Cooling performance of Persian wind towers

M. Hejazi[1] & B. Hejazi[2]
[1]*Department of Civil Engineering, Faculty of Engineering, University of Isfahan, Isfahan, Iran*
[2]*Department of Architecture, Khorasgan (Isfahan) Branch, Islamic Azad University, Isfahan, Iran*

Abstract

In hot-dry regions of Iran typical buildings are made of mud and fired brick. Temperature, humidity and airflow control comfort within such buildings. These passive cooling buildings use nature's elements in providing comfort to people: night ventilation, evaporative cooling and ground cooling. High-rise wind towers (*badgir*s) above the roofs catch the passing winds and channel them down to the ground and basement spaces in order to cool the internal spaces on summer days. In this paper Persian wind towers and their passive cooling system are described. Results from numerical analysis of wind towers with four different heights are presented. Parameters such as mass flow and temperature in wind towers are studied and the effects of their heights and the orientation and velocity of wind on these parameters are reported.
Keywords: Persian wind towers, badgir, cooling performance, passive system, airflow, mass flow, temperature.

1 Introduction

Wind tower, *badgir,* is a climatic structural element of Persian architecture in hot-dry areas such as Kashan, Yazd, Kirman, and northern coastlines of Persian Gulf. A *badgir* provides ventilation, reduces temperature, increases moisture and creates an environmental equilibrium. It consists of a vertical shaft with openings facing towards the dominant wind direction.

A wind tower is a passive cooling building that relies on natural sources of cooling. Night ventilation lowers the temperature of building thermal mass. Day evaporative cooling absorbs heat to evaporate water, and ground cooling uses wet ground, ground vegetation or a groundwater system to cool the circulating air [1, 2] (Fig. 1).

WIT Transactions on Ecology and The Environment, Vol 165, © 2012 WIT Press
www.witpress.com, ISSN 1743-3541 (on-line)
doi:10.2495/ARC120181

Figure 1: Wind towers, *badgir*s, as the main cooling system of a house in hot-dry areas by using natural sources of wind, water and vegetation.

In recent years some experts have studied the cooling system of a *badgir*. The work of Bahadori and Yaghoubi [3] is a comprehensive research about natural air conditioning and cooling in Persian traditional buildings, in which different aspects of passive systems including analysis and design formulae for different types of passive buildings such as wind towers, domical roofs, basements and cellars, courtyards and cisterns are presented. Hejazi and Mehdizadeh-Saradj [2] described climatic adaptability in Persian vernacular architecture and cooling performance of Persian *badgir*s. Bahadori described Persian wind towers [4, 5] and studied the effect of wind velocity and air temperature on performance of wind towers [6]. Bahadori [3] and Yaghoubi *et al.* [7] showed that when the wind does not blow, a wind tower functions as a ventilator and uses fresh air of the basement or courtyard, instead of wind, to cool the internal space. Researchers such as Badran Ali [8], and Nouanegue *et al.* [9] performed experimental or numerical research into cooling systems of wind towers. Bahadori *et al.* [10] tested two new designs of *badgir*s, one with wetted curtains hung inside the wind tower and the other one with wetted surfaces and they reported operation improvement of the wind tower. Kalantar [11] developed a computer code for numerical simulation of performance of natural evaporative cooling tower system.

2 Cooling operation system of a wind tower

When wind blows towards the wind tower, air flows through windward openings of the wind tower and building. Some parts of air exit from the leeward opening of the wind tower and cause air loss. At night the external and internal parts of a wind tower cool down, respectively due to heat radiation of external surface of the wind tower and circulation of cool ambient air through the wind tower and building. For massive buildings the coolness is stored in the building mass and the stored energy provides thermal comfort on the following day. During the day, warm air passing through the wind tower is cooled before entering the building. In some buildings, air passes over a moisturing surface and causes evaporative cooling. The wind tower cools inside the building until the temperature of its surfaces becomes greater than that of ambient air due to sun radiation. Thereafter, the wind tower functions as a ventilator. If the air is conducted towards the basement, over wet surfaces or over qanat water running in the basement the wind tower can continue cooling inside the building for the whole day (Figs 1 and 2).

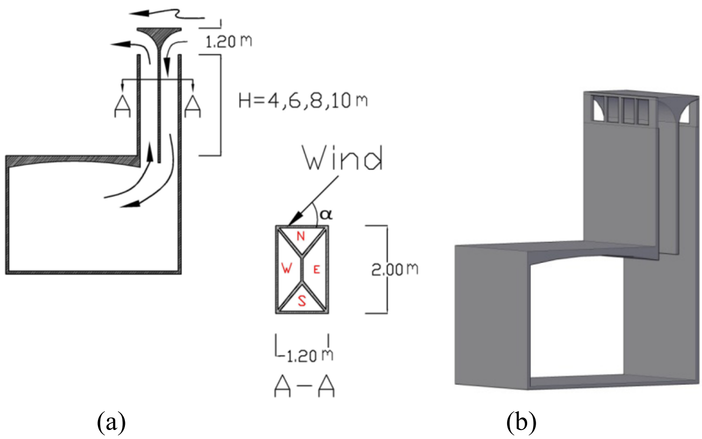

Figure 2: Wind tower, *badgir:* (a) airflow pattern, (b) isometric view.

Wind pressure on a wind tower can be determined from eqn (1).

$$q = \frac{1}{2} C_q \rho V^2 \quad (1)$$

where:
q = wind pressure
C_q = wind pressure coefficient
V = wind velocity.

The wind coefficient C_q can be obtained by performing experience on a prototype of the building and wind tower in a wind tunnel. In general, when wind blows normal to a wind tower opening, the coefficient is positive for the normal opening side and negative for other sides. Hence, a pressure difference occurs between the windward side and other sides according to eqn (2).

$$\Delta q_{ab} = q_a - q_b = \frac{1}{2}(C_{qa} - C_{qb})\rho V^2 \quad (2)$$

where:
a, b = openings a, b
ab = denoting air path from a to b.

The pressure difference causes a certain amount of air to flow through the wind tower calculated from eqn (3).

$$\bar{V}_{ab} = \frac{\Delta q_{ab}}{R_{ab}} \quad (3)$$

where:
$\bar{V}_{ab}$ = volumetric airflow
R_{ab} = flow resistance.

By pressure difference Δq_{ab} between sides a and b and depending on the resistance against airflow, an airflow initiates between a and b based on eqn (2); i.e. the air enters the tower at the windward opening a with a positive wind pressure coefficient and leaves from the opening b with a smaller pressure coefficient.

The leeward opening or openings parallel to wind direction have a negative pressure coefficient; hence, some parts of entering air are lost through leeward and parallel openings at the top of the wind tower and the remaining part enters the room or basement (Fig. 2). A wall or partition is built in the middle of the wind tower in order to increase flow resistance R_{ab} of the path of some parts of air that exit from upper openings to decrease air loss; hence, by decreasing flow resistance of the path from the windward opening to the lower space, more air flows through the rooms.

Fig. 2(a) shows the airflow pattern in a wind tower. Wind blows in a direction with an angle of α with respect to the horizontal axis of cross-section A-A of the wind tower. Pressure coefficients are positive for the N and E openings, and negative for the S and W openings of cross-section A-A, respectively. Thus, air enters the N and E openings. A part of air exits from the S and W openings and a part of air enters the building and then leaves the building from the S and W openings at the top of the wind tower. As the amount of airflow $\bar{V}_{ab}$ in each path is determined by eqn (3), it can be increased or decreased by decreasing or increasing the flow resistance R_{ab} of the path. The construction of the vertical wall inside the wind tower, which divides the vertical section of the wind tower into two parts (W and E), is for increasing the flow resistance for openings with negative pressure coefficients (the S and W openings in cross-section A-A) in order to prevent air leaving from these openings.

Having wind pressure coefficients, hence, wind pressure (eqn (1)), at different points and determination of air pressure loss (eqn (2)) for each path, it is possible to use continuity equation or the law of conservation of mass (eqn (4)), i.e. total entering air mass is equal to total exiting air mass) to determine airflow at each path.

$$\sum \rho_a \bar{V}_{ab} = 0 \quad (4)$$

where:
ρ_a = mass density of air at opening a

If it is assumed that mass density of air is constant through the wind tower, i.e. temperature does not change at different paths, eqn (4) becomes eqn (5).

$$\sum \bar{V}_{ab} = 0 \quad (5)$$

Therefore, it is possible to calculate airflow for different wind velocities and directions (Fig. 2(a)).

Flow resistance R_{ab} in eqn (3) or loss of pressure of an air path depends on the Raynolds number, which is a function of air velocity and also of air properties that they themselves depend on air temperature. Therefore, in order to have more precise values of pressure loss and airflow entering the building it is necessary to know air temperature at different points of the wind tower. The temperature of airflow in the wind tower depends on the air temperature at the entering point and thermal exchange of air with internal surfaces of the wind tower. For determination of thermal exchange it is necessary to consider the thermal network of the wind tower and solve flow equation and thermal exchange equation together.

In thermal exchange calculations, outside temperature solar radiation density at different hours of a day must be measured. For determination of hourly air temperature eqns (5)-(7) are used [12].

$$T - \bar{T} = \frac{1}{2} A_t \cos\dot{\omega}(t - 15) \quad (6)$$

where:

$$\bar{T} = \frac{1}{2}(T_x + T_n) \quad (7)$$

$$A_t = \frac{1}{2}(T_x - T_n) \quad (8)$$

$\dot{\omega} = 2\pi/24$
T = hourly temperature
t = time (h)
T_x = mean value of monthly maximum temperature
T_n = mean value of monthly minimum temperature
In eqns (6)-(8) maximum and minimum temperatures are assumed to occur at 3 o'clock in the afternoon and 3 o'clock in the morning, respectively.

For determination of solar radiation density on various surfaces eqns (9)–(20) are used [12].

$$I_h = k_T I_{oh} \quad (9)$$

$$I_{dh} = I_h - I_{bh} \quad (10)$$

$$I_{oh} = I_{sc}\left[1 + 0.033\cos\left(\frac{360N}{365}\right)\right]\cos\theta_z \tag{11}$$

$$k_T = [a + b\cos\dot{\omega}(t-12)]\overline{K}_T \tag{12}$$

$$a = 0.409 + 0.5016\sin(\omega_s - 60) \tag{13}$$

$$b = 0.6607 - 0.4767\sin(\omega_s - 60) \tag{14}$$

$$I_{dh}/I_h = 1 - 0.249k_T \qquad \text{for} \qquad k_T < 0.35 \tag{15}$$

$$I_{dh}/I_h = 1.557 - 1.84k_T \qquad \text{for} \qquad 0.35 < k_T < 0.75 \tag{16}$$

$$I_{dh}/I_h = 0.177 \qquad \text{for} \qquad k_T > 0.75 \tag{17}$$

$$\cos\theta_z = \cos\delta\cos\phi\cos\omega + \sin\delta\sin\phi \tag{18}$$

$$\cos\omega_s = -\tan\phi\tan\delta \tag{19}$$

$$\delta = 23.45\sin\left(360\,\frac{284+N}{365}\right) \tag{20}$$

where:
$\overline{K}_T$ = monthly filter coefficient
k_T = hourly filter coefficient
I_h = solar radiation on a horizontal surface
I_{dh} = scattered solar radiation density on a horizontal surface
I_{bh} = direct solar radiation density on a horizontal surface
I_{oh} = solar radiation density on a horizontal surface out of earth atmosphere
I_{sc} = 1353 W/m^3 = solar constant
N = day index of Gregorian year (N = 1 for the first of January, or $N = n + 80$, where n = day index of Hijri year and n = 1 for the first of the first Hijri month (*Farvardin*, 21 March)
θ_z = zenith angle
ω_s = angle of sunset
ϕ = latitude
δ = inclination angle
ω = hour angle (15° for an hour)

For calculations, the height of a wind tower is divided into smaller parts (of for example 1 m high) and flow and thermal exchange equations are written for each part to determine the velocity and temperature of the leaving air from that part. The determined velocity and temperature of exiting air from each part are the velocity and temperature of the entering air to the next part. Calculations are repeated until the last part, where the velocity and temperature of air exiting the wind tower and entering the building are calculated. It is possible to prepare a computer code for performing the calculations.

3 Studied wind towers and obtained results

Dimensions of studied wind towers are shown in Fig. 2(a). The walls of the wind towers are 0.1 m thick. The rectangular cross-section of wind towers is

1.2 × 2 m^2. Each wall of wind towers is pierced with a rectangular shaped opening. Openings of wider walls have a width of 1.8 m and a height of 1.1 m. Openings of narrower walls are 1 m wide and 1.1 m high. Wind towers can have four heights of 4, 6, 8 and 10 m from the roof level. Three different wind velocities of 0 m/s, 7.5 m/s, 15 m/s, and three wind directions of α = 0°, 45° and 90° have been used in analyses. It has been assumed that wind towers are in Kashan, Central Iran, with T_x = 34.6°C, T_n = 16.8 °C and $\overline{K}_T$ = 0.69 for July.

Results for a wind tower of 8 m high are shown in Figs. 3–5. Fig. 3 shows the temperature variation of air entering from the wind tower to the building on a typical summer day for different wind velocities and directions. The effect of the velocity and direction of wind on the temperature of air entering to the building is negligible. The minimum and maximum temperatures are about 17°C and 34°C at about 3 o'clock in the morning and at about 3 o'clock in the afternoon, respectively

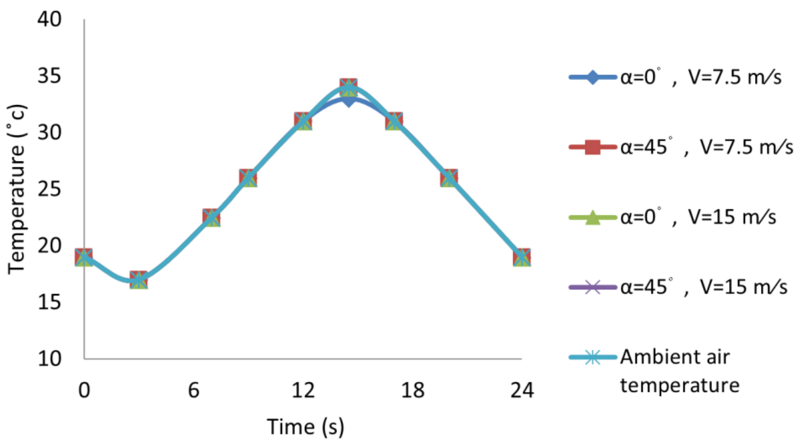

Figure 3: Temperature variation of air entering from the wind tower to the building on a typical summer day.

In Figs. 4 and 5 the variations of mass flow entering the building for wind directions of 0°, 45° and 90°, and wind velocities of 7.5 m/s (and 0 m/s) and 15 m/s (and 0 m/s) are respectively depicted for a wind tower with a height of 8 m from the roof. When the velocity of wind is equal to 0 m/s, i.e. wind does not blow, airflow is very small. From around 4 o'clock in the morning until about 10 o'clock at night airflow is negative; i.e. the wind tower functions as a ventilator and the direction of air is from the bottom to the top. The reason is that from 4 o'clock in the morning wind tower walls get warm as a result of sun radiation and outside air is cool. During the day the outside air temperature increases but solar radiation absorption also increases and still air flows upwards. From 10 o'clock at night until 4 o'clock next morning sky-radiation occurs and wind tower surfaces, and as a result air, become cooler and, therefore, airflow is downwards.

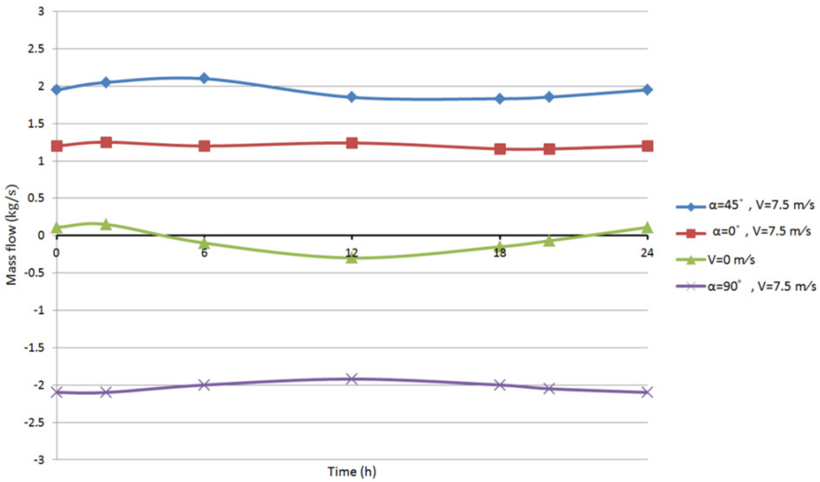

Figure 4: Variation of mass flow entering from the wind tower to the building on a typical summer day for wind velocity of 7.5 m/s (and 0 m/s) for a wind tower with a height of 8 m.

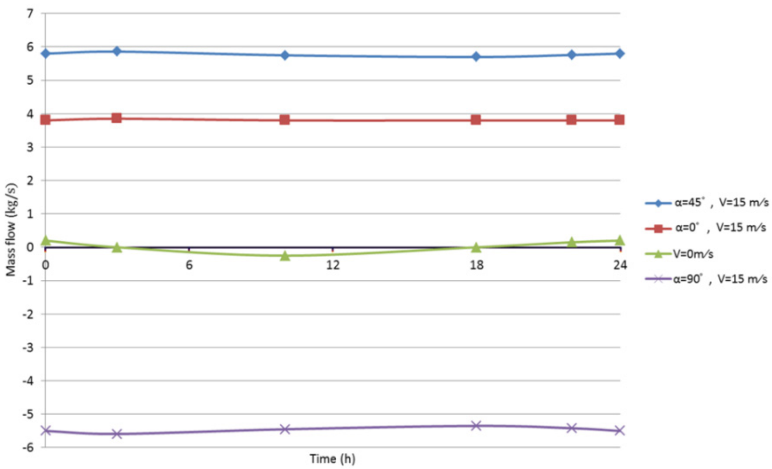

Figure 5: Variation of mass flow entering from the wind tower to the building on a typical summer day for wind velocity of 15 m/s (and 0 m/s) for a wind tower with a height of 8 m.

A larger value of wind velocity causes more mass flow. For example, for wind direction of 45°, maximum mass flows are 5.9 and 2.1 kg/s for wind velocities of 15 m/s and 7.5 m/s, respectively. For studied wind directions, a wind direction of 45° results in a greater mass flow than other directions; maximum mass flows are 2.1, 1.2 and -2.1 kg/s for wind directions of 45°, 0°

and 90°, respectively. Mass flow for the wind direction of 90°, i.e. normal to the smaller dimension of the wind tower, is negative. For this case, the wind tower functions as ventilator; the air of the courtyard on the ground floor enters the building and rises up through the wind tower. This is an important issue in choosing the dimensions of the openings of the wind tower with respect to the dominant wind direction and the courtyard. By choosing an appropriate direction, outside warm air is prevented from entering the wind tower; instead, the cool air of the courtyard, which is designed with a garden and a small pool creating a suitable microclimate (Fig. 1), passes through the ground spaces and rooms and then elevates in the wind tower.

The vairations of air temperature and mass flow entering from the wind tower to the building for different heights of the wind tower and different wind velocities and directions are shown in Figs. 6 and 7, respectively. Temperature increases for higher wind towers and winds with smaller velocities. Maximum temperature difference for different heights and different wind velocities and directions is about 0.5 °C, which is negligible. Mass flow decreases for higher wind towers. For example for wind direction of 45° and wind velocity of 15 m/s, which causes the maximum mass flow, there is a decrease of 13% in mass flow when the height increases from 4 m to 10 m. A decrease in wind velocity decreases mass flow further. For wind direction of 45° and height of 4 m, which produces the maximum mass flow, there is a decrease of 65% in mass flow when wind velocity decreases from 15 m/s to 7.5 m/s.

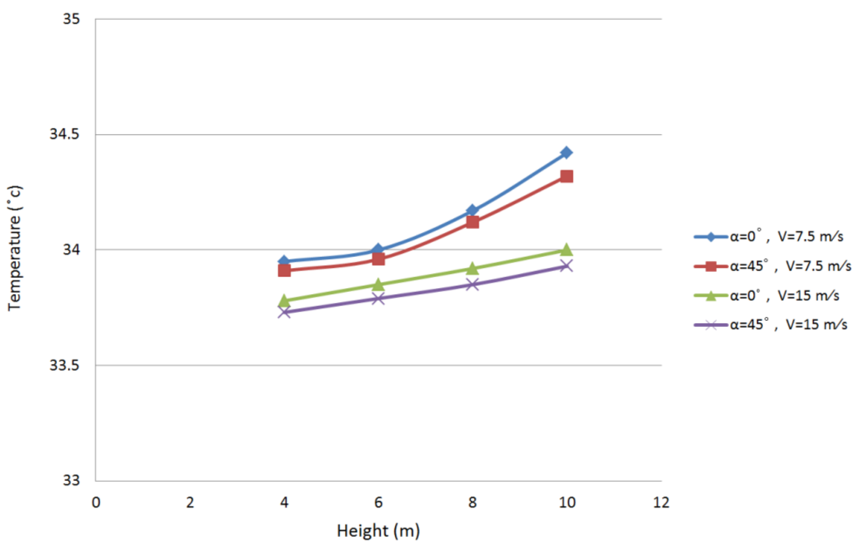

Figure 6: Variation of air temperature entering from the wind tower to the building versus wind tower height for different wind velocities and directions.

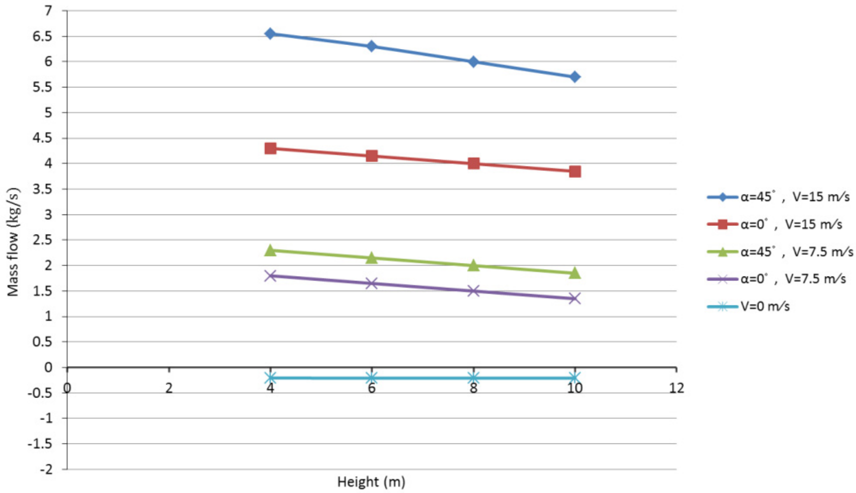

Figure 7: Variation of mass flow entering from the wind tower to the building versus wind tower height for different wind velocities and directions.

4 Conclusions

Cooling operation system of Persian wind towers, *badgirs,* have been described.

Wind towers, located in Kashan, Central Iran, with four different heights of 4, 6, 8 and 10 m from roof level were studied for mass flow and temperature. Three different wind velocities of 0 m/s, 7.5 m/s and 15 m/s were considered. Three different wind directions of 0°, 45° and 90° with respect to the normal to the wider side of the tower wind cross-section were taken into account.

When wind does not blow, a wind tower functions as a ventilator and airflow direction is upwards. Mass flow for the wind direction of 45° is, in some cases up to 43%, larger than that of other wind directions. For wind direction of 90° mass flow is negative and airflow is from the bottom to the top of the wind tower. For such a case, it is possible to use the cool air of the courtyard to cool the building. A lower wind tower and a wind with a larger velocity decrease the air temperature and increase the flow mass entering from the wind tower to the building. The decrease of air temperature is not more than 0.5 °C. The decrease of height from 10 m to 4 m can result in a more than 13% increase in mass flow. An increase of wind velocity from 7.5 m/s to 15 m/s increases mass flow more than 65%.

References

[1] Hejazi, M., *Historical Buildings of Iran: their Architecture and Structures,* Computational Mechanics Publications (WIT Press), Southampton and Boston, 1997.

[2] Hejazi, M. and Mehdizadeh-Saradj, F., *Persian Architectural Heritage: Form, Structure and Conservation,* WIT Press, Southampton and Boston, 2012.
[3] Bahadori, M.N. and Yaghoubi, M., *Natural Air Conditioning and Cooling in Persian Traditional Buildings* (in Farsi), Markaz Nashr Daneshgahi, Tehran, 2006.
[4] Bahadori, M.N., Passive cooling systems in Iranian architecture. *Scientific American,* pp. 144-154, 1978.
[5] Bahadori, M.N., Viability of wind towers in achieving summer comfort in the hot arid regions of the Middle East. *Renewable Energy,* **5(II),** pp. 879-892, 1994.
[6] Bahadori, M.N., An improved design of wind towers for natural ventilation and passive cooling. *Solar Energy,* **35(2),** pp. 119-129, 1985.
[7] Yaghoubi, M.A., Sabzevari, A. and Golneshan, A.A., Wind towers: measurement and performance. *Solar Energy,* **47(2),** pp. 97-106, 1991.
[8] Badran Ali, A., Performance of cool towers under various climated in Jordan. *Energy and Buildings,* **35,** pp. 1031-1035, 2003.
[9] Nouanegue, H.F., Alandji, L.R. and Bilgen, E., Numerical study of solar-wind tower systems for ventilation of dwellings. *Renewable Energy,* **33(3),** pp. 434-443, 2008.
[10] Bahadori, M.N., Mazidi, M. and Dehghani, A.R., Experimental investigation of new designs of wind towers. *Renewable Energy,* **33,** pp. 2273-2281, 2008.
[11] Kalantar, V., Numerical simulation of cooling performance of wind tower (Baud-Geer) in hot and arid region. *Renewable Energy,* **34,** pp. 246-254, 2009.
[12] Bahadori, M.N. and Chamberlain, Simplification of weather data to evaluate daily and monthly energy needs of residential buildings. *Solar Energy,* **36(6),** pp. 499-507, 1986.
[13] Duffie, J.A. and Beckman, W.A., *Solar Engineering of Thermal Processes,* Wiley, New York, 1991.