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Experimental investigation of a modular wind tower in hot and dry regions

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ABSTRACT

Passive cooling systems such as wind towers or wind catchers can create thermal comfort for building residents in hot and dry regions. This paper introduces an experimental study of a modular design of wind tower called the modular wind tower with wetted surfaces. Air temperature, relative humidity (RH) and airflow velocity parameters were measured at different times and at points when the velocity of the ambient air was zero. The results show that the modular wind tower can decrease the air temperature by an average of 10 °C and increase the relative humidity of airflow in a building by approximately 36% on average. Additionally, the wind tower can create the airflow velocity entering the building up to around 1.8 m/s. Furthermore, the obtained data from the measurements illustrate that the conditions of indoor air improve to the thermal comfort conditions.

Introduction

Using air conditioning systems to create ventilation and thermal comfort in buildings is an essential need during the warm months in hot and dry regions. People who are living in these regions have employed different passive cooling systems for centuries to provide natural ventilation and cooling, such as wind towers, domed roofs and courtyards. Traditional and conventional wind towers or wind catchers with different forms and structures are still used in Egypt and in some countries of the Middle East. These wind towers, with different cross sections, can be classified into four distinct types: one-sided, two-sided, four-, six-, and eight-sided, and cylindrical shapes.

Traditional and conventional wind towers have several limitations. Some of these restrictions are as follows (Bahadori, 1985; Bahadori and Dehghani-Sanij, 2014; Dehghani-Sanij et al., 2015):

- Small birds, insects, and dust enter through air openings;
- The head of wind towers is fixed and often cannot capture the maximum wind speed;
- Excluding one-sided wind towers, part of the air caught by the wind tower is lost through other openings and never enters the building;
- The value of coolness that can be stored in the mass of a traditional wind tower is commonly restricted, and may not be adequate to meet the cooling needs of the building on hot days during the warm months. In addition, the exposed surface area of the energy storing material may not be sufficient to allow a high rate of heat exchange;
- There is high erosion due to rain, wind and sun;
- In regions with a very low wind speed, the efficiency of wind towers is negligible.

To achieve higher performance and increase thermal comfort in buildings using wind towers, some researchers proposed new designs of wind towers to be used in hot and dry or windy regions (Bahadori, 1977, 1978, 1981, 1985, 1988, 1994; Bahadori and Dehghani-Sanij, 2014; Bahadori and Pakzad, 2002; Bahadori et al., 2008; Elzaidabi, 2008; Erell et al., 2008; Goudarzi et al., 2013; Issa and Chang, 2012; Karakasanis et al., 1984, 1986; M.R.Khani, 2013; Pearlmutter et al., 1996, 2008; Soutullo et al., 2011a, 2011b, 2012). Bahadori (1985) suggested two new designs of wind towers for hot and dry regions called "wind tower with wetted surfaces" and "wind tower with wetted columns". The performance of these wind towers was investigated experimentally, theoretically and numerically by Bahadori (1977, 1978, 1981, 1985, 1988, 1994), Bahadori and Pakzad (2002), Bahadori et al. (2008). The results show that both of these modern wind towers can decrease the temperature of the air entering a building and provide thermal comfort for inhabitants. However, a wind tower with wetted surfaces has a better performance overall than a wind tower with wetted columns in low wind speed regions.

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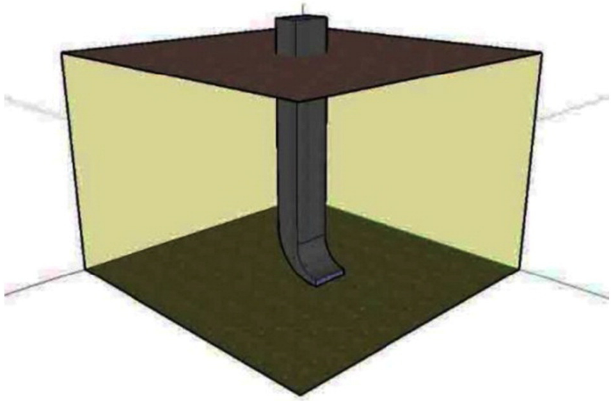

Fig. 1. A schematic of the modular wind tower column.

In another investigation, two modern wind towers for use in windy regions were proposed by Dehghani-Sanij et al. (2015). These new designs of wind towers can catch the highest rate of ambient air velocity because the wind tower head can rotate and set itself in the direction of the maximum wind speed. They showed that using a number of the wind towers and a structure called Kolah-Farangi can naturally ventilate a commercial building without using electrical power, because the Kolah-Farangi increases the rate of air conditioning in the building.

The principal objective of this paper is to introduce a modular wind tower for use in hot and dry regions. One of the significant characteristics of the proposed wind tower is its potential for easy construction in a factory. Air temperature, RH and airflow velocity parameters were studied experimentally at various times and points in order to evaluate the performance of the modular wind tower.

The proposed wind tower design

Although wind towers with wetted surfaces remove some of the limitations of the traditional and conventional wind towers, using this technology in new buildings is not easy. M.R.Khani (2013) suggested a type of wind tower to be used and installed easily in modern buildings. The modular wind tower with wetted surfaces was granted as a patent via the Industrial Property General Office of Iran in Aug. 2014 (M.R.Khani et al., 2014). It should be noted that the modular wind tower is indeed a wind tower with wetted surfaces, but its structure is slightly different. The main advantages for using the modular wind tower in new buildings are (M.R.Khani, 2013):

(1) Nowadays, structures and materials of buildings are varied compared to the past when using wind towers was more common;
(2) The proposed wind tower is a passive cooling system that can be easily built in a factory and assembled in buildings;
(3) Installation of this type of wind tower is simple and easy;
(4) The cost of electricity for air conditioning systems is high in hot

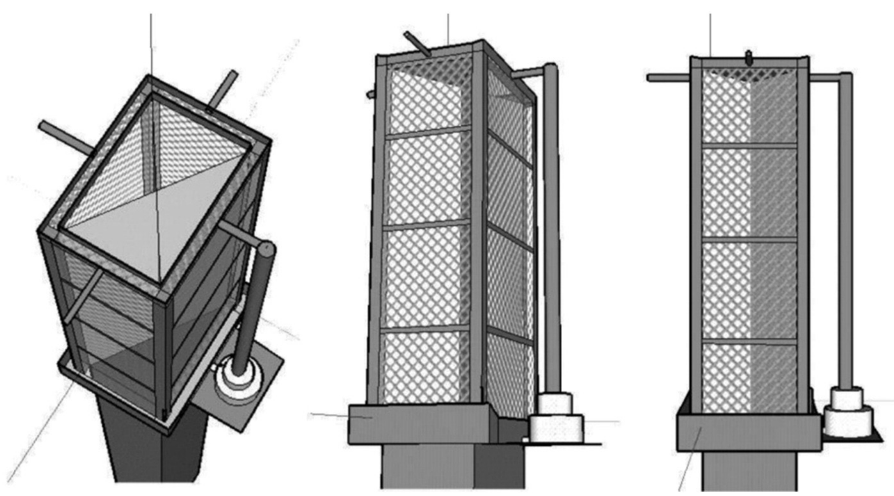

Fig. 2. Schematic representation of the head of the modular wind tower design with wetted surfaces.

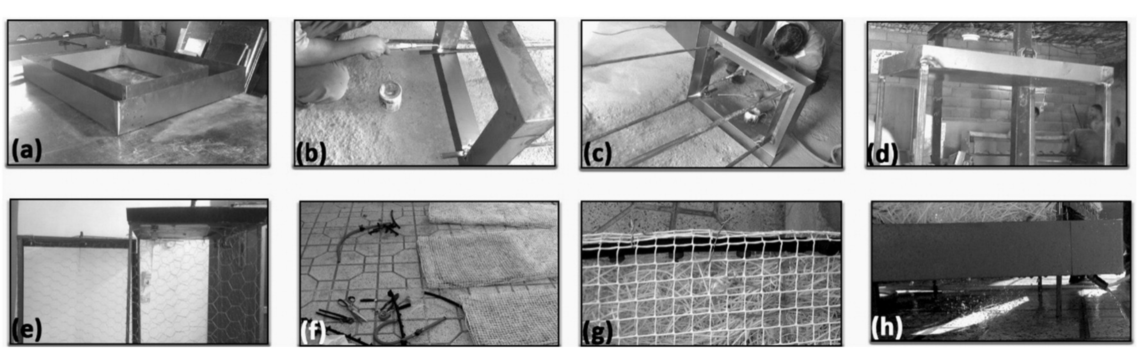

Fig. 3. Construction representation of the head of modular wind tower with wetted surfaces. Note: (a) the bottom of the wind tower head (water collector), (b) legs for connecting wind tower to the column, (c) wind tower's framework, (d) the top of wind tower's head, (e) metal net for hanging straws pads, (f) straw pads and drop irrigation parts, (g) installed drop irrigation pipes in a straw pad, and (h) water collector.

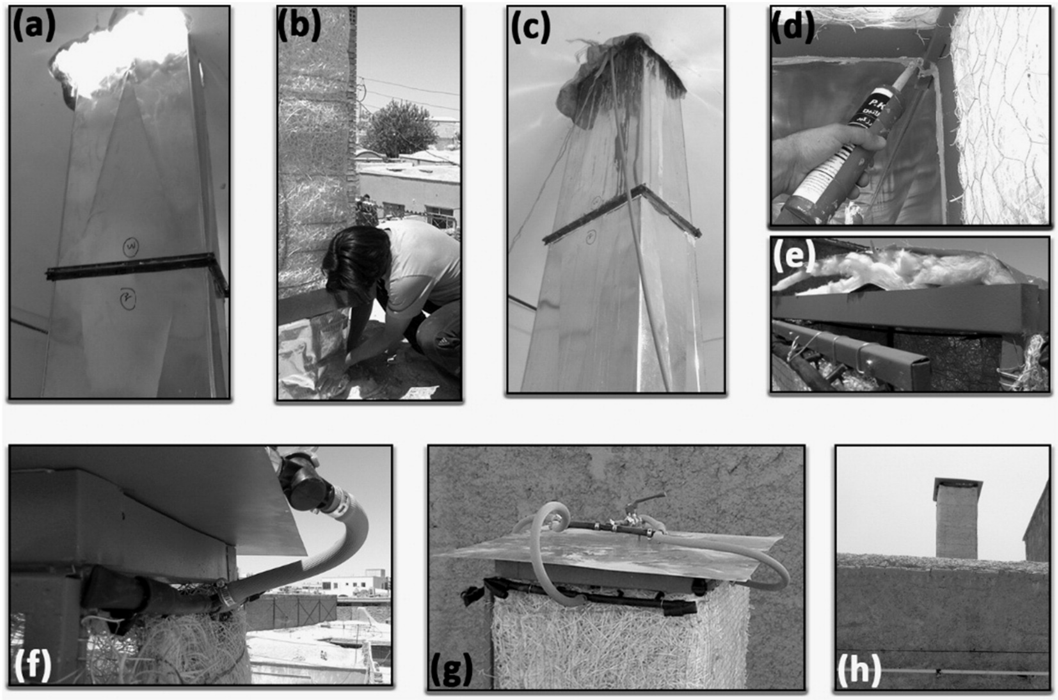

Fig. 4. Assembling, erecting, and insulating the wind tower. Note: (a) the column, (b)–(e) insulating, (f)–(g) water distribution part, and (h) the erected wind tower on the roof.

Fig. 5. A view of the constructed wind tower head with wetted surfaces.

and dry regions. Thus, this wind tower can reduce the cost, and is a good substitute for evaporative coolers.

In order to test and analyze the performance of the proposed wind tower, an actual sized modular wind tower was installed on top of a building in the city of Kerman, Iran. Kerman is located in a hot and dry region, and the temperature variations between day and night are adequate for utilizing a wind tower. Before constructing the modular wind tower, a building was chosen as a laboratory to test the performance of the wind tower. To determine the ability of the proposed wind tower to create thermal comfort conditions, the building was unoccupied to increase the accuracy of experimental measurements. Since installing the wind tower column required making a hole in the building's roof (Fig. 1), minimizing the related costs of installation and changes in the structure of the building were also considered in order

Table 1
The description of the symbols and signs.

Point at which air property was measured	Sign	Description	Measuring instrument	
Ambient (point 1)	T_1	Dry bulb temperature of ambient	LUTRON TM-947	Testo 615
	φ_1	RH of ambient	Testo 615	
	V_1	Air velocity (wind velocity)	Testo 452	
Room where wind tower outlet was located	T_r	Dry bulb temperature of room	LUTRON TM-947	Testo 615
	φ_r	RH of room	Testo 615	
After passing wetted surfaces, in the head of wind tower (point 2)	T_2	Dry bulb temperature at wind tower head	LUTRON TM-947	
Wind tower outlet (point 6)	T_6	Dry bulb temperature at wind tower outlet	LUTRON TM-947	Testo 615
	φ_6	RH of wind tower outlet	Testo 615	
	V_6	Velocity of conditioned air from wind tower to room	Testo 452	

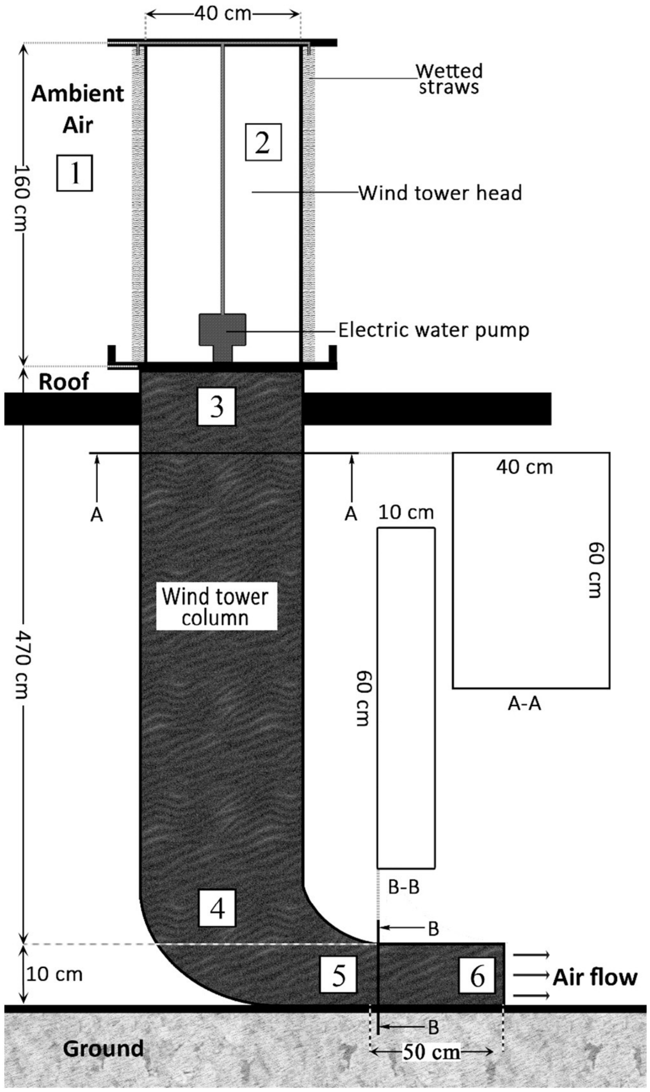

Fig. 6. Schematic of the proposed wind tower with wetted surfaces. Numbers 1 to 6 in squares have been employed as subscripts hereafter.

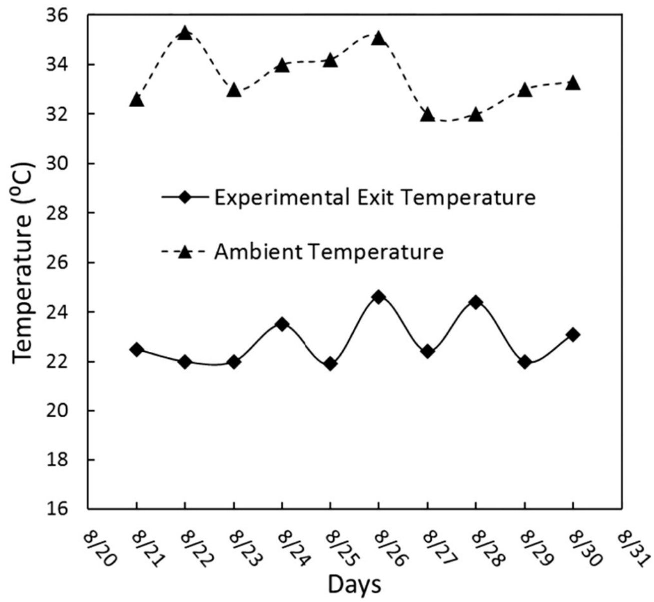

Fig. 8. Dry bulb temperature of ambient air versus ventilated air for test No. 2.

to define the size of the modular wind tower. Fig. 1 shows the schematic sketch of the modular wind tower column; the channel was employed to transfer created fresh airflow from the wind tower into the building. Fig. 2 indicates the schematic design of the head of the proposed wind tower.

Once the desired location was identified, the size of the wind tower and its channel were settled and the wind tower and its column were made using galvanized steel sheets and insulation materials available on the market. The detailed construction of the modular wind tower is illustrated in Fig. 3. As shown in Fig. 3(a), first of all the bottom part of the wind tower head (the water collector) was made. Then, four legs were welded to the collector's corners to build the framework of the wind tower (Fig. 3(b)–(c)). After completing the frame (Fig. 3(d)),

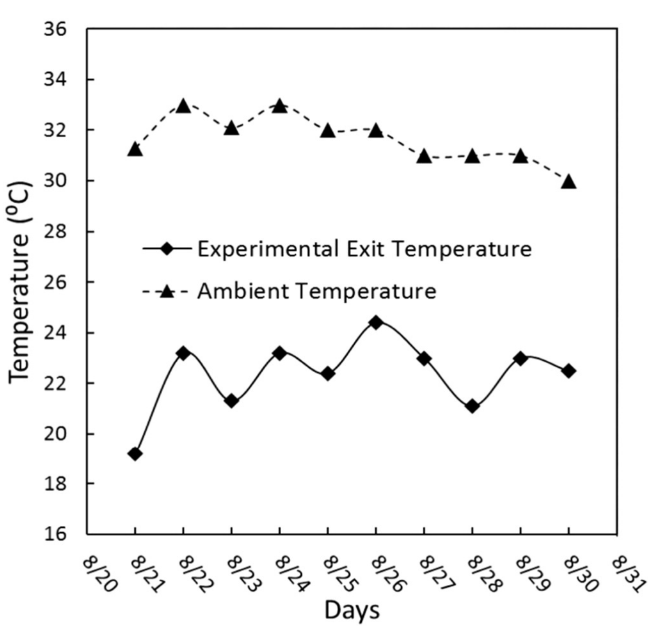

Fig. 7. Dry bulb temperature of ambient air versus ventilated air for test No. 1.

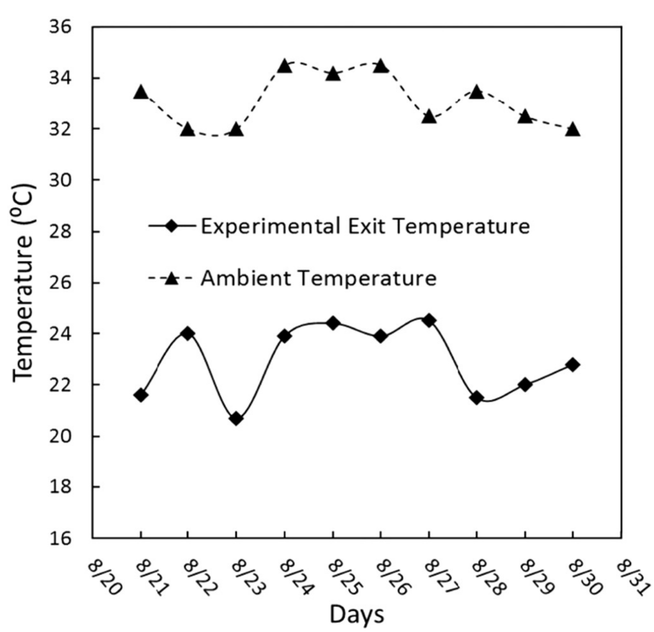

Fig. 9. Dry bulb temperature of ambient air versus ventilated air for test No. 3.

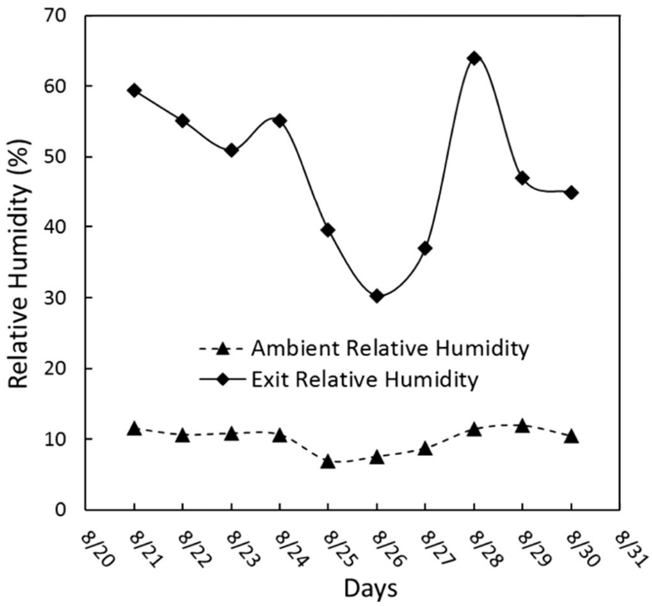

Fig. 10. The amount of RH of the ambient air versus the ventilated air for test No. 1.

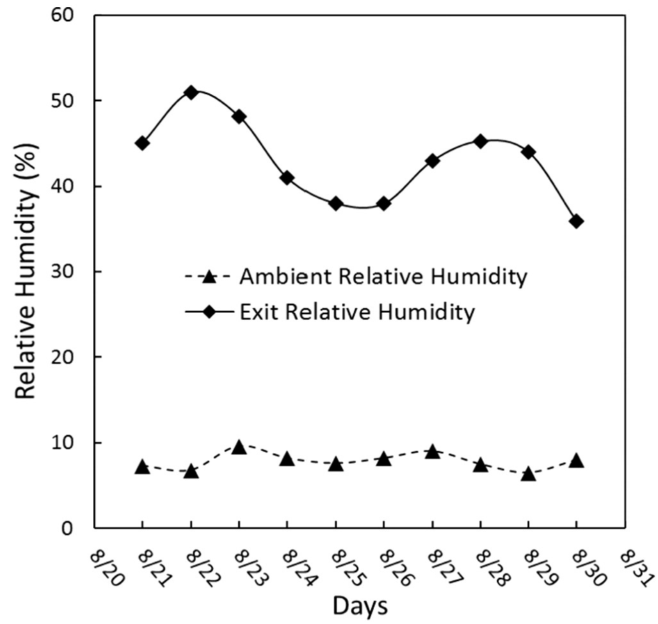

Fig. 12. The amount of RH of the ambient air versus the ventilated air for test No. 3.

a metal net was used to cover it (Fig. 3(e)). Next, four straw packs were prepared in the size of the wind tower's sides and drop irrigation parts were used for keeping the straw wet during the tests (Fig. 3(f)–(g)). Before installation of the wind tower on the roof, its water distribution pipes were tested (Fig. 3(h)). The constructed modular wind tower was carried into the building for installation and testing. On the roof of the building, at the wind tower installation site, a hole was made according to the wind tower column dimensions (40 cm × 60 cm). As illustrated in Fig. 4, the modular wind tower and its column were assembled and insulated to obtain experimental measurements. The constructed wind tower head that was installed on the rooftop of the building is displayed in Fig. 5.

The experimental measurements

To obtain the empirical results, several instruments were employed. Table 1 illustrates the measuring instruments, symbols and signs used in this study. To evaluate the performance of the proposed wind tower, temperature, airflow velocity and RH were measured at different times and points (as specified in Table 1). Note that the performance of the modular wind tower was investigated in the worst conditions, namely, during the hottest days of the year when the wind speed was zero. The measurements were performed for ten consecutive days at around 10 AM (test No. 1), noon (test No. 2), and 4 PM (test No. 3). Fig. 6 shows the cross section of the modular wind tower with details. The experimental results are presented in the following section.

Experimental results and discussion

Figs. 7–9 show the variations of different temperatures for ten consecutive days for tests No. 1, 2 and 3, respectively. According to the

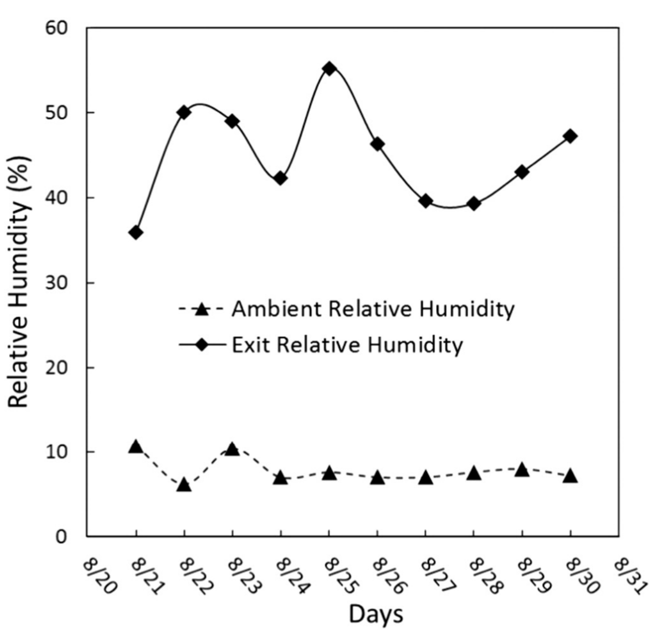

Fig. 11. The amount of RH of the ambient air versus the ventilated air for test No. 2.

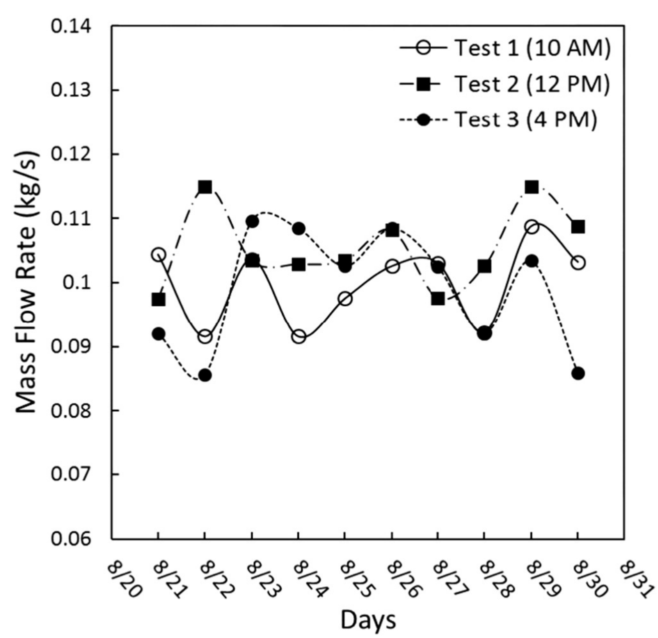

Fig. 13. The conditioned air mass flow rate from wind tower outlet to room.

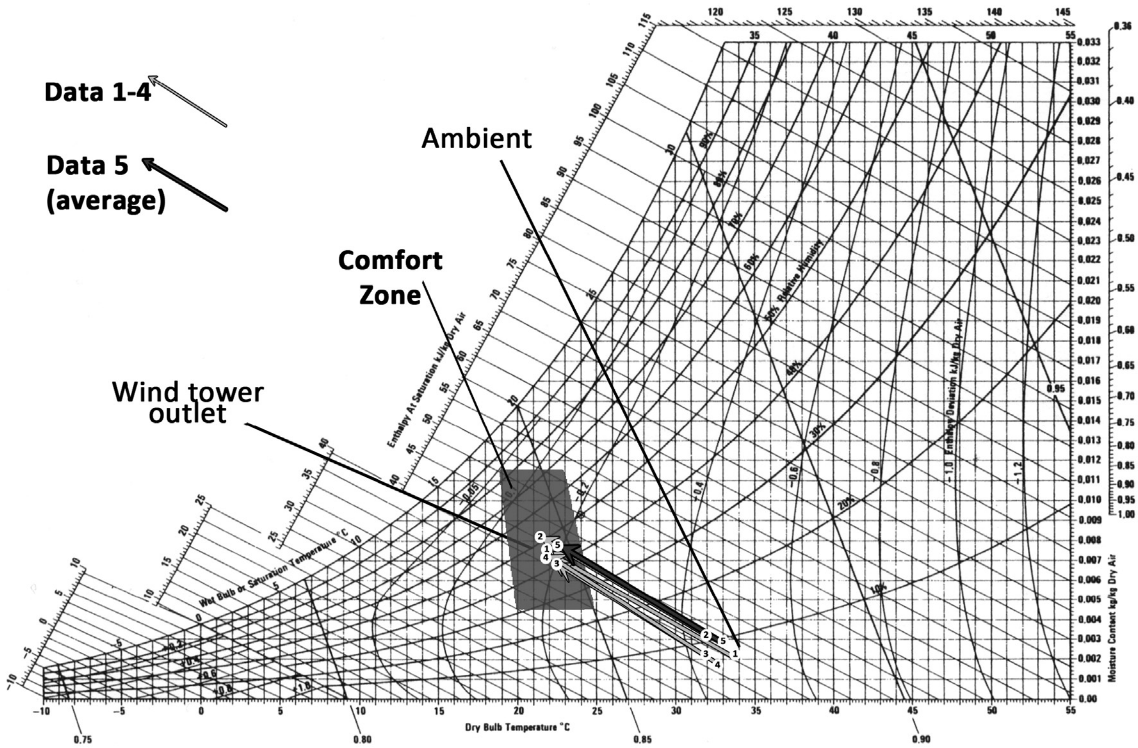

Fig. 14. Variations of airflow conditions through the modular wind tower between ambient air and the room in which wind tower is located.

data collected, the highest and lowest reduction in the dry bulb temperature of air using the modular wind tower with wetted surfaces were:

$$\text{Maximum decrease in air temperature} = \Delta T_{max} = 13.3\ ^{\circ}\mathrm{C}$$

$$\text{Minimum decrease in air temperature} = \Delta T_{min} = 7.5\ ^{\circ}\mathrm{C}$$

With regards to the data, this modern design of wind tower can reduce the dry bulb temperature of air by an average of 10 °C. Additionally, the decrease in dry bulb temperature leads to achieving thermal comfort in the building. Figs. 10–12 demonstrate the variations of ambient and exit RH of air for ten consecutive days for tests No. 1, 2 and 3, respectively.

According to the measurements, the highest and lowest increases in the amount of RH of air using the modular wind tower were equal to:

$$\text{Maximum increase in relative humidity} = \Delta\varphi_{max} = 52.5\%$$

$$\text{Minimum increase in relative humidity} = \Delta\varphi_{min} = 22.7\%$$

As a result, this modern design of wind tower can, on average, increase the RH of air by around 37%. Due to Kerman's warm dry climate (World Weather Information Services website), the amount of increase in RH can play a significant role in achieving thermal comfort in a building.

Fig. 13 displays the variations of mass flow rate entering the building when the velocity of ambient air was zero. According to the data

Table 2
Conditions of ventilated air versus ambient air.

		Dry bulb temperature (°C)	Decrease in temperature (°C)	RH (%)	Increase in RH (%)	Dew point temperature (°C)
Datum 1: 21 Aug. 4 PM	Ambient	33.5	11.9	7.3	37.8	−5.7
	Entering the room	21.6		45.1		9.2
Datum 2: 23 Aug. 10 AM	Ambient	32.1		10.9		−2
	Entering the room	21.3	10.8	51	40.1	10.8
Datum 3: 27 Aug. noon	Ambient	32		7		−3.4
	Entering the room	22.4	9.6	39.6	32.6	8
Datum 4: 29 Aug. 4 PM	Ambient	32.5		6.5		−7.7
	Entering the room	22	10.5	44	37.5	9.2
Datum 5: (Average)	Ambient	32.7	10	8.6	36.7	−4.2
	Entering the room	22.7		45.3		10.3

Table 3
Changes in the airflow velocity and pressure around the wind tower and at the wind tower's entrance to the room.

		Airflow velocity (m/s)	Increase in velocity (m/s)	Atmospheric pressure (kPa)	Density (kg/m^3)	Pressure change (Pa)
Datum 1: 21 Aug. 4 PM	Ambient	0	1.6	78.6	0.922	2.03
	Entering the room	1.6			0.959	
Datum 2: 23 Aug. 10 AM	Ambient	0	1.8	78.6	0.926	1.85
	Entering the room	1.8			0.960	
Datum 3: 27 Aug. noon	Ambient	0	1.7	78.6	0.926	1.64
	Entering the room	1.7			0.956	
Datum 4: 29 Aug. 4 PM	Ambient	0	1.8	78.6	0.925	1.79
	Entering the room	1.8			0.958	
Datum 5: (Average)	Ambient	0	1.77	78.6	0.924	1.71
	Entering the room	1.77			0.955	

collected, the highest and lowest amount of mass flow rate entering the room from the wind tower outlet were:

$$\text{Maximum mass flow rate} = \dot{m}_{max} = 0.1149 \text{ kg/s}$$

$$\text{Minimum mass flow rate} = \dot{m}_{min} = 0.0856 \text{ kg/s}$$

With regard to the obtained results, the average velocity of air entering the building from the wind tower was 1.77 m/s. Therefore, the mass flow rate of ventilated air exiting the wind tower when the wind speed was zero was, on average, 0.1015 kg/s.

Fig. 14 indicates the average values of data collected and the variations of airflow conditions on a psychometric chart. Additionally, the conditions of the ambient air and ventilated air are shown in Table 2. Note that the points of beginning (ambient) and ending (the room in which the wind tower is located) on the chart (Fig. 14) are the average values measured during the tests; thus, the variations of the airflow conditions on the chart show the average performance of the wind tower.

Table 3 illustrates the variations of airflow velocity and pressure around the wind tower and at the wind tower's entrance to the room. As can be seen in this table, whereas the ambient air velocity equals zero and the pressure around the wind tower is equal to atmospheric pressure, the airflow velocity and pressure at the wind tower's entrance to the room are changed because of buoyancy. In other words, the wetted surfaces in the wind tower head increase the RH of the air around these surfaces. Thus, the density difference between ambient air and the air inside the wind tower head, according to the equation $\Delta\rho gh$, creates a downward flow in the column. As a general result, the performance of the proposed wind tower will increase when the wind velocity is not zero.

Conclusions

The modular wind tower with wetted surfaces can provide natural air conditioning in buildings that are located in hot and dry regions. The empirical results illustrated that the wind tower can increase relative humidity and also decrease the temperature of indoor air by an average of 36% and 10 °C, respectively. In addition, this wind tower can create the airflow velocity entering the room up to approximately 1.8 m/s when the ambient air velocity is equal to zero. Additionally, as illustrated in the psychometric chart, by using this new design of wind tower, the room's air conditions fell in the comfort zone. According to the obtained experimental results, the modular wind tower could be a practical and satisfactory alternative for natural cooling of buildings in hot and dry regions.

In order to use the proposed wind tower in modern buildings, it is necessary that the cooling load of the building be determined. By considering the cooling needs of a building and its physical conditions, the size of the wind tower should be determined, before the order for building the tower is given. The most considerable advantage of this type of wind tower is that it can be built in an industrial workshop, and then transported and installed in the desired location.

To develop the modular wind tower, more research is required. Future research must consider: (1) simulation and computational fluid dynamic (CFD) modeling to evaluate the performance of the proposed wind tower in different conditions, and (2) development of a code to provide software in order to calculate the optimized cross section and height of a modular wind tower for utilization in different buildings.

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