conventional wind tower [4]. For the new designs of wind towers, we considered two designs, which eliminated the disadvantages listed above. These designs were called: (1) the wind tower with wetted column [4], or wetted curtains, and (2) the wind tower with wetted surfaces [5]. The tower head in both designs was equipped with screens at all openings and plastic curtains behind them to allow only the air to enter the tower from the outside, and prevent the air from leaving the tower from that opening.

The wind tower with wetted column was equipped with cloth curtains, spaced 10 cm from each other and suspended vertically in the wind tower column. Their widths were equal to the width of the wind tower. They were secured firmly at the bottom to prevent them from fluttering due to the air flowing between them. The length of the curtains was such as not to obstruct the air from flowing into the wind tower, or out of it. The curtains were wetted by spraying water on top of them.

The wind tower with wetted surfaces was equipped with evaporative cooling pads (similar to those employed in normal evaporative coolers), placed at the wind tower openings on the top of the tower. The pads were wetted by spraying water on top of them (similar to the evaporative coolers).

2. The experimental arrangement

To minimize the cost of the construction and measurements, it was decided to incorporate the new designs and the conventional design of the wind towers into one tower, consisting of three sections. All sections had identical heights and cross-sectional areas. The wind tower with conventional design was placed in the middle, and the new designs of the wind towers occupied the side sections. Two series of experiments were conducted. One set of wind towers was built and tested at the site of Scientific and Industrial Research Organization (SIRO) in Shahryar, Iran, about 30 km (southwest) from Tehran, and the other one on the campus of Yazd University, in the city of Yazd. The wind towers at SIRO each had a cross section of 1×1 m, and overall height of 11.70 m, a net column height of 8 m, and the opening height of 1.5 m on top and 45 cm at the bottom [6].

The performance of the other set of wind towers built at Yazd University is reported in this article.

Fig. 2 shows two cross sections, and Figs. 3 and 4 show photographs of the wind towers at Yazd University, appearing as one unit.

It should be added that the wind towers at Yazd University was incorporated with the design of the

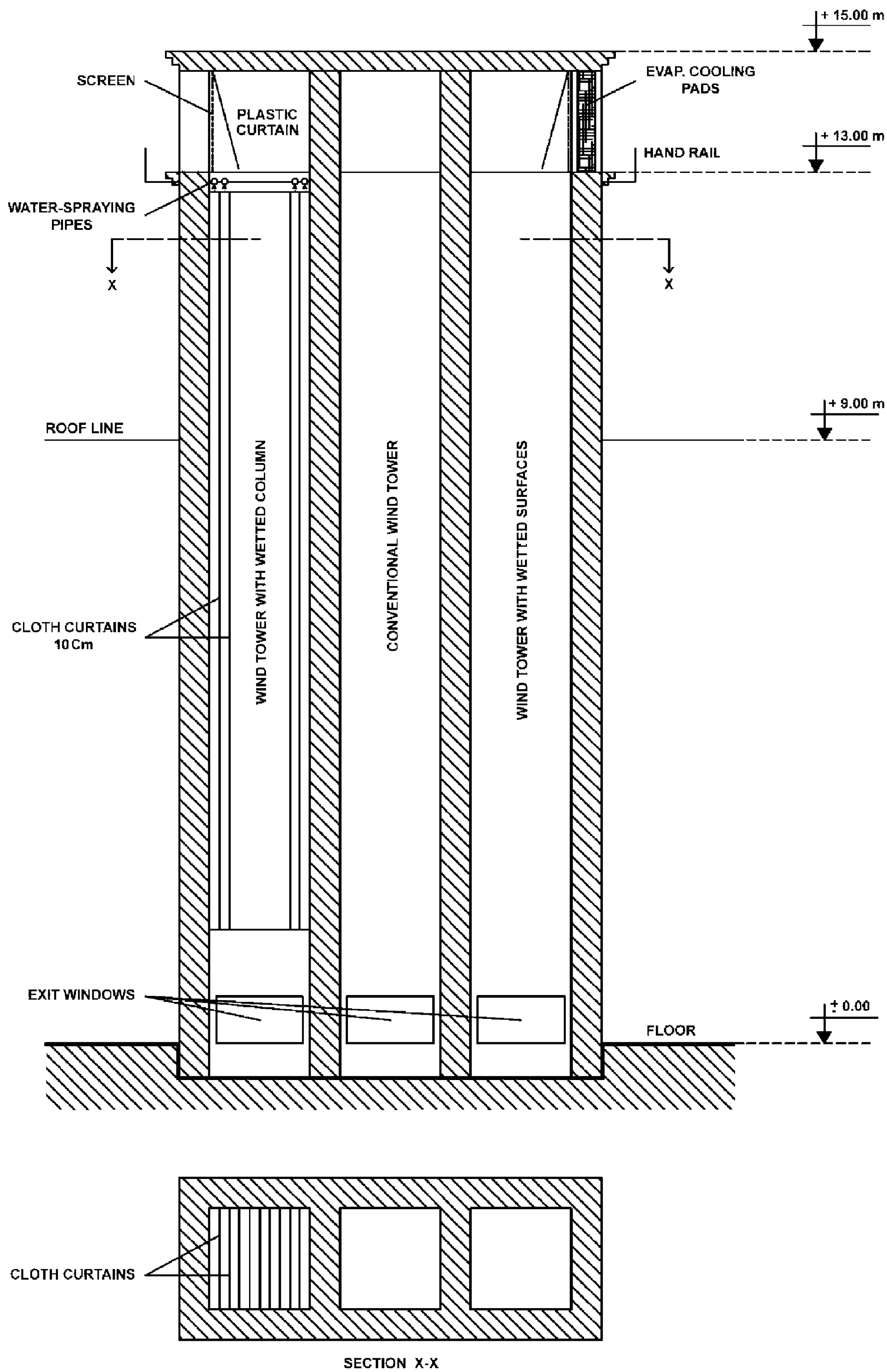


Fig. 2. Cross sections of the wind towers at Yazd University.

University Mosque, and as a unit, it became a minaret for this mosque.

3. Experimental results

Experiments were carried out during the summer of 2003. Table 1 shows the results for 10 September, which was a typical day in September, and Table 2 shows the results at 2 p.m. for the days of 4–13 September. Wind speed and direction (which were quite variable) as well as the ambient air temperature and relative humidity were measured in an open space not obstructed by any building. The temperature, relative humidity, and velocity of the air leaving each tower were measured

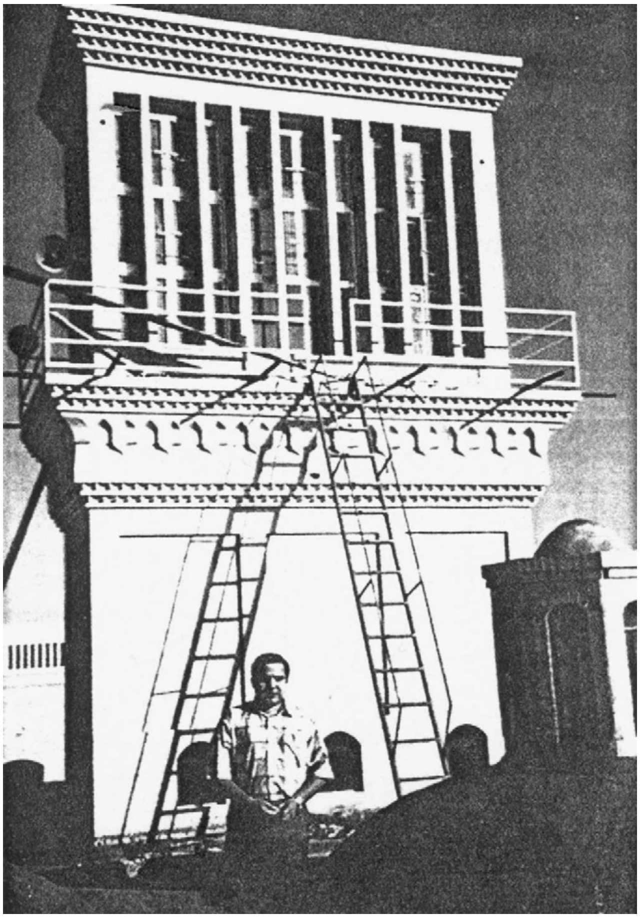


Fig. 3. Photographs of the wind towers built and tested at Yazd University.

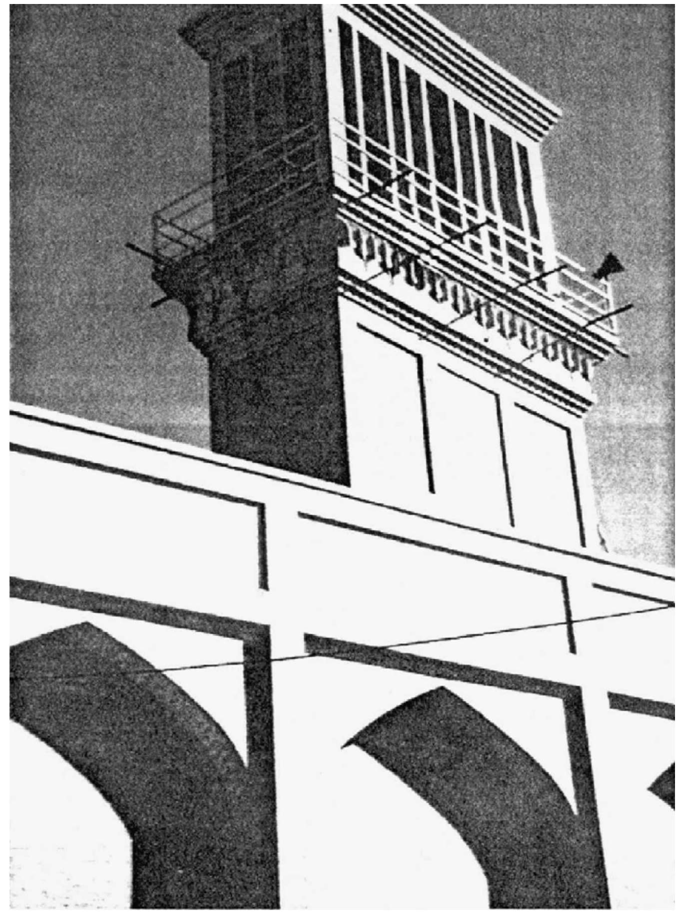


Fig. 4. Photographs of the wind towers built and tested at Yazd University.

at its exit openings. Each exit opening was at $1.3 \times 0.6\,\mathrm{m}$ dimensions, and was divided into 12 rectangles by strings. The measurements were made at the centers of these rectangles and were then averaged. Measurements were carried out from hour 9 to 18 (9 a.m. to 6 p.m.) for several days in the second half of the summer of 2003. Figs. 5–7 show the average temperature T, relative humidity φ, and velocity V, of the air measured at different hours on 10 September. Ambient air temperature T_0, relative humidity φ_0, and average wind velocity V_0, along with the average wind direction, are also shown in these figures.

4. Numerical study

Through a flow- and a thermal network analysis for all three types of wind towers, described in details in Refs. [4–8], we estimated the amount of air flowing out from each tower, along with its temperature and relative humidity.

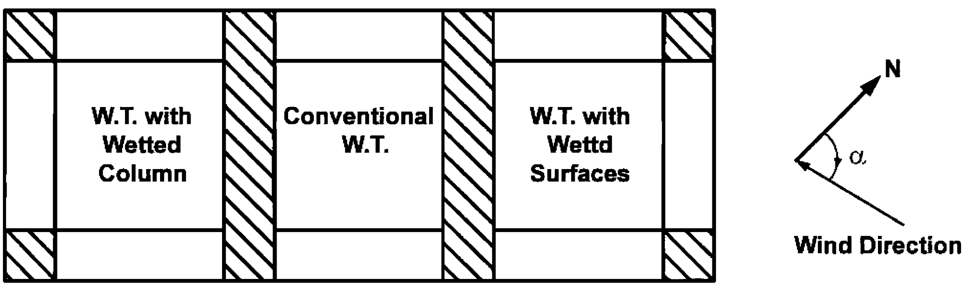
In this analysis, we considered the air flowing into each tower opening on top, and leaving through the aperture at the bottom. That is, the plastic curtains hang behind the screens at the tower openings on top allowed only the air to enter the wind tower through the windward opening(s), and prevented it from leaving the tower through the leeward opening(s). The air leaving each wind tower entered the praying area of the mosque.

In the thermal network analysis, we considered solar radiation gain, thermal and sky-radiation exchanges of the exposed walls with the ground and the surrounding surfaces, convection exchange with the outside air, radiation exchange of the wall with other walls in the tower, and convection exchange with the air flowing in the wind tower.

Fig. 8 shows a portion of the thermal network drawn for an exposed wall and a partition wall separating two adjacent wind towers, or a wetted curtain in the tower with wetted column. In this figure, S is the solar radiation received by the external surface of the exposed wall, $h_{\mathrm{r,wo\text{-}sk}}$ and $h_{\mathrm{r,wo\text{-}gr}}$ are, respectively, the heat transfer coefficients of thermal radiation exchange with the sky and ground, h_{wo} the convection heat transfer coefficient with the outside air, and h_{c} the convection heat transfer coefficient with respect to the air flowing

Table 1
Temperature, relative humidity and velocity of the air leaving the wind towers (WT)

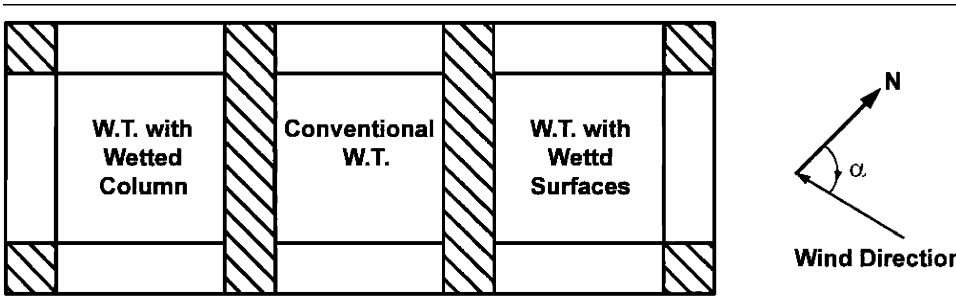
Time (h)	Outside air				Wetted column WT			Conventional WT			Wetted surfaces WT		
	T_0	Φ_0	$\bar{V}_0$	$\bar{\alpha}$	T	φ	V	T	φ	V	T	φ	V
9	28.7	13.7	2.5	250	19.8	80	1.5	25.8	16.5	1.7	20.9	71	2.1
10	30.2	12.4	2.1	240	20.7	78	1.2	27.4	15.2	1.8	22.1	71	1.9
11	32.1	12.1	1.8	212	20.4	82	1.5	28.4	15.1	1.7	23.2	71	1.1
12	32.8	11.5	1.8	195	20.3	73	1.4	29.1	14.5	1.5	22.8	68	0.9
13	33.3	11.1	2.1	245	19.9	71	1.8	30.4	13.8	1.7	21.3	75	1.4
14	34.1	10.8	1.7	195	20.4	70	1.5	30.8	13.5	1.5	22.7	65	1.2
15	35.6	9.5	1.7	205	20.7	83	1.4	31.2	12.8	1.6	22.8	75	1.1
16	37.2	9.3	1.8	217	21.2	71	1.3	33.5	12.1	1.5	24.1	63	1.0
17	36.4	9.4	1.6	165	20.1	71	1.2	31.8	12.8	1.4	23.4	65	1.1
18	35.8	9.7	1.9	215	20.1	84	1.4	30.4	13	1.7	22.9	72	1.1



WT exit areas are all 0.78 m^2. T, φ, and V are in °C, %, and m/s, respectively. All measured data are for 10 September 2003.

Table 2
Temperature, relative humidity and velocity of the air leaving the wind towers (WT)

Day	Outside air				Wetted columns WT			Conventional WT			Wetted surfaces WT		
	T_0	Φ_0	$\bar{V}_0$	$\bar{\alpha}$	T	φ	V	T	Φ	V	T	φ	V
4	33.2	10	2.5	145	22.8	64	1.7	31.2	10.8	2.1	24.1	43	0.8
5	32.5	9.3	1.4	198	18.5	80	1.4	29.8	11.2	1.2	21.4	68	0.5
6	35.1	7.1	1.8	158	19.2	75	1.4	31.4	8.8	1.6	20.3	71	0.9
7	37.7	5.8	1.6	193	19.2	68	1.2	31.5	9.4	1.3	21.1	73	0.8
8	35.8	9.1	1.8	245	18.3	74	1.1	30.7	12.5	1.4	20.5	71	0.6
9	36.3	10.3	2.1	158	18.8	73	1.7	30.4	13.2	1.7	21.2	68	1.4
10	34.1	10.8	1.7	195	20.4	70	1.5	30.8	13.5	1.5	22.7	65	1.2
11	34.5	11.2	2.1	270	20.1	81	1.8	30.5	15.1	1.9	23.1	72	1.2
12	34.2	10.7	1.8	258	19.2	73	1.4	30.1	14.3	1.6	21.5	68	1.2
13	33.4	12.5	1.8	225	20.4	74	1.5	30.1	15.1	1.7	23.5	70	0.8



WT exit areas are all 0.78 m^2. T, φ, and V are in °C, %, and m/s, respectively. All measured data are taken at 2 p.m. on 4–13 September 2003.

in the tower, and $h_{r,\text{wi-c}}$ is the coefficient of thermal radiation between the exposed wall and another wall, or the adjacent wetted curtain.

Similar thermal networks were considered at various sections of all three wind towers, with surfaces at different temperatures exchanging thermal radiation with one

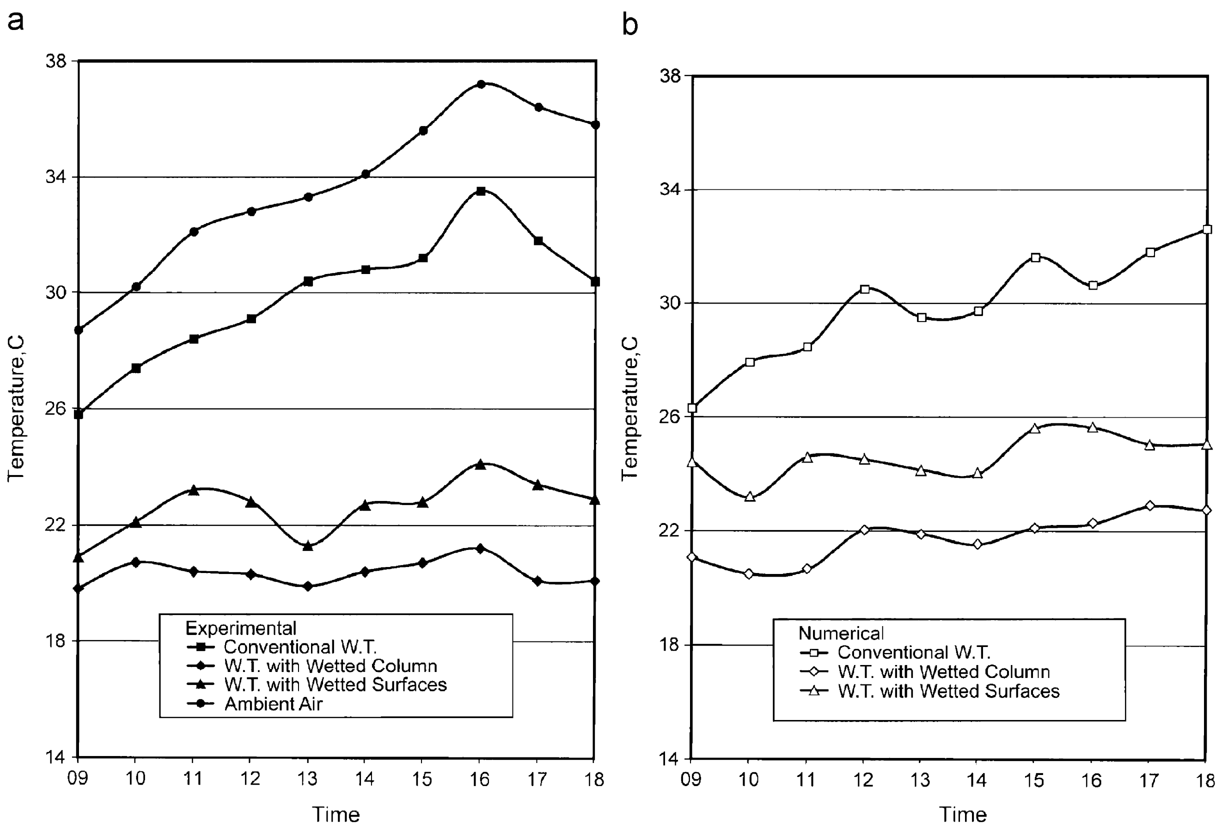


Fig. 5. Temperature of the air leaving the wind towers.

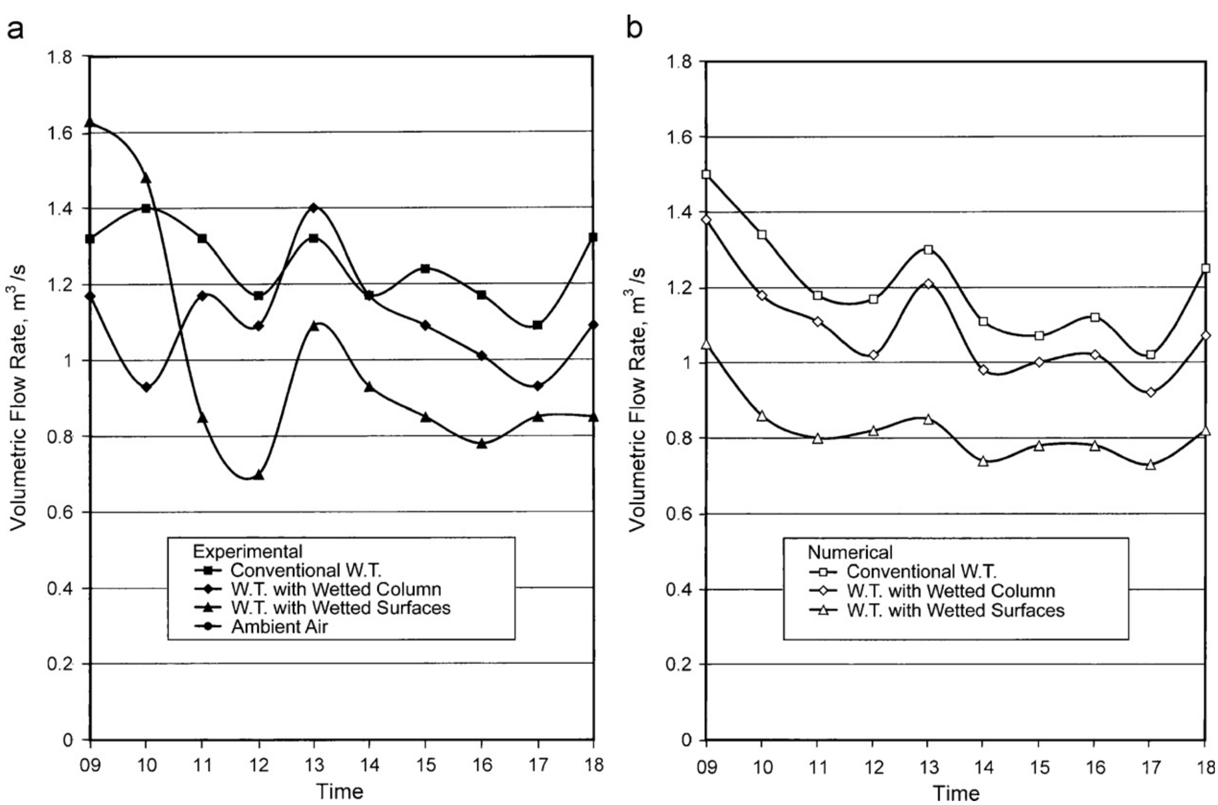


Fig. 6. Volumetric flow rate of the air leaving the wind towers. The area of the window through which the air leaves each wind tower is $0.78\,m^2$.

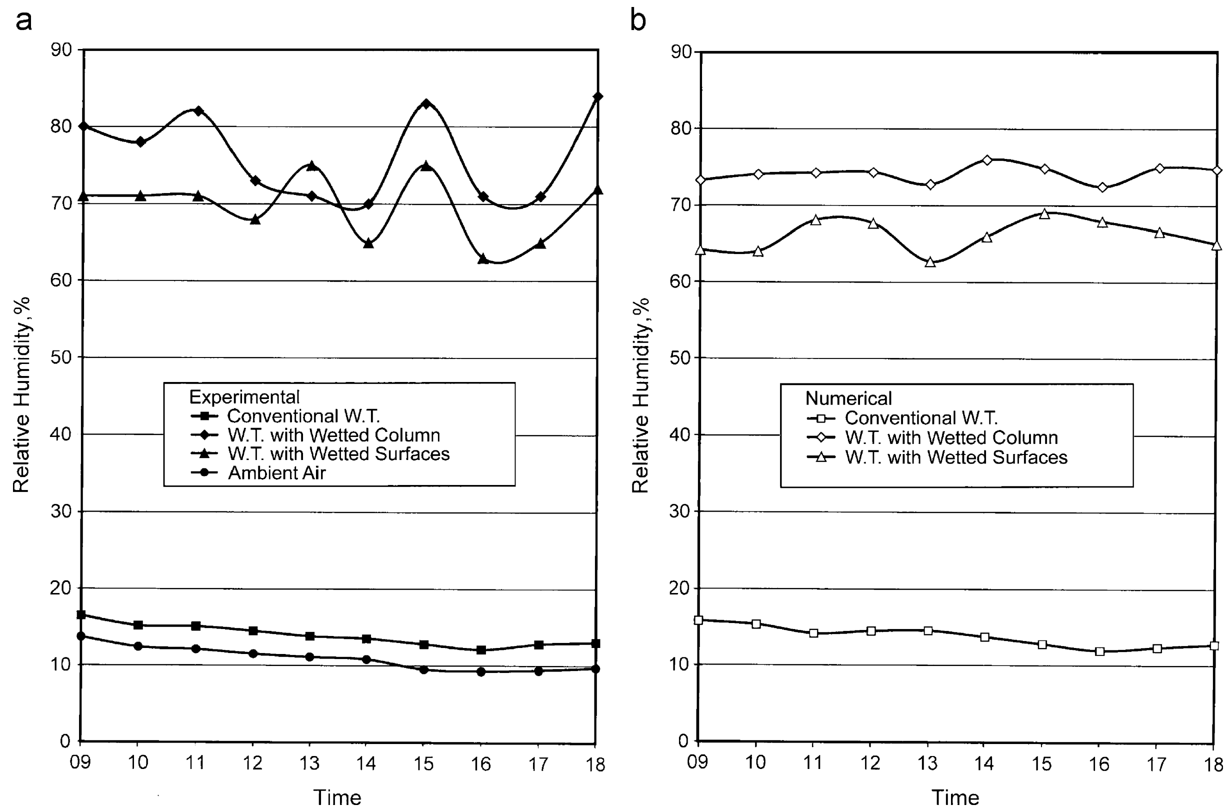


Fig. 7. Relative humidity of the air leaving the wind towers.

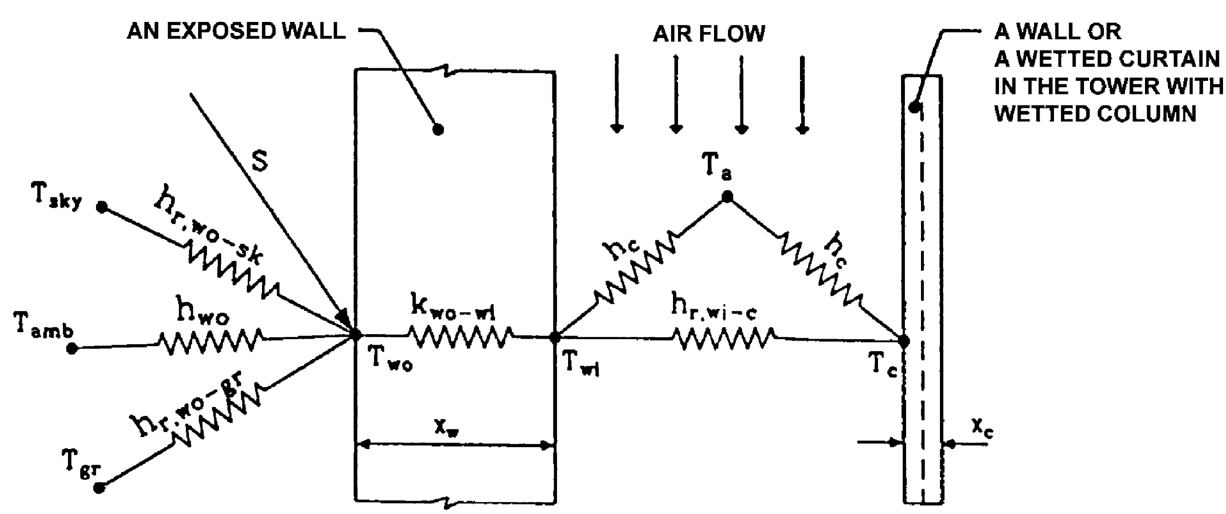


Fig. 8. A portion of the thermal network considered for the numerical analysis of the wind towers.

another. We divided the towers into sections with 1 m height and assumed, for simplicity, that at each section and at any time interval all properties, for example, the temperature and the humidity of the air as well as the temperature of the wetted curtains are constant.

For the thermal network shown in Fig. 8 and for a unit surface area of the wall, we can write the following energy equations [7,8].

For the node designated by wo, with the temperature of T_{wo}:

$$\alpha S + h_{r,wo\text{-}sk}(T_{sky} - T_{wo}) + h_{wo}(T_{amb} - T_{wo}) + h_{r,wo\text{-}gr}(T_{gr} - T_{wo}) + \frac{k_{wo\text{-}wi}(T_{wi} - T_{wo})}{x_w} = \frac{\rho_w c_w x_w (T'_{wo} - T_{wi})}{2t} \quad (1)$$

For the node designated by wi, with the temperature of T_{wi}:

$$h_c(T_a - T_{wi}) + \sum h_{r,wi-c}(T_c - T_{wi}) = \frac{\rho_w c_w x_w (T'_{wi} - T_{wi})}{2t} \quad (2)$$

In these equations, S is the solar radiation intensity on the wind tower exposed wall and α is its absorptivity, t is the time interval, considered in this analysis to be 150 s, and T is the temperature of a node at time $t=0$, and T' I s the temperature at time t. In this equation, ρ_w and c_w are, respectively, the density and the specific heat of the wall. In Eq. (2), $\sum$ designates the thermal radiation exchange between surface wi and all other surfaces that it can "see".

Similar thermal networks were considered at all sections of the wind towers, and energy equations, similar to Eqs. (1) and (2), were written for the nodes representing the surface at each section.

For the flow of air flowing in each wind tower, we used the following general equation:

$$gh_t(\Delta\rho) + \Delta C_p\left(\frac{\rho_0 V_0^2}{2}\right) = \sum \Delta P + \Delta P_e \quad (3)$$

where h_t is the height of the wind tower, $\Delta\rho$ the change of density of the air inside and outside the tower, ΔC_p the change of wind pressure coefficient between the inlet and outlet openings of the wind tower, ρ_0 the density and V_0 the velocity of the wind, ΔP the pressure losses of the air as it flows through various portions of the tower, and ΔP_e is the pressure loss of the air as it flows through the entrance section of the wind tower. For the wind tower with wetted surfaces, ΔP_e includes the pressure losses due to the flow of air through the evaporative cooling pads.

The energy equations written for various sections of each wind tower, along with the equations determining the air flow, were solved simultaneously, employing appropriate relations given for various terms in these equations [7–15]. The measured values of T_0, φ_0 and V_0 were employed as the input data. Figs. 5–7 include the results obtained numerically and experimentally.

It can be seen in these figures that the outside air is cooled appreciably as it passes through either of the new designs of wind towers. Because this is an evaporative cooling process, the relative humidity is increased, as can be seen in Fig. 7. The air going through the conventional wind tower is slightly cooled due to heat transfer to the adjacent wind towers. The amount of air passing through the conventional wind towers is higher than any of the other new designs of the towers, and that is because of very little flow resistance provided as the air is passing through this tower.

Table 1 gives the wind speed and direction on one of the days that the measurements were carried out. During this day, as well as all other days of experimentation, the wind tower with wetted column was almost always in the windward direction. This caused more air to flow through this tower. The evaporative cooling effect of this tower was also better than the wind tower with wetted surfaces, because of its larger evaporative cooling surfaces (in the form of wetted curtains). There was no chance in this experiment to observe the performance of the wind tower with wetted surfaces, when this wind tower was on the windward direction. However, numerical studies show that the wind towers with wetted surfaces perform better than the towers with wetted column when the wind speed is very low [8].

5. Conclusions

Two new designs of wind towers, with evaporative cooling provisions in them, were tested side by side along with a conventional wind tower. All wind towers were of identical dimensions. The experiment was carried out in the city of Yazd, in the central region of Iran, during the month of September. Both new designs performed better than the conventional unit, with the air leaving these towers at a much lower temperature and a higher relative humidity than the ambient air. These towers can easily replace the evaporative coolers currently employed in the hot arid regions of Iran, with a great saving in the electrical energy consumed for the summer cooling of buildings. It is recommended that these new designs of wind towers, particularly the design utilizing evaporative cooling pads at the entrance region of the tower, be manufactured in various sizes and be incorporated in the designs of new buildings in the hot arid regions of Iran, and other countries with similar climate.

Acknowledgement

The authors wish to thank the Iranian National Research Council for financially supporting the research reported in this article.

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