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Performance Evaluation of a Modular Design of Wind Tower with Wetted Surfaces

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Abstract: Wind towers or wind catchers, as passive cooling systems, can provide natural ventilation in buildings located in hot, arid regions. These natural cooling systems can provide thermal comfort for the building inhabitants throughout the warm months. In this paper, a modular design of a wind tower is introduced. The design, called a modular wind tower with wetted surfaces, was investigated experimentally and analytically. To determine the performance of the wind tower, air temperature, relative humidity (RH) and air velocity were measured at different points. Measurements were carried out when the wind speed was zero. The experimental results were compared with the analytical ones. The results illustrated that the modular wind tower can decrease the air temperature significantly and increase the relative humidity of airflow into the building. The average differences for air temperature and air relative humidity between ambient air and air exiting from the wind tower were approximately 10 °C and 40%, respectively. The main advantage of the proposed wind tower is that it is a modular design that can reduce the cost of wind tower construction.

Keywords: wind tower; passive cooling systems; experimental measurements; analytical method

1. Introduction

For centuries, people living in the Middle East have used various passive cooling systems to provide pleasant cool air [1–5] and cold drinkable water [6–15] during the hot summer months. One of these systems is the wind tower, or wind catcher, which creates passive ventilation and provides thermal comfort for the building inhabitants. Traditional wind towers are still employed in some countries of the Middle East, such as Iran, Egypt, Pakistan, Afghanistan and the UAE. Figures 1–3 show traditional wind towers in the city of Yazd in Iran, Cairo in Egypt and Heydar Abad in Pakistan, respectively. These wind towers naturally ventilate buildings.

More than forty percent of all of the energy in the world is used in buildings, and air conditioning, heating and cooling systems employ over sixty percent of all energy used in buildings [16–18]. Thus, passive cooling systems, such as wind towers or wind catchers, can help reduce the energy needed for air conditioning in buildings, especially at peak times. It should be noted that traditional wind towers have some restrictions. Several researchers proposed new designs of wind towers to use in windy and hot, dry zones to improve the performance of conventional wind towers [19,20].

Figure 1. Two four-sided wind towers in Yazd, Iran [3].

Figure 2. A traditional wind tower in Cairo, Egypt [21].

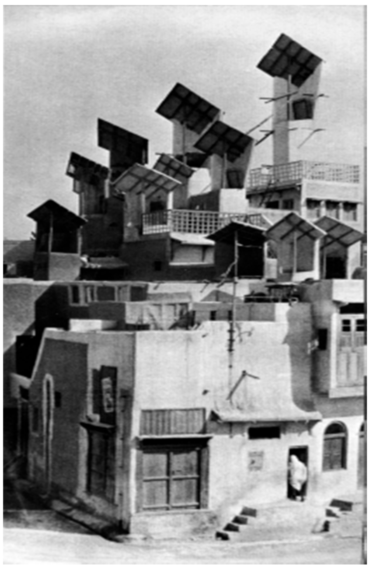

Figure 3. View of wind towers or wind scoops in Heydar Abad, Pakistan [22].

As mentioned, one of the most effective ways to reduce energy consumption in air cooling is to use natural ventilation. This issue was first considered by Bahadori [1,2] and led to the scientific evaluation of wind towers as a viable alternative for passive cooling in hot, arid areas. Bahadori et al. [1,2,23–36] investigated and optimized the performance of wind towers, using analytical, numerical and experimental methods. To improve the performance of wind towers, Bahadori introduced two new models of wind towers, named "wind tower with wetted surfaces" and "wind tower with wetted columns" [3,19]. The improvements made in the structure of these new designs of wind towers have enhanced performance compared to that of the conventional ones [3,19]. Numerical, analytical and experimental studies that were carried out on these two new models of wind towers illustrate provide a better performance than that of the traditional ones [3,19]. The experimental studies also show that in areas with low wind speed, "wind towers with wetted surfaces" work better than "wind towers with wetted columns" [3,29].

- *Wind tower with wetted columns*: This type of wind tower has thick curtains or clay conduits, which are installed in the wind tower column [3,19,28,29]. Water is sprayed on the curtains or clay conduits and wets them. Then, the water, which is collected in a pool at the bottom of the wind tower, is recirculated by pumping it up. Therefore, warm and dry air that passes from the wind tower column is evaporatively cooled, and finally, the air that is both high in moisture and low in temperature enters the room from the wind tower outlet [3,19,28,29]. Figure 4 shows a wind tower with wetted columns. The flow density increases along the channel; the air density inside is higher than that of the outside. Accordingly, the downward airflow is enhanced due to buoyancy [3,19,28].
- *Wind tower with wetted surfaces*: In this type of wind tower, pads or straw are placed at the top of the wind tower column (wind tower head). They are wetted by means of an electric water pump (Figure 5) [3,36]. The water in wetted pads or straw is evaporated by the air at the wind tower head (the highest part of the wind tower column where air inlets are located) and decreases the air temperature (similar to the evaporative cooling process in evaporative coolers) [3,28,36]. Since the contact surface between the air and wetted straw is extremely large, the moisture in the air will increase. The difference of density between ambient air and the air inside the head of the wind tower, as well as the height of the wind tower column, produce a pressure dissimilarity, causing a downward airflow inside the column. The difference of density at the topmost point of the column (wind tower head) and the ambient air increases the buoyancy effect [3,28,36]. Therefore, it is expected that in places where the wind speed is low, or the ambient air is still, this type of wind tower will be more effective.

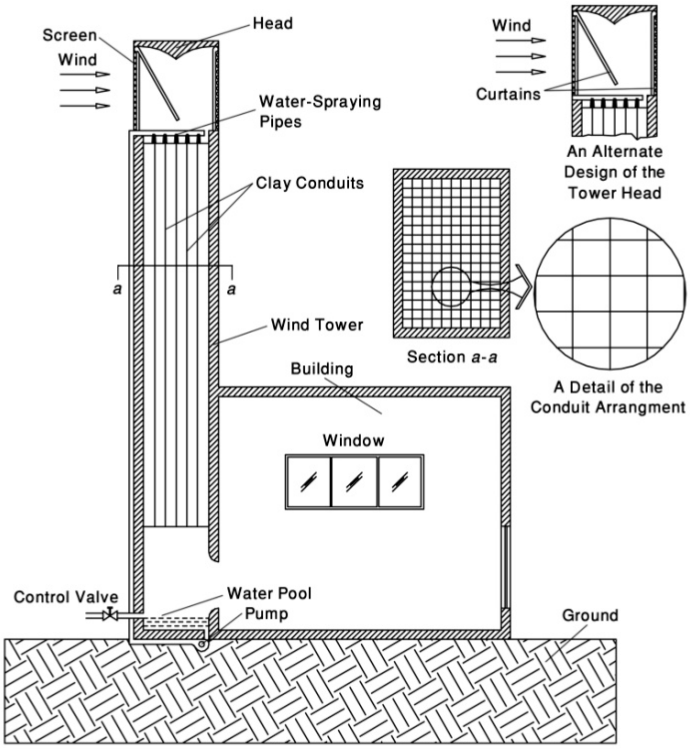

Figure 4. Cross-sectional view of a wind tower with wetted columns [19].

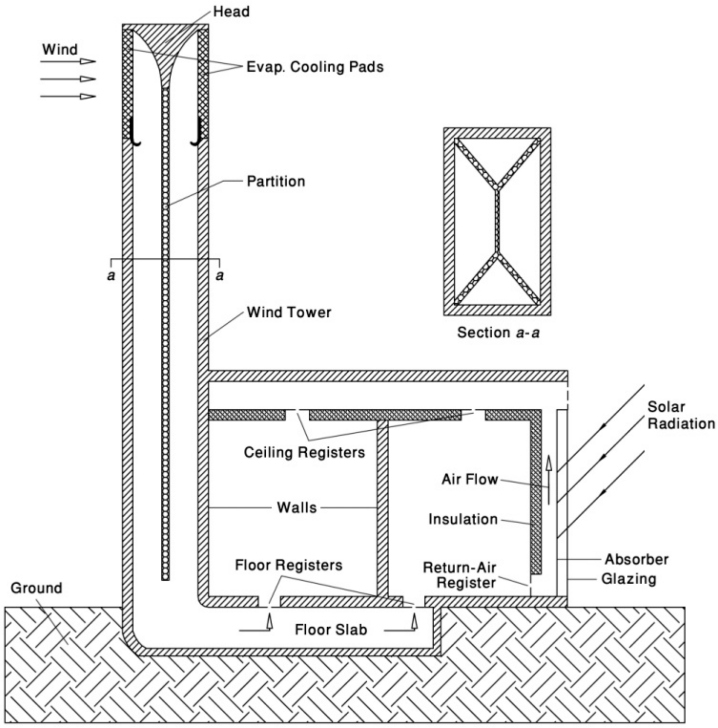

Figure 5. Cross-sectional view of a wind tower with wetted surfaces combined with a solar chimney [26].

Dehghani-Sanij et al. [20] introduced two new designs of wind towers to be applied in windy zones. The modern wind towers include a movable head, a fixed column and two windows at the lower end of the column to adjust the airstream. The movable head can be located manually or electrically in the direction of the wind. Moreover, the wind tower head can be placed into an empty internal space of the column when the airstream does not need to enter the building. Further, they suggest that to improve the performance of the proposed wind towers, a solar chimney or another wind tower in a different direction can be combined with them. It should be noted that wind towers are not only considered for indoor ventilation in hot and arid climates. As Aliabadi et al. [37] suggested, wind and turbulence also can be directed/enhanced by passive architectural elements down to street canyons for urban climate control.

The major goal of the present research was to introduce a modular design of the wind tower with wetted surfaces that can create low energy air conditioning in buildings and bring thermal comfort to the inhabitants. The significance of this new design of wind tower is the possibility of industrial manufacture. Moreover, simple assembly and installation with minor changes in a building's structure can be considered as another positive aspect of the design. The height and cross-section of the modularly-produced wind tower are determined by the building's cooling needs. In order to obtain the performance of the proposed wind tower, air temperature, relative humidity (RH) and air velocity parameters were investigated at different points. In addition, the experimental results were compared with the analytical ones.

2. The Proposed Wind Tower Design

Despite the fact that wind towers with wetted surfaces overcome many shortcomings of the conventional ones, installing them in modern buildings creates some problems. This issue paved the way in designing and constructing a certain type of wind tower with wetted surfaces, which could be installed and used in modern houses. A modular design of the wind tower was built with galvanized steel sheets, installed and tested in Kerman, located in a hot, arid zone in the southeast of Iran. The detailed head of the proposed wind tower is shown in Figure 6. Figure 7 demonstrates the final manufactured wind tower head located on the rooftop of a building. It should be noted that this modular wind tower was also granted a patent by Industrial Property General Office of Iran in August 2014 [38].

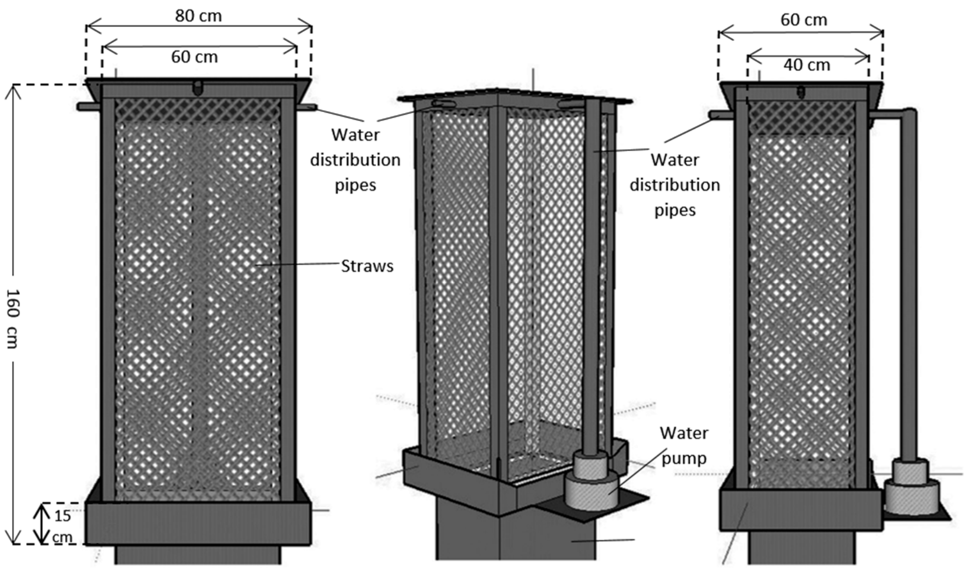

Figure 6. Schematic illustration of the head of the modular wind tower design with wetted surfaces.

Figure 7. View of the manufactured wind tower head with wetted surfaces.

The difference between this type of wind tower and a wind tower with wetted surfaces is the materials used in its construction, such as galvanized steel sheets and heat insulation (glass wool), instead of bricks. The main reasons for making this type of wind tower are as follows [36,39]:

1. Building materials have changed nowadays, and above all, finding a professional who can build a conventional wind tower is very difficult.
2. To revive wind towers as an ancient system of natural cooling, it was necessary to present a product that could be built easily in a factory. On the other hand, the transportation and installation should be as easy as the evaporative coolers used extensively in Iran.
3. To install wind towers in existing buildings, there needs to be minor changes in the structure of the buildings. Additional costs and major changes should be avoided or minimized.

4. People who live in hot, arid zones pay high costs for air conditioning and cooling. Consequently, this type of wind tower could be an acceptable alternative for natural ventilation and cooling of buildings in these zones.

In the following section, explanations about the methods of testing, measuring instruments and, finally, the experimental results obtained at different time intervals are provided.

3. The Experimental Arrangement

The modular wind tower was installed on the roof of a building located in Kerman. The main reason for choosing Kerman was that it is located in a hot, arid zone, and the potential of evaporative cooling in this city is sufficient. Hence, people of Kerman have used wind towers for centuries. The building where the wind tower was installed and tested was located in a place that was not surrounded by any tall buildings; therefore, evaluating the wind tower's performance when winds were strong or weak was also possible. In order to create conditions with the least errors, the building was also unoccupied.

3.1. Measuring Instruments

Instruments used in this research were in Table 1:

Table 1. Instruments used to measure the velocity, relative humidity and temperature of air.

Measuring Instrument	Used to Measure	Accuracy
Testo 452 with high accuracy velocity probe	Velocity of air	$\pm 0.7\ \mathrm{m{\cdot}s^{-1}}$
Testo 615	Relative humidity of air Temperature of air	±3% ±0.7 °C
LUTRON TM-947 SD 4 Channels Thermometer data logger	Temperature of air	$\pm[(4\times10^{-4})T + 0.5)]$ °C

3.2. Experimental Measurements

To obtain experimental results, five tests were carried out, and data were recorded every day from sunrise to 9:00 p.m. (about one and a half hour after sunset). Every 45 min, all of the following parameters were measured. Moreover, data were taken for one day (24 h) every 45 min to one hour. The measured parameters were as follows:

(1) Dry bulb temperature, RH and wind velocity of the ambient air (Point 1 in Figure 8) and of the conditioned air at the outlet of the wind tower (Point 6 in Figure 8);
(2) Dry bulb temperature at the head of the wind tower (Point 2 in Figure 8);
(3) Dry bulb temperature and RH in the room where the wind tower outlet was installed;
(4) Dry bulb temperature and RH in another sample room beside the wind tower room.

The hottest days of the year in Kerman were selected for testing. The data recording was made when the wind speed was zero. Note that zero means that ambient air velocity is lower than 0.01 m/s. The wind speed was measured on the building roof, with no surrounding tall buildings at a height of 6 m. The following information is presented in the form of comparative tables and charts. The tests' information is as follows:

Test No. 1: Data recording at 10:00 a.m. for ten continuous days, from 21 to 30 August 2013,
Test No. 2: Data recording at 12:00 p.m. for ten continuous days, from 21 to 30 August 2013,
Test No. 3: Data recording at 4:00 p.m. for ten continuous days, from 21 to 30 August 2013,
Test No. 4: A one-day data recording on 24 August 2013, from 6:30 a.m. to 9:00 p.m., and
Test No. 5: A 24-h data recording from 5:15 p.m. on 22 August 2013.

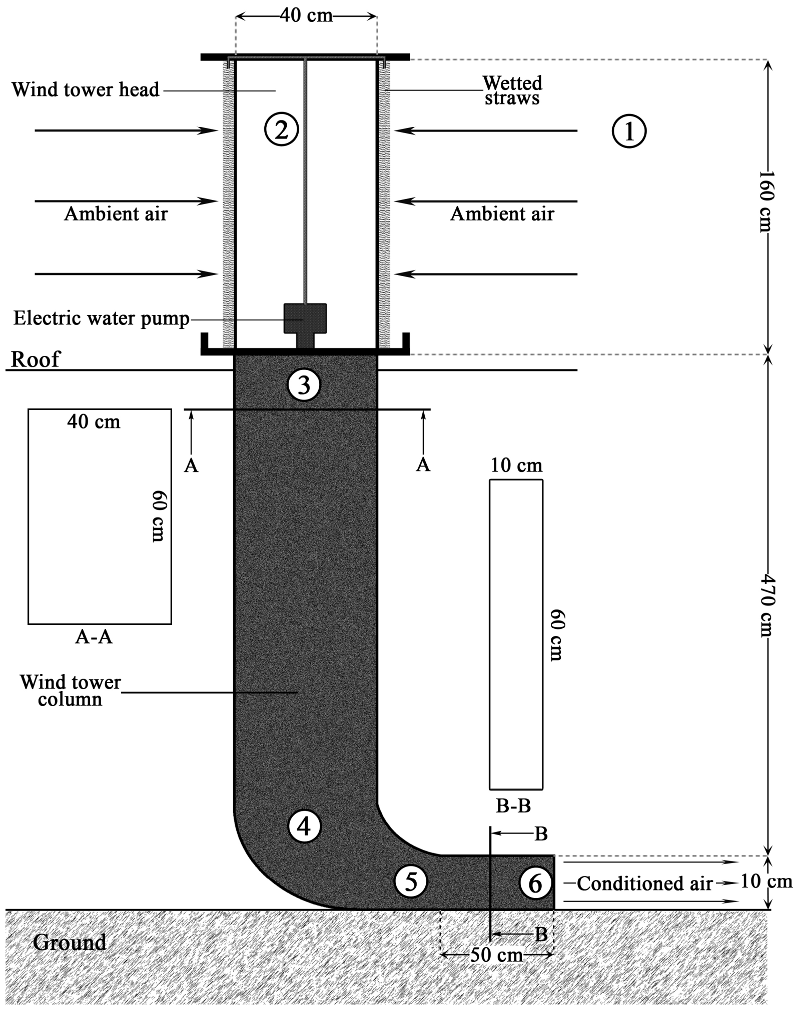

Figure 8. Cross-sectional view of the modular wind tower with wetted surfaces. Numbers in circles (1 to 6) have been used as subscripts hereinafter.

Table 2 shows the symbols and signs used in the following tables and charts. In the following charts, the units for temperature, air speed and mass flow rate are in degrees centigrade (degrees Celsius), meters per second (m·s^{-1}) and kilograms per second (kg·s^{-1}), respectively.

Table 2. The description of the symbols and signs.

Location	Sign	Description	Measuring Instrument
Ambient	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 wetted surfaces (in the head of wind tower)	T_2	Dry bulb temperature at wind tower head	LUTRON TM-947
Wind tower outlet	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

4. Analytical and Experimental Results

4.1. Analytical Results

To compare and validate the experimental measurements, an analytical method is applied to the modular wind tower with wetted surfaces. The analytical method used is provided by [3]. To determine the air velocity distribution in the wind tower, first the pressure head must be calculated. According to Figure 8, to compute the pressure head, the following equation can be employed:

$$P_{atm} - \Delta P_{1-2} + P_B - \Delta P_{3-4} - \Delta P_{4-5} - \Delta P_{5-6} - \Delta P_{out} = P_{atm} \tag{1}$$

Furthermore, Equation (1) can be written as follows:

$$P_B = \Delta P_{1-2} + \Delta P_{3-4} + \Delta P_{4-5} + \Delta P_{5-6} + \Delta P_{out} = \sum \Delta P \tag{2}$$

In the equations above, P_{atm} is the atmospheric pressure; ΔP_{1-2} is the pressure drop in straw; P_B is the driving potential; ΔP_{3-4} is the frictional pressure drop in the vertical column; ΔP_{4-5} is the dynamic pressure drop in the elbow; ΔP_{5-6} is the frictional pressure drop in the horizontal section; ΔP_{out} is the outlet pressure drop; and $\sum \Delta P$ is the total pressure drop. By assuming air as an ideal gas to calculate density (ρ), each part of Equation (2) can be expressed as follows:

Continuity equation:

$$\rho_6 A_6 V_6 = \rho_2 A_2 V_2 = \rho_3 A_3 V_3 \Rightarrow \begin{cases} V_6 = 4.00 V_3 \\ V_2 = 0.075 V_3 \end{cases} \tag{3}$$

Driving potential:

$$P_B = \Delta\rho g h_t + \Delta C_p \left(\frac{1}{2} \rho_0 {V_0}^2 \right) \xrightarrow{no\ wind} P_B = \Delta\rho g h_t = K_0 \text{ (Pa)} \tag{4}$$

$$\Delta P_{1-2} = 1.029\ V_2\ {d_p}^{0.755} \xrightarrow{Eq.\ (3)} \Delta P_{1-2} = K_1 \times V_3 \text{ (Pa)} \tag{5}$$

Pressure drops:

$$\Delta P_{3-4} = f \frac{l_{3-4}}{d_{e_{3-4}}} \rho_3 \frac{{V_3}^2}{2} \Rightarrow \Delta P_{3-4} = K_2 \times {V_3}^2 \text{ (Pa)} \tag{6}$$

$$\Delta P_{4-5} = \frac{1}{2} C_{4-5} \rho_3 {V_3}^2 \Rightarrow \Delta P_{4-5} = K_3 \times {V_3}^2 \text{ (Pa)} \tag{7}$$

$$\Delta P_{5-6} = f \frac{l_{5-6}}{d_{e_{5-6}}} \rho_6 \frac{{V_6}^2}{2} \xrightarrow{Eq.\ (3)} \Delta P_{5-6} = K_4 \times {V_3}^2 \text{ (Pa)} \tag{8}$$

$$\Delta P_{out} = \frac{1}{2} C_{out}\ \rho_6\ {V_6}^2 \xrightarrow{Eq.\ (3)} \Delta P_{out} = K_5 \times {V_3}^2 \text{ (Pa)} \tag{9}$$

In the equations above, ρ is the ambient air density (kg·m^{-3}); ρ_3 is the air density in the vertical channel (kg·m^{-3}); ρ_6 is the air density in the horizontal channel (kg·m^{-3}); A is the cross-sectional area (m^2); V is the velocity of air passing through straw (m·s^{-1}); V_0 is the wind velocity (m·s^{-1}); V_3 is the air velocity in the vertical channel (m·s^{-1}); and V_6 is the air velocity in the horizontal channel (m·s^{-1}). Additionally, h_t is the wind tower height (m); l_{3-4} is the length of the vertical part of the channel (m); g is the gravity (m·s^{-2}); $d_{e_{3-4}}$ is the equivalent diameter of the vertical channel (m); d_p is the straw's thickness (cm); l_{5-6} is the length of the horizontal column (m); f is the coefficient of friction; $d_{e_{5-6}}$ is the equivalent diameter of the horizontal channel (m); C_{4-5} is the coefficient of pressure drop in the elbow; C_{out} is the coefficient of the pressure drop at the exit; and K_0 to K_5 are constants.

By substituting Equations (4) to (9) in Equation (2), the following quadratic equation can be obtained.

$$(K_1)\ V_3 + (K_2 + K_3 + K_4 + K_5)\ {V_3}^2 = K_0 \tag{10}$$

As illustrated in Equation (10), the only remaining unknown parameter is V_3. By solving Equation (10) and using Equation (3), the conditioned air exit velocity at the outlet of the wind tower channel (V_6) was obtained by the analytical method. This method was applied in order to find $V_{6\text{-}Analytical}$ for all recorded data.

To find the exit temperature from the wind tower ($T_{6\text{-}Analytical}$) using the analytical method, the rate of heat transfer from the airflow passing throughout the wind tower must be calculated. First, a value for T_6 is assumed. Then, the amount of heat transfer is calculated from the internal airflow in the wind tower column using two different approaches, which will be explained in the following section. Finally, the values obtained from these approaches will be compared. The process is an iterative method, repeated for as long as the difference between the heat transfer value reaches less than the reasonable error. These approaches are expressed in the following equations:

$$\dot{Q}_{2-6} = \begin{cases} \dot{m}c_p(T_6 - T_2) = \rho_3 A_3 V_3 c_p (T_6 - T_2) & \text{(11a)} \\ \frac{1}{R_{tot}}\Delta T = \frac{(T_r - T_i)}{R_{tot}} & \text{(11b)} \end{cases}$$

where $\dot{m}$ is the mass flow rate (kg·s^{-1}), ΔT is the temperature difference between conditioned air inside the channel and room, c_p is the specific heat capacity (J·kg^{-1}·K^{-1}), $\dot{R}_{tot}$ is the thermal resistance (K·W^{-1}), T_2 is the dry bulb temperature at the wind tower head, A_3 is the vertical channel cross-section (m^2), T_r is the dry bulb temperature of the room, T_6 is the dry bulb temperature at the wind tower exit and T_i is the dry bulb temperature of the conditioned airflow inside the wind tower.

To compute the amount of heat transfer from Equation (11a), the parameter of c_p can be obtained by [3,40]:

$$c_p = 1.05 - 0.365\theta + 0.85\theta^2 - 0.39\theta^3 \tag{12}$$

where:

$$\theta = \frac{(T_3 + 273.15)}{1000} \tag{13}$$

It should be noted that by assuming $T_3 = \frac{T_6 + T_2}{2}$, all parameters in Equation (11a) are known, except for T_6. Therefore, c_p only depends on T_6.

In order to determine the value of the heat transfer from Equation (11b), the following equation can be used.

$$\dot{Q}_{2-6} = \frac{(T_r - T_i)}{R_{tot}} = \frac{(T_r - T_3)}{R_{hi_v} + R_{cond.v} + R_{ho_v}} + \frac{(T_r - T_5)}{R_{hi_h} + R_{cond.h} + R_{ho_h}} \tag{14}$$

where T_3 is the dry bulb temperature of conditioned airflow in the vertical channel, T_5 is the dry bulb temperature of conditioned airflow in the horizontal channel, $\dot{R}_{hi_v}$ is the thermal resistance related to natural convection heat transfer inside the vertical channel (K·W^{-1}), $\dot{R}_{cond.v}$ is the thermal resistance against conduction heat transfer in the wall of the vertical channel (K·W^{-1}), $\dot{R}_{ho_v}$ is the thermal resistance due to natural convection heat transfer outside the vertical channel (K/W), $\dot{R}_{hi_h}$ is the thermal resistance related to natural convective heat transfer inside the horizontal channel (K·W^{-1}), $\dot{R}_{cond.h}$ is the thermal resistance against conductive heat transfer through the wall of horizontal channel (K·W^{-1}) and $\dot{R}_{ho_h}$ is the thermal resistance due to natural convective heat transfer outside the horizontal channel (K·W^{-1}). Figure 9 shows the thermal resistances model for heat transfer of the cool air between the inside of the channel and the room. Since a downward flow in the channel is only caused by buoyancy force, there is natural convection inside the channel. The conditioned airflow inside the channel is also turbulent, because the airflow Reynolds number is more than 10^4. Outside the channel there is no fan or other devices for creating a forced flow; therefore, free convective heat transfer occurs outside the wind tower column, as well.

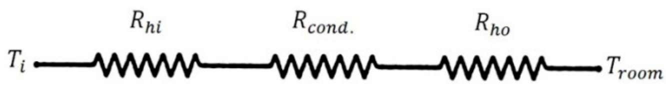

Figure 9. The thermal resistances between the cool air inside the channels and the room.

To obtain thermal resistances, the following equations can be employed [41].

$$\begin{cases} R_{cond._v} = \frac{t}{K \times A_{s_v}} = 1.1 \times 10^{-6} \approx 0 & \text{(15a)} \\ R_{cond._h} = \frac{t}{K \times A_{s_h}} = 1.4 \times 10^{-5} \approx 0 & \text{(15b)} \end{cases}$$

$$\begin{cases} R_{hi_v} = \frac{1}{h_{i_v} \times A_{s_v}} = \frac{1}{9h_{i_v}} & \text{(16a)} \\ R_{hi_h} = \frac{1}{h_{i_h} \times A_{s_h}} = \frac{1}{0.4h_{i_h}} & \text{(16b)} \end{cases}$$

$$\begin{cases} R_{ho_v} = \frac{1}{h_{o_v} \times A_{s_v}} = \frac{1}{9h_{o_v}} & \text{(17a)} \\ R_{ho_h} = \frac{1}{h_{o_h} \times A_{s_h}} = \frac{1}{0.4h_{o_h}} & \text{(17b)} \end{cases}$$

where t is the thickness of the galvanized sheets (m), A_{s_v} is the lateral surface of the vertical channel (=9 m^2), K is the thermal conductivity of the galvanized sheets ($W \cdot m^{-1} \cdot K^{-1}$), A_{s_h} is the lateral surface of the horizontal channel (=0.4 m^2), h_{i_v} is the convective heat transfer coefficient inside the vertical channel ($W \cdot m^{-2} \cdot K^{-1}$), h_{i_h} is the convective heat transfer coefficient inside the horizontal channel ($W \cdot m^{-2} \cdot K^{-1}$), h_{o_v} is the convective heat transfer coefficient just outside the vertical channel ($W \cdot m^{-2} \cdot K^{-1}$) and h_{o_h} is the convective heat transfer coefficient just outside the horizontal channel ($W \cdot m^{-2} \cdot K^{-1}$). In addition, to calculate the parameters of h_{i_v}, h_{i_h}, h_{o_v} and h_{o_h}, the following equations are employed.

$$\begin{cases} h_{i_v} = 2.39 - \left(3.16 \times 10^{-4}\right) T_3 & \text{(18a)} \\ h_{i_h} = 8.90 - \left(1.18 \times 10^{-3}\right) T_5 & \text{(18b)} \end{cases}$$

$$\begin{cases} h_{o_v} = (1.31)(T_r - T_3)^{0.33} & \text{(19a)} \\ h_{o_h} = (0.702)(T_r - T_5)^{0.25} & \text{(19b)} \end{cases}$$

By assuming $T_3 = \frac{T_6 + T_2}{2}$ and $T_5 = \frac{T_6 + T_3}{2}$, substituting Equations (18) and (19) into Equations (16) and (17), respectively, and replacing Equations (15)–(17) in Equation (14), Equation (11b) is only a function of T_6.

As mentioned above, by initial approximation of T_6, Equation (11a, b) are solved and the obtained values estimated by these approaches for $\dot{Q}_{2-6}$ are compared. If the difference between these values is more than the reasonable error (10^{-4}), by using the iteration method, the value of T_6 as $T_{6\text{-}Analytical}$ is obtained.

4.2. Experimental Results

4.2.1. Test Nos. 1, 2 and 3

Data for these tests were collected before noon (10:00 a.m.), at noon (12:00 p.m.) and in the afternoon (4:00 p.m.) for ten continuous days from 21 to 30 of August 2013. Table 3 illustrates recorded data for test Nos. 1, 2 and 3. Figure 10 shows the amount of reduction in dry bulb temperature of the air, and Figure 11 shows the rise in RH of the air using the wind tower. Furthermore, Figure 12 shows the amount of mass flow rate of ventilated air entering the room from the wind tower.

Table 3. Test Nos. 1, 2 and 3, recorded data before noon, at noon and in the afternoon for 10 continuous days.

Date	Time	T_1 (°C)	ϕ_1 (%)	V_1 (m·s^{-1})	T_r (°C)	ϕ_r (%)	T_2 (°C)	T_6 (°C)	ϕ_6 (%)	V_6 (m·s^{-1})
21 August	10:00	31.3	11.60	0	25.0	36.70	18.5	19.2	59.40	1.8
	12:00	32.6	10.80	0	25.5	29.00	21.1	22.5	35.90	1.7
	16:00	33.5	7.30	0	24.7	23.00	21.0	21.6	45.10	1.6
22 August	9:45	33.0	10.70	0	26.0	30.60	22.2	23.2	55.10	1.6
	12:15	35.3	6.20	0	26.0	26.10	21.0	22.0	50.00	2.0
	16:00	32.0	6.80	0	27.0	20.50	23.0	24.0	51.00	1.5
23 August	10:15	32.1	10.90	0	25.4	34.00	20.0	21.3	51.00	1.8
	12:15	33.0	10.40	0	26.0	32.00	21.0	22.0	49.00	1.8
	16:15	32.0	9.60	0	25.9	35.00	20.0	20.7	48.20	1.9
24 August	9:45	33.0	10.70	0	26.0	30.60	22.2	23.2	55.10	1.6
	11:45	34.0	7.00	0	26.4	26.90	22.8	23.5	42.30	1.8
	16:10	34.5	8.20	0	26.5	25.50	23.2	23.9	41.00	1.9
25 August	10:15	32.0	7.00	0	27.0	24.70	22.0	22.4	39.60	1.7
	12:15	34.2	7.60	0	26.8	27.90	20.8	21.9	55.20	1.8
	16:15	34.2	7.60	0	26.3	22.60	23.3	24.4	38.00	1.8
26 August	10:00	32.0	7.60	0	26.3	22.60	23.3	24.4	30.30	1.8
	12:20	35.1	7.00	0	25.0	35.30	23.5	24.6	46.30	1.9
	15:55	34.5	8.20	0	26.5	25.50	23.2	23.9	38.00	1.9
27 August	9:50	31.0	8.80	0	27.5	19.00	21.6	23.0	37.00	1.8
	12:00	32.0	7.00	0	27.0	24.70	22.0	22.4	39.60	1.7
	16:10	32.5	9.00	0	27.5	19.00	23.5	24.5	43.00	1.8
28 August	10:00	31.0	11.50	0	23.5	42.00	20.0	21.1	64.00	1.6
	12:10	32.0	7.60	0	26.3	22.60	23.3	24.4	39.30	1.8
	16:00	33.5	7.50	0	24.9	23.50	21.2	21.5	45.30	1.6
29 August	10:15	31.0	12.00	0	26.0	29.50	22.4	23.0	47.00	1.9
	12:10	32.0	7.60	0	26.3	22.60	23.3	24.4	39.30	1.8
	16:00	32.5	6.50	0	26.5	25.70	20.7	22.0	44.00	1.8
30 August	9:50	30.0	10.50	0	26.5	25.50	21.7	22.5	45.00	1.8
	12:00	33.3	7.20	0	26.5	25.60	22.1	23.1	47.20	1.9
	16:10	32.0	8.00	0	26.1	26.90	21.9	22.8	35.90	1.5

Note: T_r and ϕ_r are, respectively, the air temperature and RH of air in the room in which the outlet of the wind tower was placed.

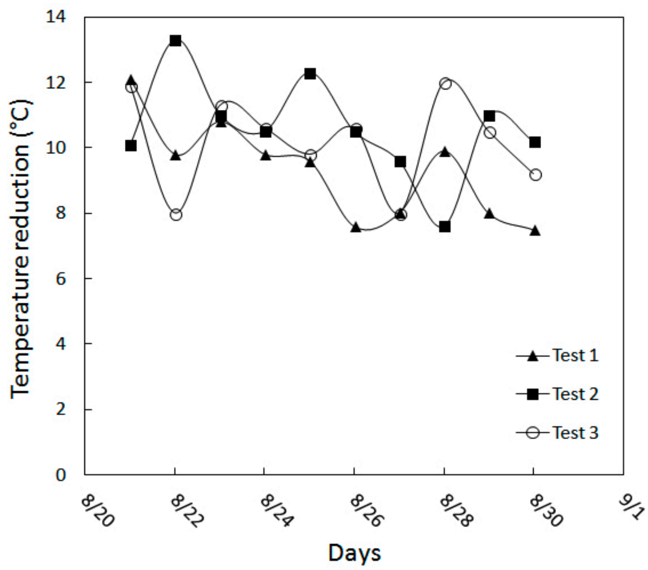

Figure 10. The amount of reduction in temperature for test Nos. 1, 2 and 3 (21 to 30 August 2013, 10:00 a.m., 12:00 p.m. and 4:00 p.m.).

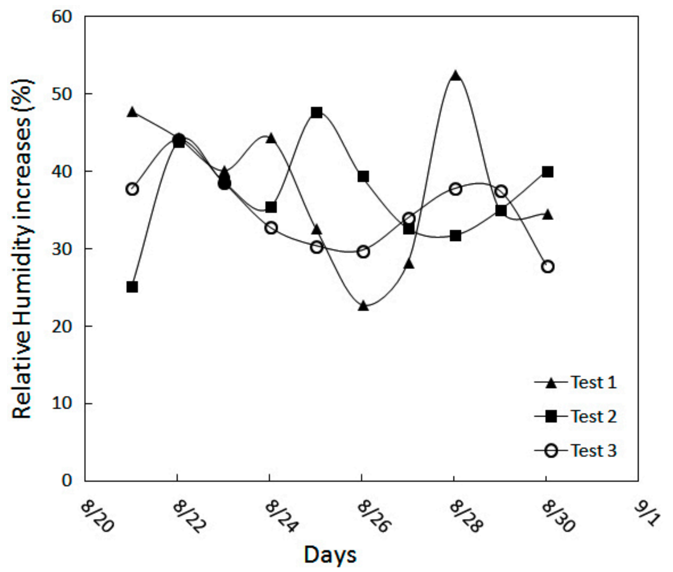

Figure 11. The amount of increase in RH for test Nos. 1, 2, and 3 (21 to 30 August 2013, 10:00 a.m., 12:00 p.m. and 4:00 p.m.).

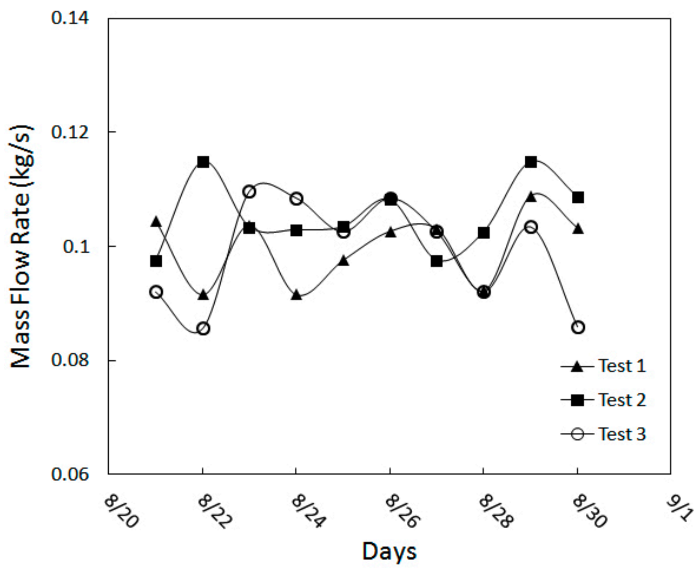

Figure 12. The mass flow rate entering the room from wind tower outlet for test Nos. 1, 2 and 3 (21 to 30 August 2013, 10:00 a.m., 12:00 p.m. and 4:00 p.m.).

4.2.2. Test No. 4

This test was for one day, 24 August 2013, from 6:30 a.m. to 9:00 p.m. Table 4 includes the recorded data for test No. 4. Figure 13 shows the air temperature at the wind tower outlet and of the ambient air. Figure 14 shows the amount of RH of the air at the wind tower outlet and the ambient air temperature. Furthermore, Figure 15 shows the mass flow rate of ventilated air entering the room from the wind tower.

Table 4. Recorded data for test No. 4, from 6:30 a.m. to 9:00 p.m., 24 August 2013.

Time	T_1 (°C)	ϕ_1 (%)	V_1 (m·s^{-1})	T_r (°C)	ϕ_r (%)	T_2 (°C)	T_6 (°C)	ϕ_6 (%)	V_6 (m·s^{-1})
6:30	20.0	18.00	0	25.0	29.00	15.8	16.2	68.00	1.2
7:15	22.0	19.00	0	23.0	42.00	18.5	19.0	62.00	1.1
7:45	22.5	18.10	0	24.5	38.60	18.4	19.2	66.00	1.0
8:15	25.8	13.00	0	25.0	38.00	19.0	19.5	65.00	1.0
8:55	31.0	11.50	0	23.5	42.00	20.0	21.1	64.00	1.6
9:45	33.0	10.70	0	26.0	30.60	22.2	23.2	55.10	1.6
11:00	33.5	10.00	0	26.1	33.00	23.0	24.4	53.00	1.7
11:45	34.0	7.00	0	26.4	26.90	22.8	23.5	42.30	1.8
12:45	34.2	7.60	0	26.8	27.90	20.8	21.9	55.20	1.8
13:45	35.1	7.00	0	25.0	35.30	23.5	24.6	46.30	1.9
14:00	38.0	7.50	0	25.0	27.00	23.3	24.4	43.00	1.9
14:45	36.0	7.40	0	26.5	24.00	23.5	24.4	46.00	1.8
16:10	34.5	8.20	0	26.5	25.50	23.2	23.9	41.00	1.9
17:25	32.5	9.00	0	27.5	19.00	23.5	24.5	44.00	1.8
18:15	31.0	10.00	0	26.0	29.50	22.4	23.0	47.00	1.9
18:45	30.0	10.50	0	26.5	25.50	21.7	22.5	45.00	1.8
19:30	29.5	11.00	0	25.3	37.00	19.8	20.1	52.00	1.6
20:15	28.5	11.80	0	26.5	24.00	18.5	19.3	49.00	1.3
21:00	28.3	11.90	0	25.1	25.30	18.7	19.2	49.00	1.5

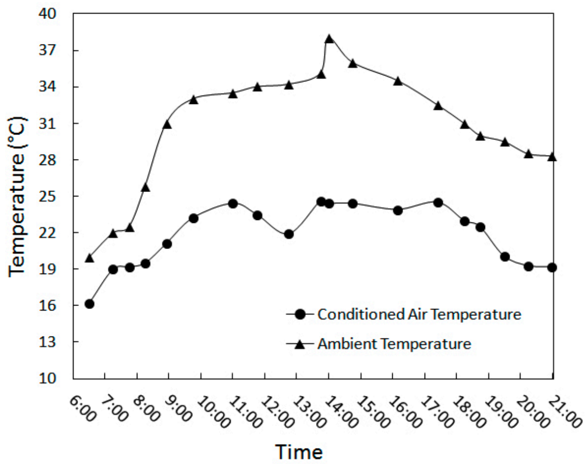

Figure 13. The air temperature at wind tower outlet and ambient air for test No. 4 (from 6:30 a.m. to 9:00 p.m., 24 August 2013).

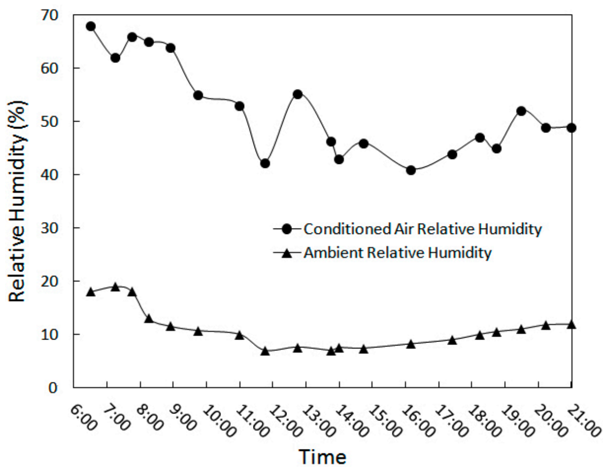

Figure 14. The amount of RH of air at the wind tower outlet and the ambient air for test No. 4 (from 6:30 a.m. to 9:00 p.m., 24 August 2013).

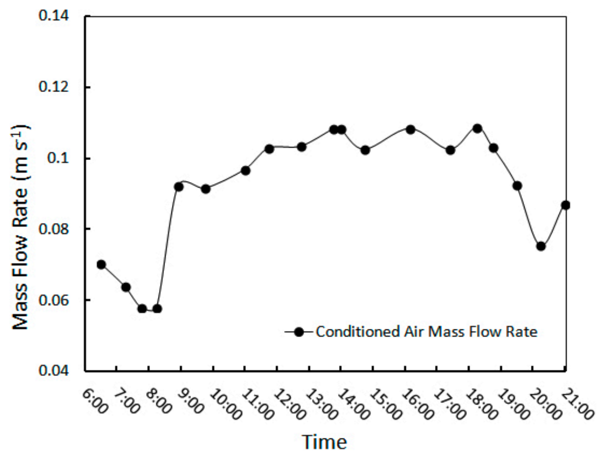

Figure 15. The conditioned air mass flow rate from the wind tower outlet to room for test No. 4 (from 6:30 a.m. to 9:00 p.m., 24 August 2013).

4.2.3. Test No. 5

This test is for a 24-h data recording, from 5:15 p.m. on the 22nd to 5:15 p.m. on the 23rd of August 2013. Table 5 illustrates recorded data for test No. 5. Figure 16 shows the air temperature at the wind tower outlet and the ambient air. Figure 17 demonstrates the amount of RH of air at the wind tower outlet and the ambient air. Figure 18 shows the amount of mass flow rate of the conditioned air entering the room from the wind tower.

Table 5. Recorded data for test No. 5, from 5:15 p.m., the 22nd, to 5:15 p.m., the 23rd of August 2013.

Date	Time	T_1 (°C)	ϕ_1 (%)	V_1 (m·s^{-1})	T_r (°C)	ϕ_r (%)	T_2 (°C)	T_6 (°C)	ϕ_6 (%)	V_6 (m·s^{-1})
22 August	17:15	32.0	7.00	0	27.0	24.70	22.0	22.4	39.60	1.7
22 August	18:15	32.0	7.60	0	26.3	22.60	23.1	24.0	30.30	1.7
22 August	19:15	31.0	8.80	0	27.5	19.00	21.6	23.0	44.00	1.8
22 August	20:15	29.5	8.00	0	26.5	24.00	21.5	22.5	46.00	1.7
22 August	21:15	29.4	8.90	0	25.3	28.90	21.5	23.0	43.00	1.9
22 August	22:15	25.5	10.50	0	24.5	30.70	15.5	17.5	46.00	1.8
22 August	23:15	24.8	13.00	0	22.0	31.50	15.0	16.0	58.00	1.8
23 August	0:15	24.0	14.00	0	23.9	33.00	16.0	16.5	67.00	1.4
23 August	1:15	21.0	14.40	0	22.0	38.00	13.0	14.0	65.00	1.5
23 August	2:15	20.0	14.60	0	22.5	34.00	13.0	13.5	54.00	1.3
23 August	3:15	19.0	15.00	0	22.5	24.00	12.2	13.0	55.00	1.8
23 August	4:15	17.5	17.00	0	22.0	32.00	12.0	13.0	55.00	1.7
23 August	5:15	17.3	17.00	0	22.5	33.00	11.5	12.2	60.00	1.8
23 August	6:15	18.0	19.50	0	22.8	38.00	11.0	12.5	68.00	1.6
23 August	7:15	20.1	19.60	0	23.0	35.00	12.2	13.0	61.00	1.7
23 August	8:15	24.2	14.00	0	25.0	37.00	16.0	17.2	64.00	1.6
23 August	9:15	31.3	11.60	0	25.0	36.70	18.5	19.2	59.40	1.8
23 August	10:15	32.1	10.90	0	25.4	34.00	20.0	21.3	51.00	1.8
23 August	11:15	32.6	10.80	0	25.5	29.00	20.1	22.5	49.00	1.7
23 August	12:15	33.0	10.40	0	26.0	32.00	21.0	22.0	49.00	1.8
23 August	13:15	35.0	9.70	0	25.8	33.00	21.5	22.1	49.00	1.8
23 August	14:15	34.6	10.00	0	25.8	33.00	21.6	22.0	51.00	1.8
23 August	15:15	33.0	10.40	0	26.0	32.00	21.0	22.0	49.00	1.8
23 August	16:15	31.5	9.60	0	25.9	35.00	20.0	20.2	48.20	1.9
23 August	17:15	30.4	9.60	0	25.8	30.40	20.0	21.4	43.50	1.6

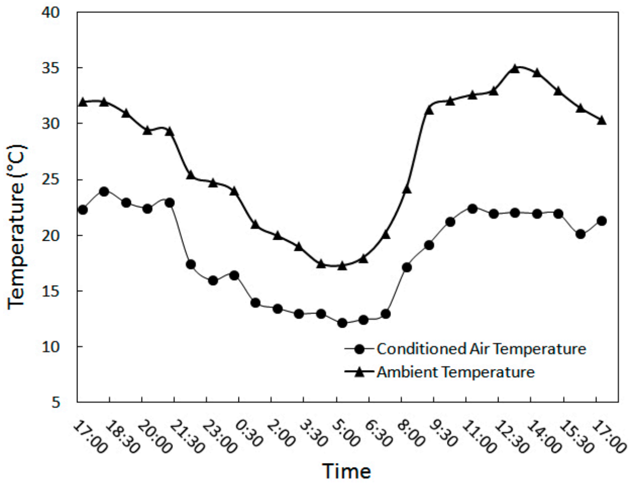

Figure 16. The air temperature at wind tower outlet and the ambient air for test No. 5 (from 5:15 p.m. on the 22nd to 5:15 p.m. on the 23rd of August 2013).

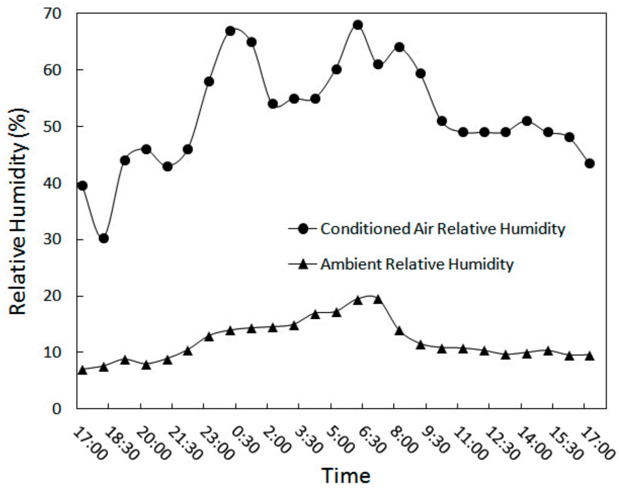

Figure 17. The amount of RH of air at wind tower outlet and the ambient air for test No. 5 (from 5:15 p.m. on the 22nd to 5:15 p.m. on the 23rd of August 2013).

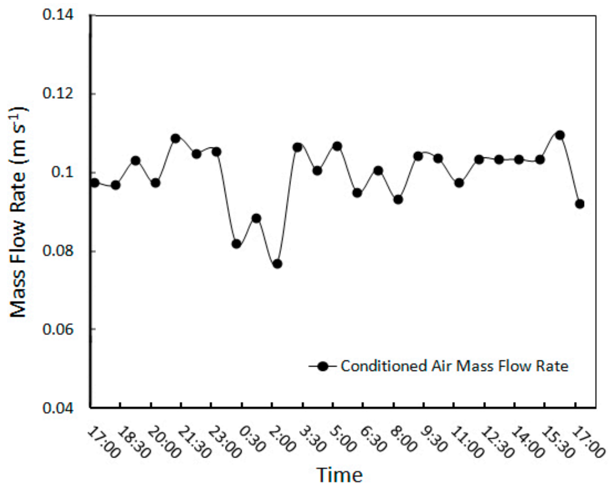

Figure 18. The conditioned air mass flow rate from the wind tower outlet to the room for test No. 5 (from 5:15 p.m. on the 22nd to 5:15 p.m. on the 23rd of August 2013).

5. Discussions

5.1. Temperature Reduction

According to the data collected during the five mentioned tests, the highest, lowest and average measured dry bulb temperature of ambient air were as follows:

Maximum ambient air temperature = $T_{1\text{-}max}$ = 38.0 °C
Minimum ambient air temperature = $T_{1\text{-}min}$ = 17.3 °C
Average ambient air temperature = $T_{1\text{-}ave}$ = 30.3 °C

Table 6 illustrates the highest, lowest and average dry bulb temperature of the conditioned air entering the room from the wind tower outlet for both analytical and experimental results. Additionally, the amount of maximum, minimum and average decrease in air temperature is presented in Table 7.

Table 6. The highest, lowest and average dry bulb temperature of the conditioned air entering the room from wind tower outlet.

Parameter	Experimental Results	Analytical Results
Maximum air temperature ($T_{6\text{-}max}$)	24.6 °C	23.9 °C
Minimum air temperature ($T_{6\text{-}min}$)	12.2 °C	12.4 °C
Average air temperature ($T_{6\text{-}ave}$)	21.1 °C	20.7 °C

Table 7. The highest, lowest and average reduction in dry bulb temperature of air using the modular wind tower.

Parameter	Experimental Results	Analytical Results
Maximum decrease in air temperature (ΔT_{max})	13.6 °C	14.6 °C
Minimum decrease in air temperature (ΔT_{min})	3.0 °C	2.9 °C
Average decrease in air temperature (ΔT_{ave})	9.2 °C	10.0 °C

Note that the minimum data were measured at midnight. As a result, the experimental and analytical results illustrate that the average air temperature entering the room was approximately 21 °C when the average ambient air temperature was 30.3 °C. In other words, the modular wind tower can significantly decrease the air temperature entering the room.

5.2. Increase in Relative Humidity

The highest, lowest and average RH of ambient air were equal to:

Maximum air ambient RH = $\phi_{1\text{-}max}$ = 19.6%
Minimum air ambient RH = $\phi_{1\text{-}min}$ = 6%
Average air ambient RH = $\phi_{1\text{-}ave}$ = 10%

Note that the above maximum value of RH (19.6%) was measured in the middle of the night and early morning. If midnight measurements were ignored, the average RH of ambient air was around eight percent. Furthermore, the highest, lowest and average RH of air entering the room from the wind tower outlet were as follows:

Maximum exit RH = $\phi_{6\text{-}max}$ = 68%
Minimum exit RH = $\phi_{6\text{-}min}$ = 30%
Average exit RH = $\phi_{6\text{-}ave}$ = 49%

The highest, lowest and average increase in the amount of RH of air using the wind tower were equal to:

Maximum increase in RH = $\Delta\phi_{max}$ = 53%

Minimum increase in RH = $\Delta\phi_{min}$ = 23%
Average increase in RH = $\Delta\phi_{ave}$ = 39%

The RH plays an important role in the thermal comfort of building inhabitants in hot, arid zones. Thus, the proposed wind tower can substantially increase the amount of RH of air entering the room.

5.3. Mass Flow Rate

According to the data collected through measurements and the analytical results, the highest, lowest and average air speed measured at the outlet of the wind tower and entering the room are shown in Table 8.

Table 8. The highest, lowest and average dry bulb temperature of the conditioned air entering the room from wind tower outlet.

Parameter	Experimental Results	Analytical Results
Maximum exit velocity ($V_{6\text{-}max}$)	2.0 m·s^{-1}	2.10 m·s^{-1}
Maximum volumetric flow rate	0.120 m^3·s^{-1}	0.126 m^3·s^{-1}
Minimum exit velocity ($V_{6\text{-}min}$)	1.0 m·s^{-1}	1.02 m·s^{-1}
Minimum volumetric flow rate	0.060 m^3·s^{-1}	0.061 m^3·s^{-1}
Average exit velocity ($V_{6\text{-}ave}$)	1.7 m·s^{-1}	1.74 m·s^{-1}
Average volumetric flow rate	0.102 m^3·s^{-1}	0.104 m^3·s^{-1}

The mass flow rate entering the room was calculated using the following relation:

$$\overset{\&}{m} = \rho\, AV\ (\mathrm{kg{\cdot}s^{-1}}) \tag{20}$$

By considering the air as an ideal gas, the amount of ρ was computed by:

$$\rho = \frac{P}{RT}\ (\mathrm{kg{\cdot}m^{-3}}) \tag{21}$$

In the equation above, P is the average air pressure in Kerman (Pa), and T is in unit K. Therefore, the highest, lowest and average amount of mass flow rate from the wind tower outlet entering the room were equal to:

Maximum mass flow rate = $\dot{m}_{\max}$ = 0.1149 kg·s^{-1}
Minimum mass flow rate = $\dot{m}_{\min}$ = 0.0580 kg·s^{-1}
Average mass flow rate = $\dot{m}_{ave}$ = 0.0982 kg·s^{-1}

These results display that the wind tower can provide a mass flow rate entering the room when the wind speed is zero because of buoyancy force. As a result, the efficiency of the proposed wind tower will increase significantly when the wind speed is not zero. According to the results obtained, the modular wind tower with wetted surfaces, which was built and tested for the first time, could be a practical and satisfactory alternative for natural cooling of buildings in hot and arid zones. To use this technology, computational modeling should be performed in order to apply the modular wind tower to different types of buildings and weather conditions.

To show a more tangible performance of the proposed wind tower, Figure 19 displays the air property changes at a sample point by using a modular wind tower with wetted surfaces on a psychrometric chart. A psychrometric chart is a graphical illustration of changes in the physical and thermodynamic properties of air. In the psychrometric chart, there is a zone called the comfort zone, which represents thermal comfort conditions, and air conditioning systems designed by engineers must be able to provide indoor air conditions in that zone [42]. Sample data shown in Figure 19 were taken at 13:45 on 26 August 2013. The direction of the arrow in the psychrometric chart indicates ambient air changes by cooling and humidifying processes while passing through the wind tower. As can be observed in Figure 19, RH of ambient air increased from 7% (ambient air) to 44.3% (at the wind tower outlet). Furthermore, ambient air temperature decreased from 37.2°C to 22.5 °C. As a result, the proposed modular wind tower can provide conditions of greatly increased comfort for building inhabitants.

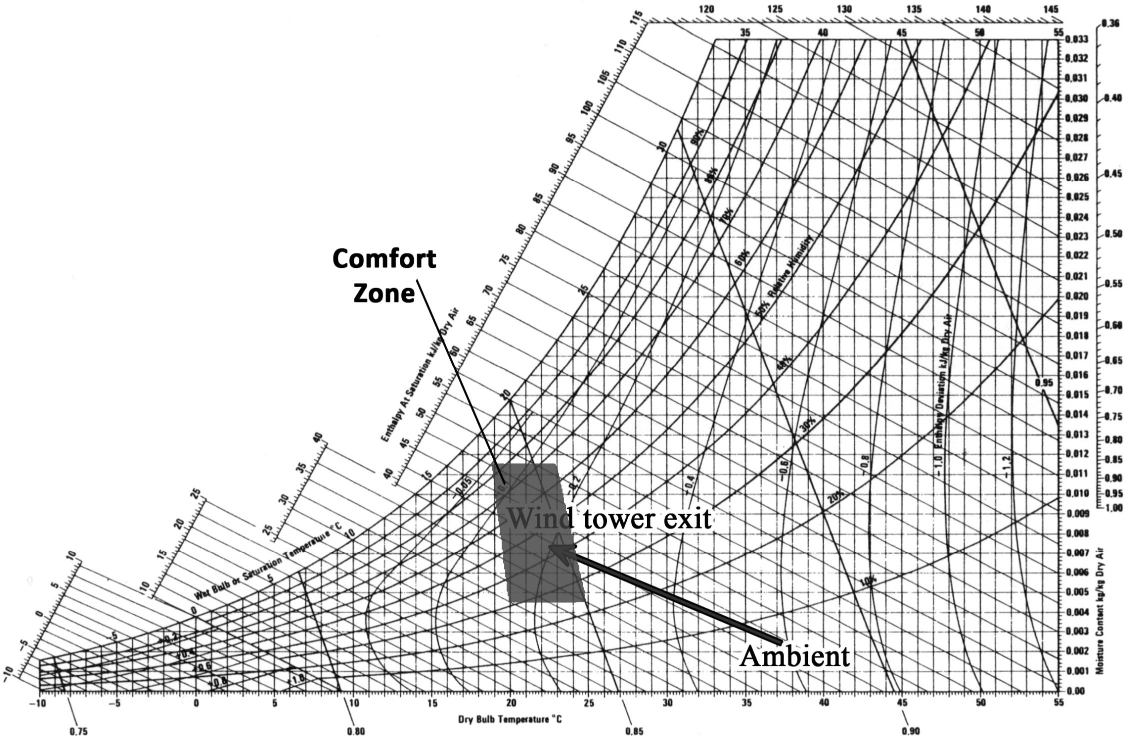

Figure 19. Property changes of the air passing throughout the modular wind tower with wetted surfaces.

6. Conclusions

The experimental and analytical results presented in this paper clearly illustrate that using this new design of wind tower makes the air inside the building closer to thermal comfort conditions. The results obtained show that a wind tower with wetted surfaces can reduce air temperature and increase air humidity by an average of approximately 10 °C and 40%, respectively. It was observed that when ambient air temperature is more than 35 °C and RH is under 10% without any wind, this wind tower is capable of altering the air properties to less than 23 °C with an RH of around 45%. Note that the modular wind tower with wetted surfaces has a better performance when the wind speed is not zero. The only electricity usage is for the electric water pump, which keeps the straw wet. It should be noted that Kerman (as well as other cities where wind towers are used) is located in a sunny region; therefore, by providing the needed electricity for the water pump using solar cells, this air conditioning system becomes completely passive. Thus, during the warm days of summer, the thermal comfort for the residents of a building can be provided without any use of electrical energy from the grid.

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

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Author Contributions: Mehdi N. Bahadori gives the idea, Mehdi N. Bahadori, Ahmad Nourbakhsh and Sajad M.R. Khani conceived and designed the experiments; Sajad M.R. Khani performed the experiments; Sajad M.R. Khani and Alireza Dehghani-Sanij analyzed the data; Mehdi N. Bahadori, Sajad M.R. Khani and Alireza Dehghani-Sanij contributed reagents/materials/analysis tools; Alireza Dehghani-Sanij and Sajad M.R. Khani wrote the paper.

Conflicts of Interest: The authors declare no conflict of interest.

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