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A new design of wind tower for passive ventilation in buildings to reduce energy consumption in windy regions

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ABSTRACT

In today's world, the significance of energy and energy conservation is a common knowledge. Wind towers can save the electrical energy used to provide thermal comfort during the warm months of the year, especially during the peak hours. In this paper, we propose a new design for wind towers. The proposed wind towers are installed on top of the buildings, in the direction of the maximum wind speed in the region. If the desired wind speed is accessible in several directions, additional wind towers can be installed in several positions. The proposed wind tower can also rotate and set itself in the direction of the maximum wind speed. In the regions where the wind speed is low, to improve the efficiency of the system a solar chimney or a one-sided wind tower can be installed in another part of the building in the opposite direction. Using transparent materials in the manufacturing of the proposed wind towers improves the use of natural light inside the building. The major advantage of wind towers is that they are passive systems requiring no energy for operation. Also, wind towers reduce electrical energy consumption and environmental pollution.

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1. Introduction

Wind towers or wind catchers are small towers installed on top of buildings. Wind towers have different shapes and structures. For centuries wind towers have been used for ventilation and cooling of buildings in the hot and arid or humid areas [1]. Wind towers are still used in some areas of Middle East and Egypt (Figs. 1 and 2). By leading the outside air into the building, wind towers serve as a natural ventilation system for workplaces and houses.

Bahadori is a pioneer in research on wind towers who has worked on wind towers' operation and efficiency for almost 40 years [1,3–13]. He introduced two new designs of wind towers: the wind towers with wetted columns, and the wind towers with wetted surfaces. Wind towers with wetted columns consist of

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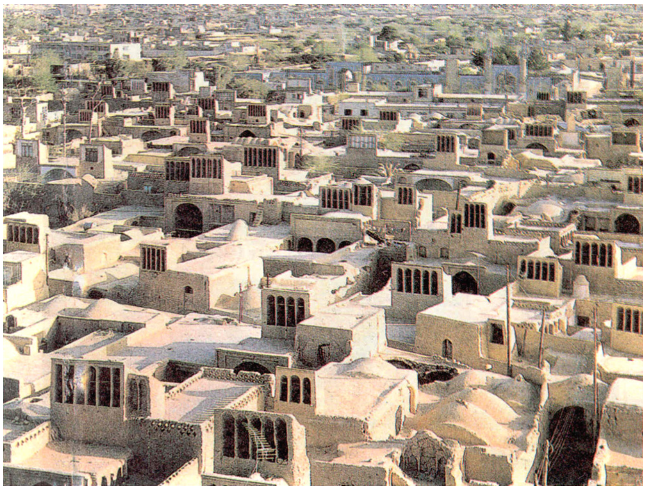

Fig. 1. The view of one-sided wind towers in Meybod city, Yazd province, Iran [1].

Fig. 2. The one-sided wind tower of a house in Al-Jawhara in Cairo, Egypt [1,2].

unglazed ceramic conduits stacked lengthwise on top of one another or thick dampers. Water is uniformly sprayed on the surface of the column, dampening the entire column. The excessive water leaving the column is collected in a sump located at the bottom of the wind tower and can be reused using a pump (Fig. 3). This way, the proposed design can utilize the evaporative cooling potential to deliver much cooler air to the building [1,6,7].

In the areas where wind speed is low, wind towers with wetted surfaces can be used. The surface of the wind tower consists of a series of straws or cellulose called pads commonly used in evaporative coolers (Fig. 4). These pads are placed at the apertures on top of the wind tower and are kept wet by spraying water on them. The air passing through these pads is evaporatively cooled and therefore its density is increased. Since the cooler air is heavier than the ambient air, there will be a downward circulation of the air [1,6,7]. In Fig. 4, wind tower is combined with an air heater or solar chimney [1,8]. In this design, the airflow conducted outside through doors and windows of the rooms and solar chimney. In winter, when wind towers are not operating (i.e., dampers D2, D3 and D4 are closed), the solar chimney can naturally warm the room [1,8].

Bahadori et al. [13–19] examined the new designs of wind towers theoretically and experimentally and compared their performance with that of the conventional wind towers. Results showed that both new designs performed better than the conventional wind towers. The evaporative coolers currently used in the hot and arid regions can be easily replaced by the new designs of wind towers, bringing significant saving in the electrical energy during the warm months.

The influence of wind speed and direction on the ventilation capacity of one-sided wind towers was investigated both experimentally and theoretically [20]. A wind tunnel was used to obtain the experimental results. The roof of one-sided wind towers used during the experiment was flat, inclined or curved. Results showed that the internal pressure field and induced airflow rate inside the wind towers were strongly influenced by the geometry of the wind tower's roof and wind direction. Also, the results of theoretical and experimental methods were very close. These results help improve the design of one-sided wind towers [20]. In another study, the smoke visualization method was used to obtain empirical results for the main flow characteristics around and inside different types of one-sided wind towers [21]. Using this method, the operation of these types of wind towers was analyzed. Results showed that the wind tower with curved roof had better performance than other types of wind towers.

Montazeri et al. [22] numerically, analytically, and experimentally investigated the operation of a two-sided wind tower. A wind tunnel was used to measure the experimental results. The model wind tower was connected to a model house. In the investigation of experimental and numerical model, the pressure coefficient distribution and airflow pattern around and through the wind tower at various wind angles were evaluated. Results demonstrated that the maximum performance is obtained at 90° angle. Also, numerical and analytical modeling results were in good agreement with the experimental results. These results help improve the design of two-sided wind towers.

Zarandi [23] investigated the thermal behavior of conventional wind towers in Yazd, a city in the middle of Iran popular for its conventional wind towers. He analytically and numerically studied 53 conventional wind towers with optimum operation and recorded their specifications. Results illustrated the formal characteristics of wind towers with optimum performance. The information obtained from their study helps designing new structures with better performance. Yavarinasab and Mirkhalili [24] examined the optimum relationship among the length, width, and height of wind towers. They obtained the linear regression equation due to relationship between coefficients. The equation can be used to obtain the optimum model.

Ghadiri et al. [25] numerically investigated the performance of square wind towers with different dimensions in hot and arid regions. They introduced wind towers as a green ventilation system capable of increasing the air quality inside buildings with minimum energy consumption. In another study, Ghadiri et al. [26] examined the effect of traditional wind towers' geometry on the internal thermal behavior of a building. They used FLUENT software for simulation of two different square wind towers. Results of their studies help the researchers to better understand how the traditional wind towers work.

Dehnavi et al. [27] studied the effect of physical properties of square wind towers (such as length to width ratio and height to air openings height ratio) on their performance and found the optimum characteristics of square wind towers for best performance. Their results also show a good agreement between the numerical

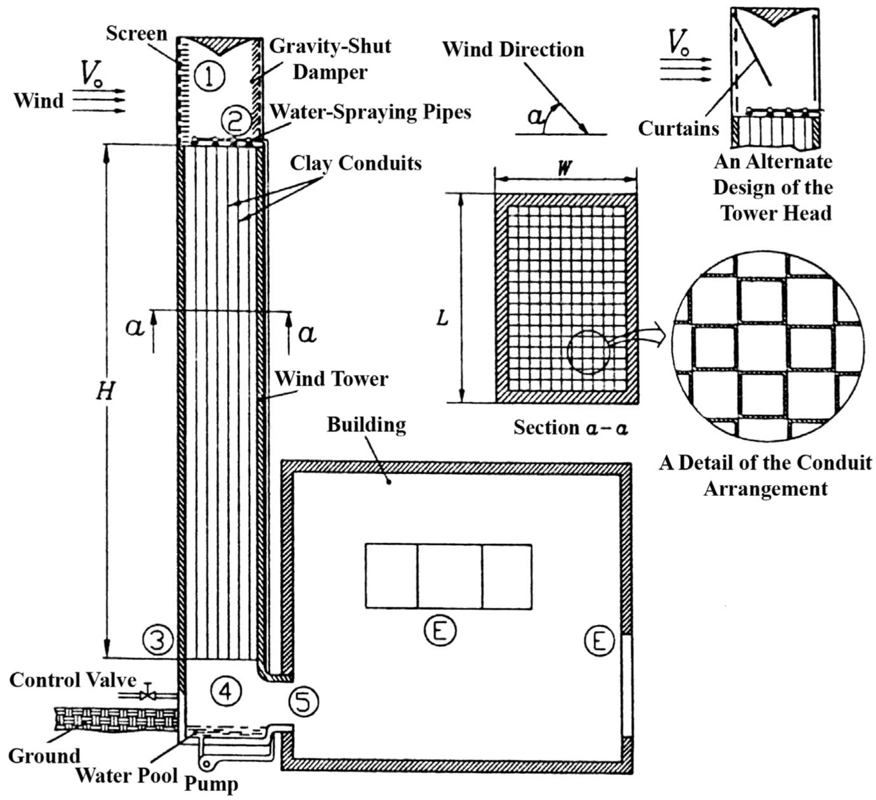

Fig. 3. Cross-section of a wind tower with wetted columns [1,8].

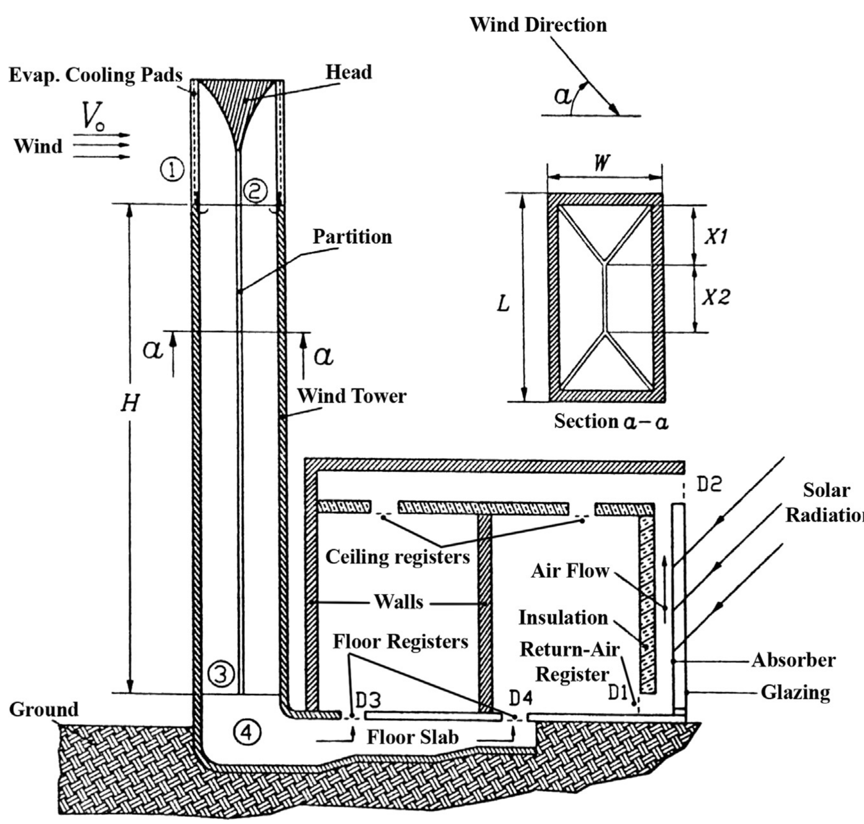

Fig. 4. Cross-section of a wind tower with wetted surfaces, with a solar chimney [1,8].

and experimental methods. Masrour et al. [28] examined the air circulation in the traditional wind towers and buildings. They compared the mass flow rate of intake air into the building with different wind speeds in different directions during the day. The results obtained can be used for designing better wind towers with higher performance.

Tavakolinia [29] suggested using a wind tower and a solar chimney in a building for natural ventilation and heating. In fact, a passive cooling system was used to create thermal comfort for inhabitants. The wind tower and solar chimney were combined with an underground air channel. Such system reduces energy use, CO_2 emission, and pollution.

Elmualim [30] installed a wind tower to allow passive ventilation of a seminar room in the School of Construction Management and Engineering, University of Reading, UK. He analyzed the performance of the wind tower using ventilation tracer gas measurements, indoor climate measurements (temperature, humidity, CO_2), and

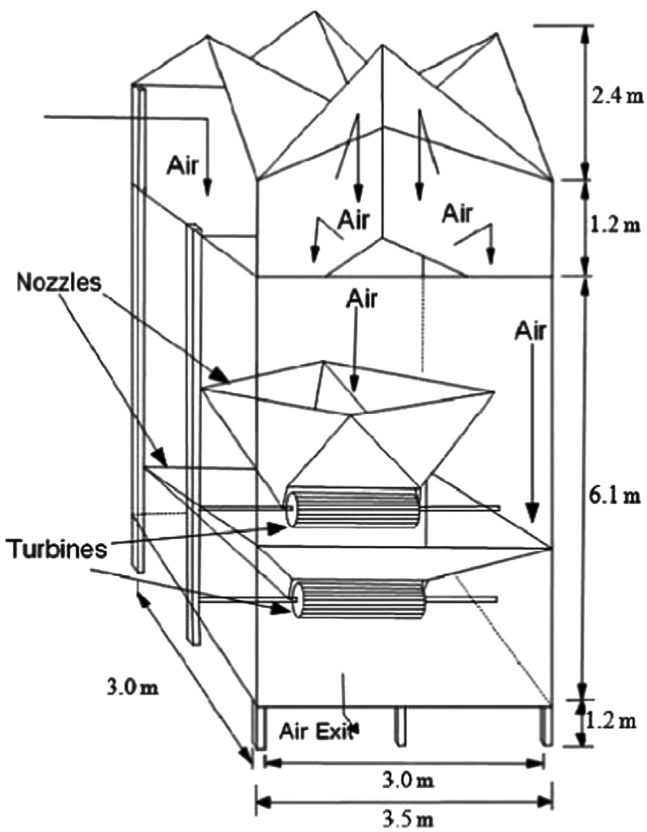

Fig. 5. Schematic representation of the wind tower proposed by Goudarzi et al. [31].

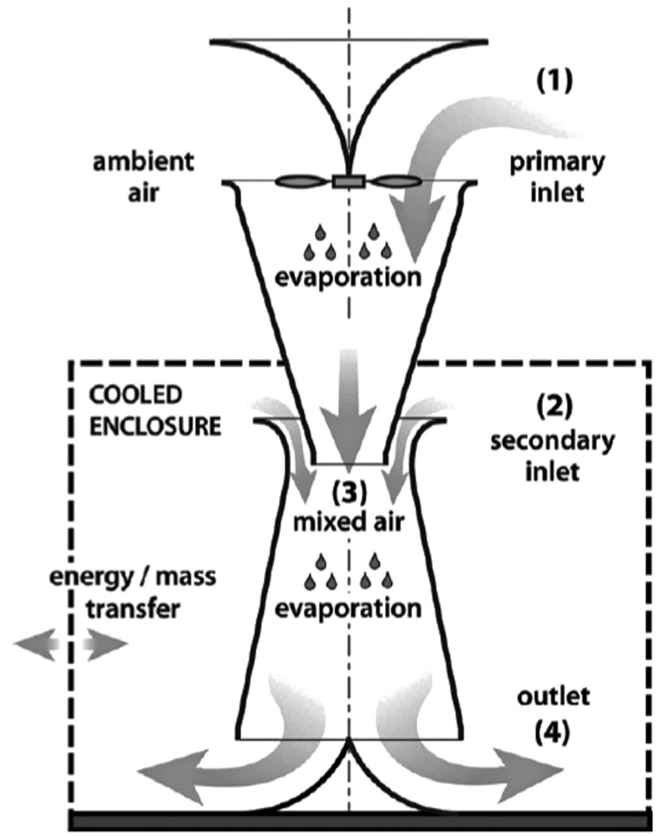

Fig. 7. Schematic representation of the DECT [33–35].

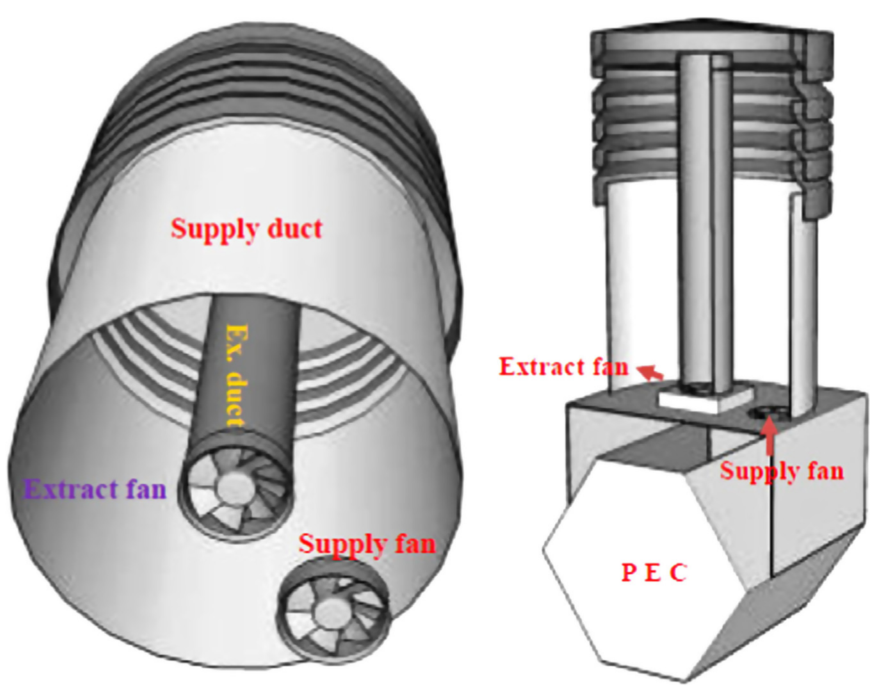

Fig. 6. Schematic representation of the modified wind tower with the PEC and fans [32].

interviewing the building's occupants. He also evaluated the observed ventilation results with those predicted by an explicit ventilation model and the AIDA[1] implicit ventilation model. Results confirmed that wind tower is a useful tool for thermal comfort.

Goudarzi et al. [31] theoretically and experimentally studied a new design of wind tower. The wind tower includes a four-quadrant-peak wind-catcher rooftop, nozzles, and turbines (Fig. 5). To obtain numerical results, a mathematical model is investigated. For evaluation of numerical results and improvement the mathematical model, the experimental results are used. The numerical and experimental results showed that the wind power in this wind tower is a function of several parameters; the most important of them are speed and direction of ambient air around the building. Also, there was a good agreement between the numerical and experimental results. This wind tower with its simple design is a possible and suitable choice for power generation in residential and commercial scale applications.

Elzaidabi [32] investigated a new indirect evaporative cooling system that uses a psychometric energy core (PEC) unit. The authors built an indirect evaporative cooler system by combining a modified wind tower and a diamond shape PEC unit (Fig. 6). The PEC-Wind tower was numerically and experimentally evaluated for different parameters such as wind velocity, fan velocity and water flow rate. Results showed that the system had good performance with over 80% cooling capacity. Under controlled operation conditions, the unit could generate about 2.4 kW cooling capacity and achieved a COP of 33.56.

Pearlmutter and colleagues [33–35] developed and studied, both experimentally and theoretically, a multi-stage down-draft evaporative cool tower (DECT). The DECT (Fig. 7) was built in a glazed courtyard located at the heart of a building complex in the arid Negev Highlands of southern Israel. In this system, dry ambient air enters the upper part of the tower. After the air is cooled by water spraying system, it moves to the bottom of the tower. In this part, the airflow is mixed with other airstream and the mixture is cooled by evaporation. The experimental results demonstrated that during summer days, the outlet air was 10 °C cooler than the inlet air.

Soutullo et al. [36,37] built cylindrical cross section evaporative wind towers for thermal ventilation of urban spaces and analyzed and optimized their operation. For this purpose, they considered two theoretical models: a thermal model and a fluid model. In the thermal model, an auxiliary fan and nozzles have been used. In the fluid model however, there was no fan or nozzle. Figs. 8 and 9 show these cooling systems. Wind, temperature and humidity measurements showed that on average the wind towers decreased the temperature by 3.5 °C. Also, the average saturated cooling efficiency was approximately 32%. In another research, Soutullo et al. [38] numerically and experimentally studied the physical processes taken place in an evaporative wind tower. The model was evaluated in summer when the weather was hot and dry. Numerical and experimental results showed an average temperature drop of 6.5 °C and an average increase of relative humidity of 27%.

Issa and Chang [39] investigated the performance of a multi-stage wind tower for internal cooling. A mathematical model was used to evaluate the temperature, wind velocity, and relative humidity. Fig. 10 shows a three-stage wind tower system consisting of two interconnected venturi tubes. The wind tower was designed for the dry and hot climate of rural West Texas. Results demonstrated that the wind tower showed good performance regarding thermal comfort and was environmentally friendly.

Ji et al. [40] evaluated a wind tower system in China using EnergyPlus simulation. The wind towers (Fig. 11) were installed on top of an office building in Beijing. Results illustrated that the wind towers reduced the inside temperature by more than 2 °C. The wind towers were useful for almost 50% of engaged hours in a period when the basic air conditioning was needed. Also, using openable top-hung windows may improve the performance of the system in naturally ventilating the building. This system is energy efficient with potential positive impact on Beijing's economy.

Saadatian et al. [41] reviewed wind tower technologies. They showed that wind towers can be used as a sustainable cooling and ventilation method to compensate for lack of energy supply. They suggested use of wind towers as a green architectural feature in the future generation of buildings. They also suggested use of hybrid wind towers, a combination of mechanical cooling and natural ventilation systems.

Fig. 8. View of the cylindrical evaporative wind towers in Madrid [37].

Fig. 9. View of the wind catcher installed at the top of each tower shown in fig. 8 [37].

[1] Air infiltration development algorithm.

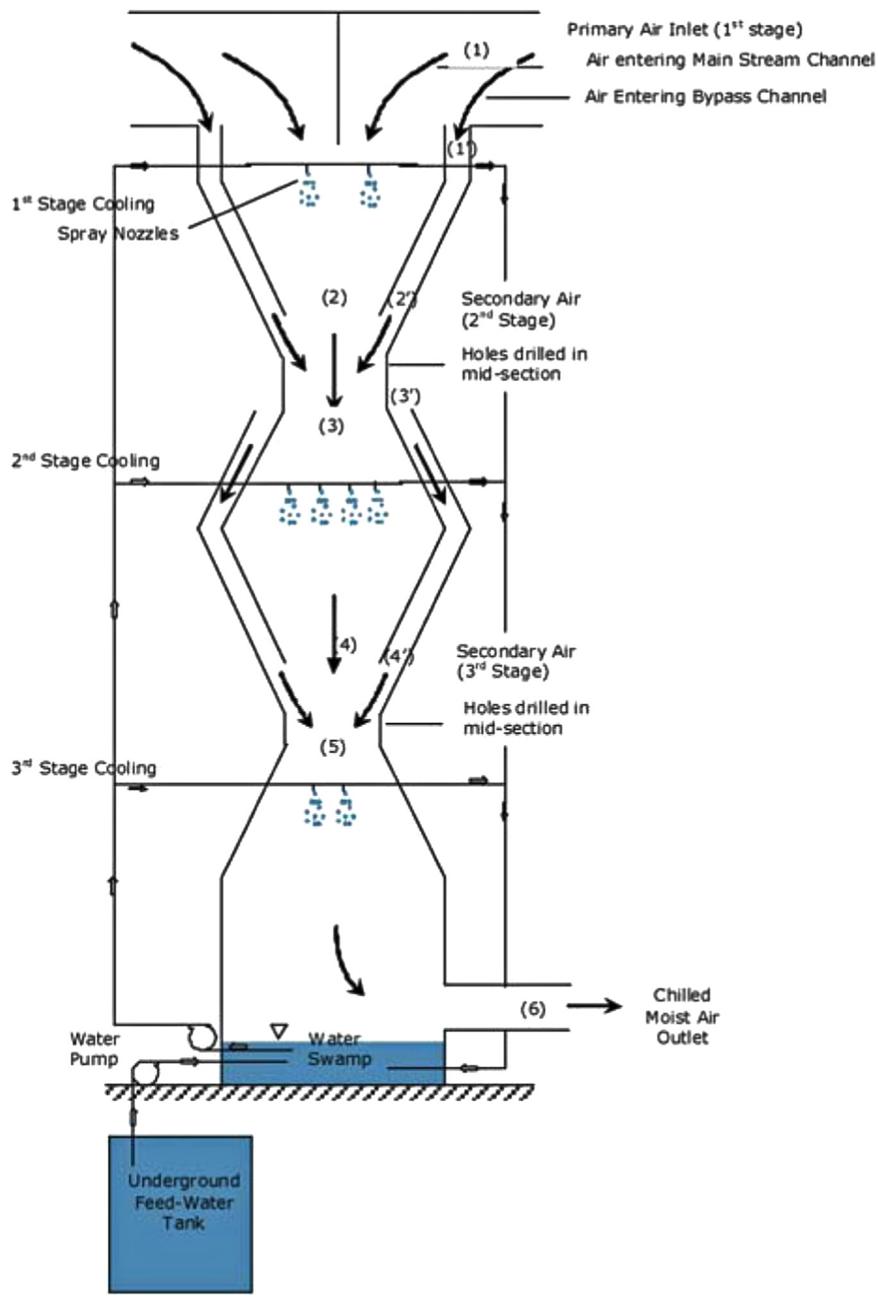

Fig. 10. Schematic representation of a three-stage wind tower system [39].

The first wind towers were built approximately 1200 years ago in the central and hot and arid regions of Iran [1,42–44]. Subsequently the technology spread to other regions of Iran, other Middle East countries, and Egypt. Fig. 12 illustrates some regions of Iran and other Middle East countries and also Egypt where conventional and traditional wind towers have been used [1]. Table 1 summarizes the important features of different types of traditional wind towers and their functionalities.

2. The proposed design

Conventional and traditional wind towers are categorized into four general types.

2.1. One-sided wind towers

The air openings of this type of wind towers are only open in the desired direction of the wind. There is no opening in other directions (Fig. 13).

The main goal of this paper is to explore a new design of wind towers. The modern wind tower can be used to create natural ventilation in buildings and thermal comfort for occupants in windy regions. The design, components, and performance of the newly designed wind tower are discussed.

2.2. Two-sided wind towers

From architectural point of view, these are simple and rather small wind towers. In comparison with the one-sided wind towers, the two-sided ones are more efficient for circulating airflow and have

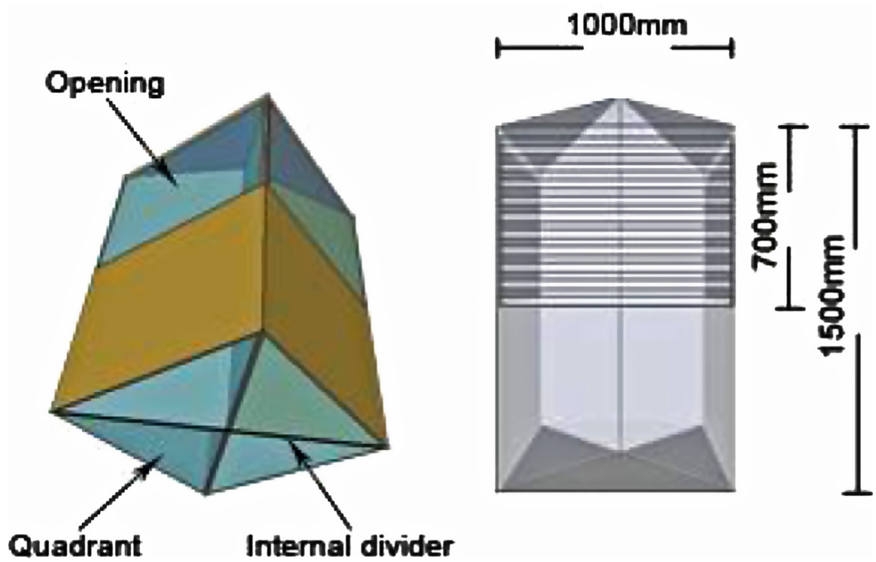

Fig. 11. View of the wind tower model with its dimensions [40].

Fig. 12. The regions in Iran and other Middle East countries as well as Egypt that use wind towers [1].

better performance (Fig. 14). This type of wind tower has two roles: blowing and sucking airflow into the building.

2.3. Four, six, eight-sided wind towers

Four, six, eight-sided wind towers are bigger and also usually taller than the previous two types. The height and the structure of each opening depend directly on the climate of the region the wind tower is used in (Fig. 15).

2.4. Cylindrical wind towers

Cylindrical wind towers are the most advanced type of wind towers with better performance than the other three types of wind towers previously described (Fig. 16).

Conventional and traditional wind towers have several limitations. Some of these limitations are:

- They allow small birds and insects to enter the building.
- The head of wind towers is fixed and cannot rotate in the direction of the maximum ambient air.
- A part of inlet air flow exit without circulating in the building.
- They do not have any application in regions with very low wind speed-high erosion against rain, wind and sun.
- Installation limitations and the number of wind towers that can be used in one building.

The proposed wind tower (Fig. 17) is designed to address the limitations of conventional and traditional wind towers and improve their performance. It is designed to be installed in the maximum wind speed direction of the region.

2.5. Design of the wind tower's components

Fig. 18 shows the details of the proposed wind tower. The proposed wind tower has an air opening in the direction of the maximum wind speed of the region. The cross section of the proposed

Table 1
Traditional wind towers used in various climatic zones of the Middle East [1,45].

	 Iran's arid zone	 Persian gulf	 Iraq	 Egypt	 Pakistan	 Afghanistan
Climatic zone	Hot and dry	Hot and humid	Hot and dry	Hot and dry	Hot and humid	Dry and semi hot
Air direction	North-east	Breeze	North-west	North-west	South-west	North
Shape of cross-section	Square/rectangle hexagon, octagon	Square	Rectangle	Rectangle	Square	Square
Average dimensions (m)	0.5×0.8 0.7×1.1	1×1	0.5×0.15 1.20×0.60	-	1×1	1×1
Height (m)	3–5	3–5	1.80–2.10	One story above roof	5 And above	1.5 From roof
Direction according to the airblow	Diagonal	Diagonal	Ordinary	Ordinary	Diagonal	Ordinary
Ceiling of the Wind tower	45° Slope	30° Slope	45° Slope	30° Slope	45° Slope	30° Slope
Ventilated area	Dining room and basement	Dinning plus others	Only basement	Dinning plus one room	All rooms	All rooms
Airblow	Multi-side	Multi-side	One, two-side	One-side	One-side	One-side
Evaporative cooling	Sometimes	Never	Sometimes	Sometimes	Never	Never

Fig. 13. A view of a one-sided wind tower in Ardakan city, Yazd province, Iran [1].

Fig. 14. Two-sided wind towers of the underground water reservoir in Dowlat Abad Garden, Yazd, Iran [1].

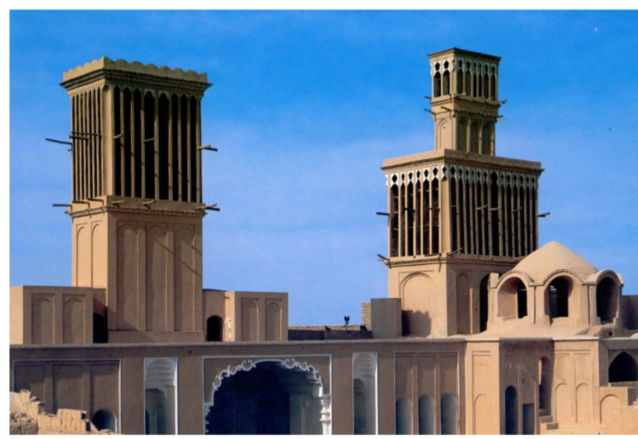

Fig. 15. A two story wind tower along with the dome (Kolah-farangi) of the Aghazadeh mansion in Abarkuh city, Yazd, Iran [1,46].

design can be a square, a rectangle, or a circle. The new design has several components described below:

1. *Head*: The head includes a moving column that can be opened and closed manually or electronically. The roof of the wind tower is inclined to prevent water from entering the building in the rainy or snowy days. The screen prevents small birds, insects and solid particles suspended in the air to enter the building.
2. *Column*: This part of the wind tower is fixed and can be installed on the rooftop using bolts. The interior surface of this column is equipped with a rail route to allow easy movement of the head of the wind tower. The column can be designed to accommodate the flat and inclined roofs.
3. *Windows*: Two windows are installed at the lower end of the column to control the airflow. They can be sliding windows and can be opened or closed manually or electronically.

The dimensions of the wind tower depend on several parameters including: (1) the mass flow rate required for air conditioning and thermal comfort, (2) the dimensions of the building and the material used in the building, (3) wind rate in the region, and (4) building security.

The proposed wind tower will be built from the same material as the building on which the wind tower will be installed. For example, for wooden buildings, wooden wind towers will be used. Weather condition of the region (e.g. humidity, rain, snow) will also be considered when selecting the proper material for building the wind towers. Using the material to reduce moisture on internal surface of wind tower can reduce the rate of relative humidity of inlet airflow. Transparent materials can also be used in the manufacturing of the wind tower to maximize use of natural light inside the building.

In conditions that proper wind speed is accessible from different directions at different times of the day/season, a proposed wind tower with a rotating head capable of setting itself to allow maximum input can be used. The cross section of the rotating wind tower has to be circular (Figs. 19 and 20).

A wind vane can be used to detect the direction of the wind. The wind tower's head can be rotated manually or electronically to face the direction of the maximum wind speed.

Fig. 16. A cylindrical wind tower in Yazd, Iran [1].

2.6. Applications

The proposed wind towers can be used for passive ventilation of residential buildings, closed arenas, and commercial and administrative buildings. The number of wind towers will depend on the ventilation rate and thermal comfort of the building. A combination of methods can be employed to obtain proper ventilation and thermal comfort. For example one can use: (1) a wind tower and one or more windows, (2) a wind tower and a solar chimney or air heater, (3) two wind towers in different directions.

The first method is best suited for small spaces like a single room or a hallway. The air enters through the wind tower, and after circulating inside the room, exits through one or more windows (Fig. 21).

In the second method, a solar chimney or an air heater is used in another part of the building (Fig. 22). In this design, the air enters through the wind tower and exits the building through doors, windows, and the solar chimney. In winter, when wind tower is not operating, the solar chimney can warm the room naturally.

When wind speed is low, air heater or solar chimney can create natural airflow in the building; the fresh air enters the building through wind tower as the warm air exits through the air heater or solar chimney.

In the third method, two (or more) wind towers are installed; one in the direction of the maximum wind speed and another in the opposite direction (Fig. 23). The coefficient of air pressure is positive ($C_p > 0$) for the wind tower which is in the direction of the maximum wind speed and negative ($C_p < 0$) for the other one. Based on the fundamental of fluid mechanics, due to the pressure difference or negative pressure gradient, the air is sucked out of the building through the wind tower that is in the opposite direction of the maximum wind speed. Based on the direction of the maximum wind speed, the proposed wind towers in the third method can be adjusted manually or electronically for best results.

If possible, ventilation rate can be improved by installing a dome or Kolah-farangi (Fig. 24). Use of Kolah-farangi facilitates the use of natural light inside the building too.

Kolah-farangi has several windows that can be opened or closed to let the air flow in and out of the building. When the windows are opened, due to the pressure difference or negative pressure gradient, the air is sucked out of the building through Kolah-farangi and wind tower (Fig. 24). Installing a Kolah-farangi

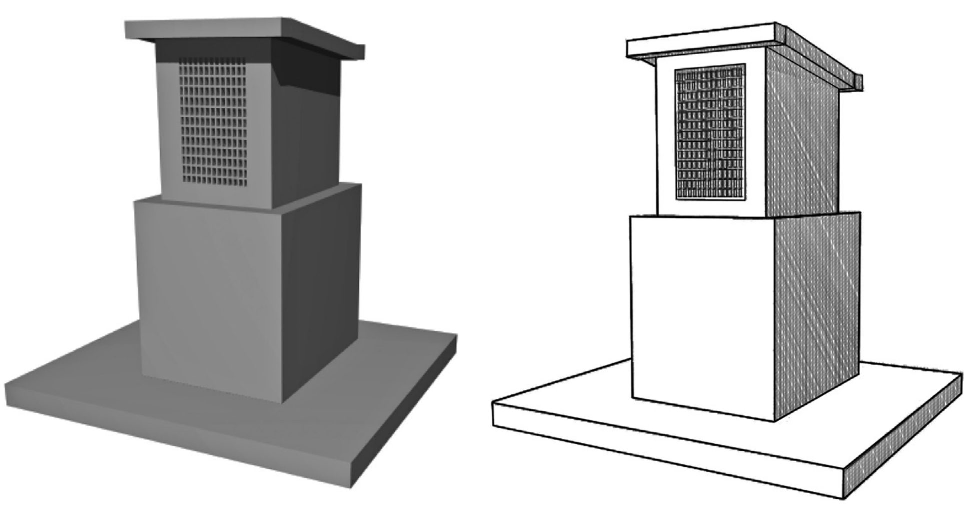

Fig. 17. A view of the proposed wind tower.

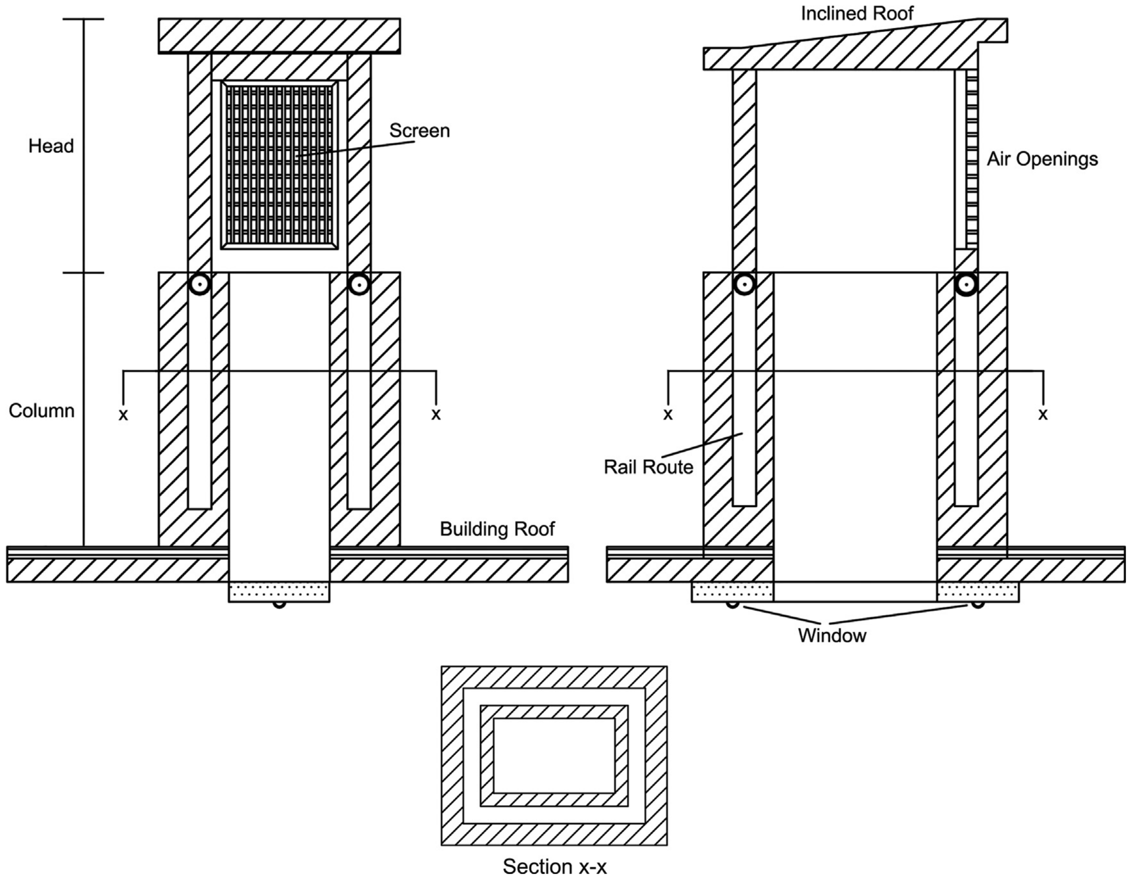

Fig. 18. Schematic representation of the proposed wind tower.

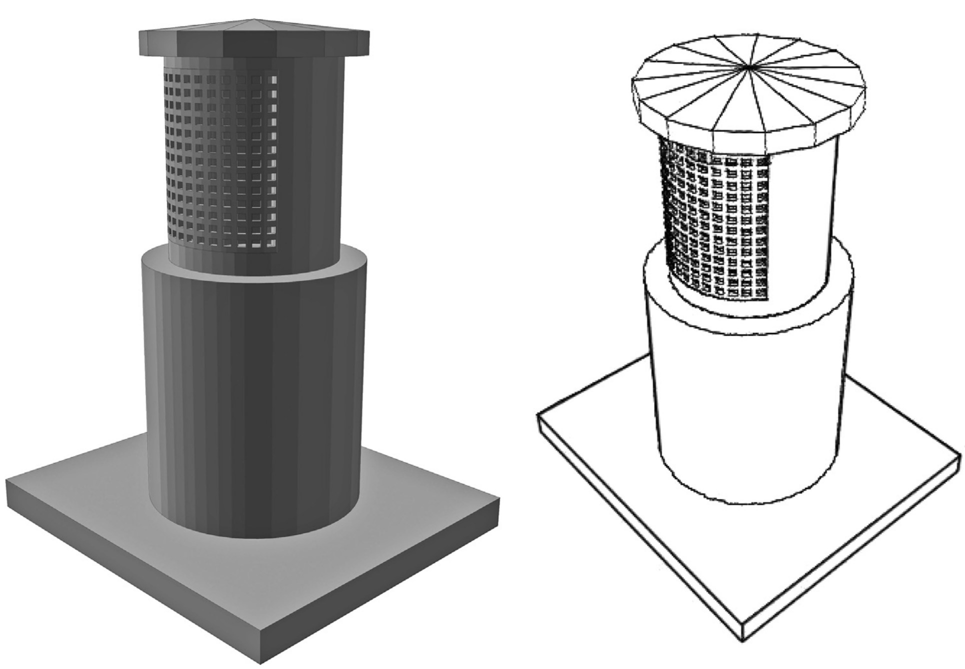

Fig. 19. The view of the proposed circular wind tower.

increases the ventilation rate and therefore, the thermal comfort of the residents.

Buildings sector accounts for more than 40% of the world's total energy consumption [41,47], and the energy used for ventilation, heating, and cooling systems accounts for more than 60% of the total energy consumption in buildings [41,48]. The modern wind towers decrease the electrical energy consumption of the buildings, especially during the peak times, between 20 and 80%. Also,

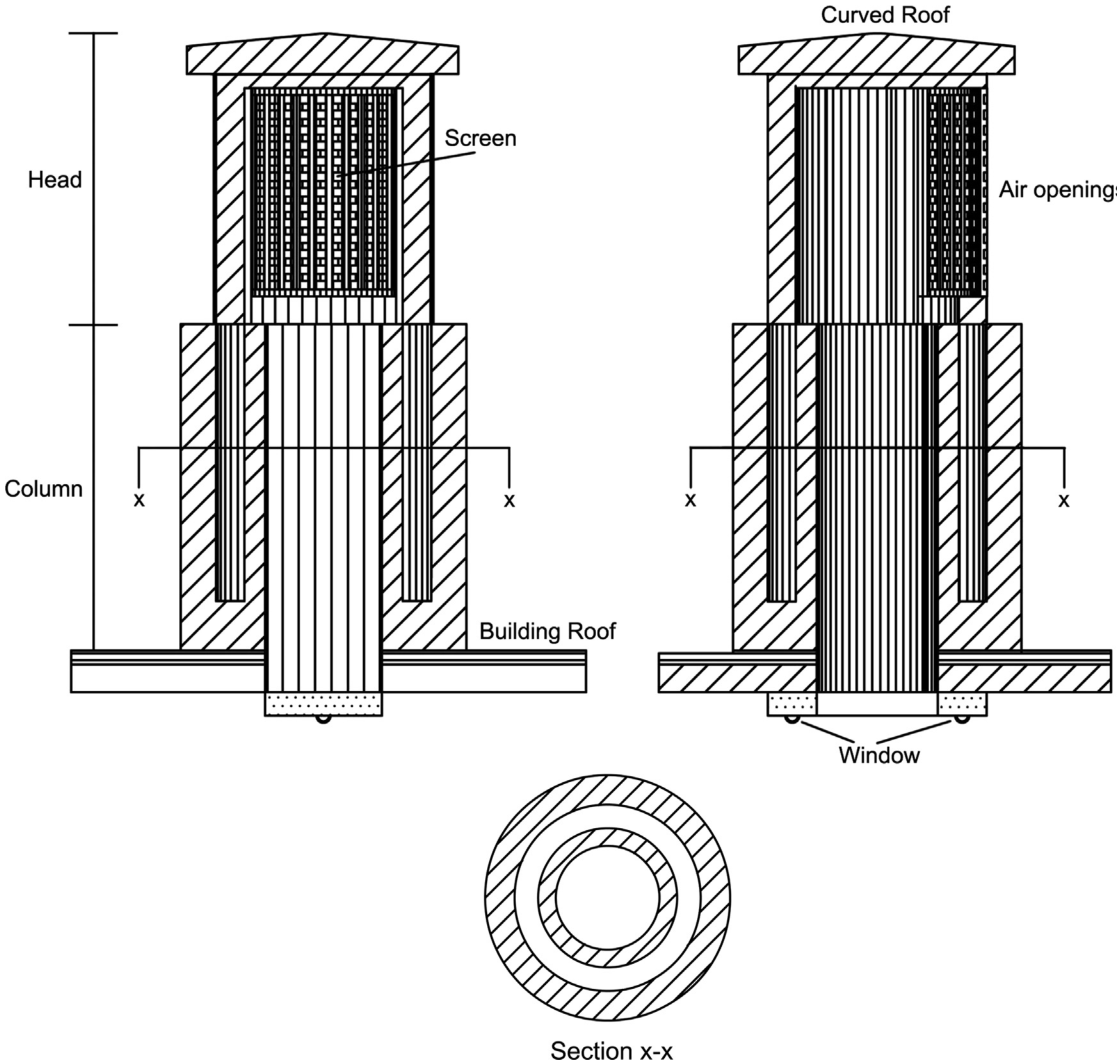

Fig. 20. Schematic representation of the proposed circular wind tower.

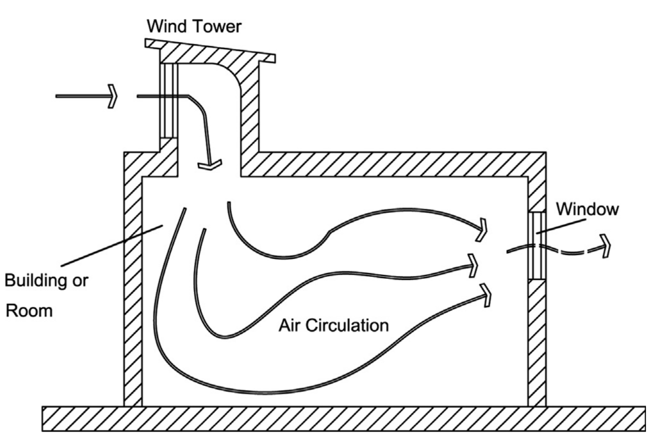

Fig. 21. Schematic representation of air movement in the first method.

the proposed design can help to reduce environmental pollution. Wind is a renewable energy. Using wind towers in windy regions can reduce the consumption of electrical energy in the residential and commercial buildings in these areas. For example, in most parts of Canada wind speed is suitable for using the new designs of wind towers (Fig. 25). Fig. 26 shows an example of using the proposed wind towers in a commercial building. The wind towers play two roles: air conditioning and lighting.

3. Summary and conclusion

This study proposes a new design of wind towers that improves the performance of wind towers in natural ventilation. The proposed wind towers have several important features, including:

- Easy installation;
- Low maintenance cost;
- The implementation of the design does not require sophisticated technology;
- The ability to rotate and set itself in the direction of the maximum wind speed;
- They are passive cooling systems and work without electrical energy;
- The wind towers can be combined with an air heater or solar chimney, or another wind tower in the opposite direction and Kolah-farangi to increase the ventilation rate of the building;
- Using transparent materials in manufacturing of the wind towers allows more natural light inside the building;
- Using channel, the air flows to any part of the building.

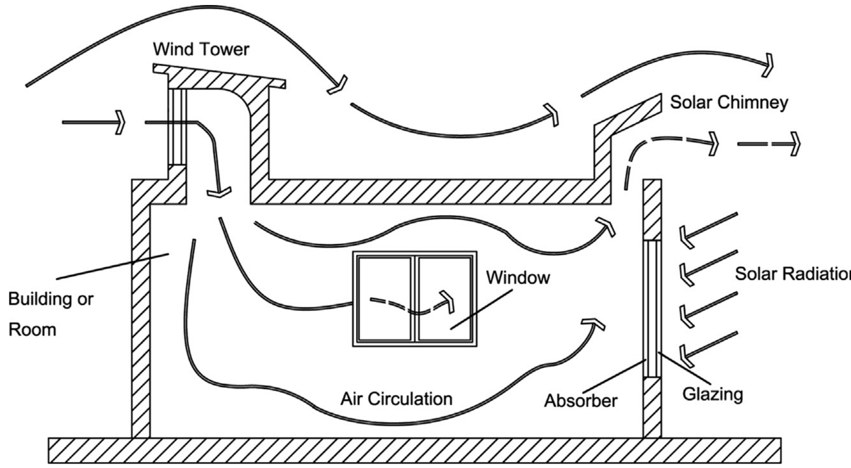

Fig. 22. Schematic representation of air movement in the second method.

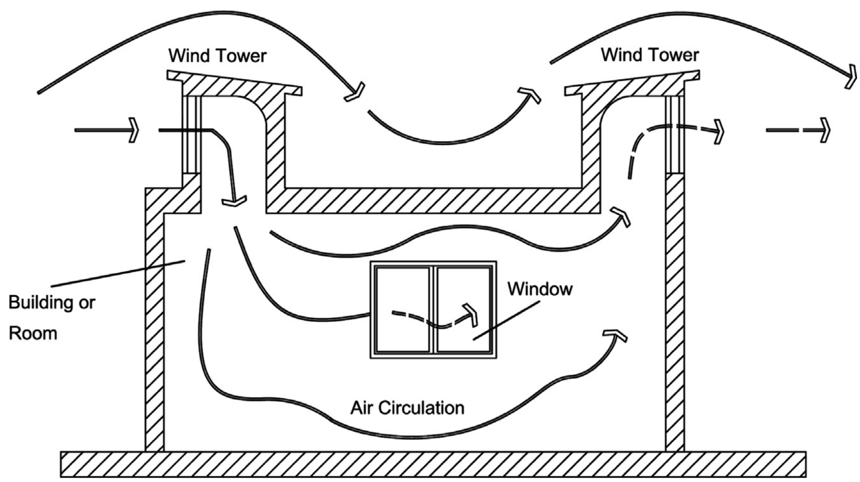

Fig. 23. Schematic representation of air movement in the third method.

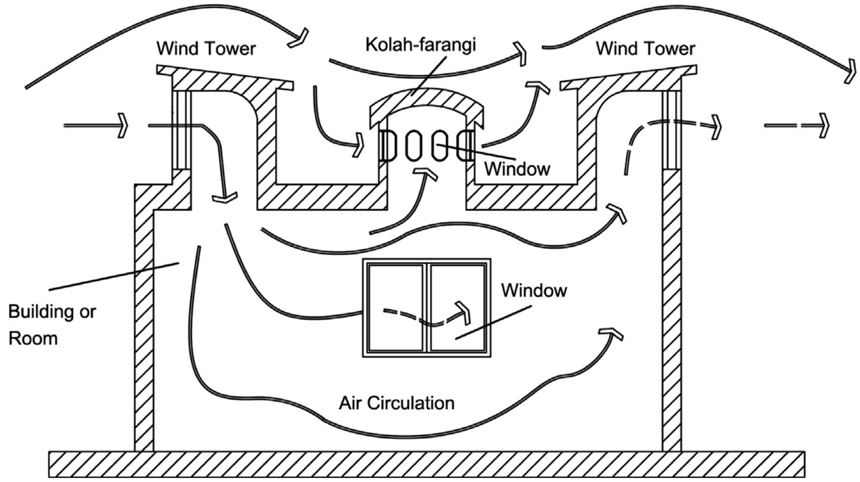

Fig. 24. Schematic representation of using a combination of two wind towers and a Kolah-farangi as the ventilation system of a building.

The previously designed wind towers and cool towers generally require evaporative cooling systems. The proposed design however, does not require such system. The proposed design of wind towers can help save energy. These wind towers can be used in most countries, especially in the developing countries. The use of these wind towers reduces greenhouse gas emission and air pollution.

4. Suggestions for further studies

Wind towers are passive cooling systems that can be used in the residential, commercial and administrative buildings and small covered arenas in hot and arid or hot and humid regions. Two new designs of wind towers that called 'wind tower with wetted columns' and 'wind tower with wetted surfaces' are useful for

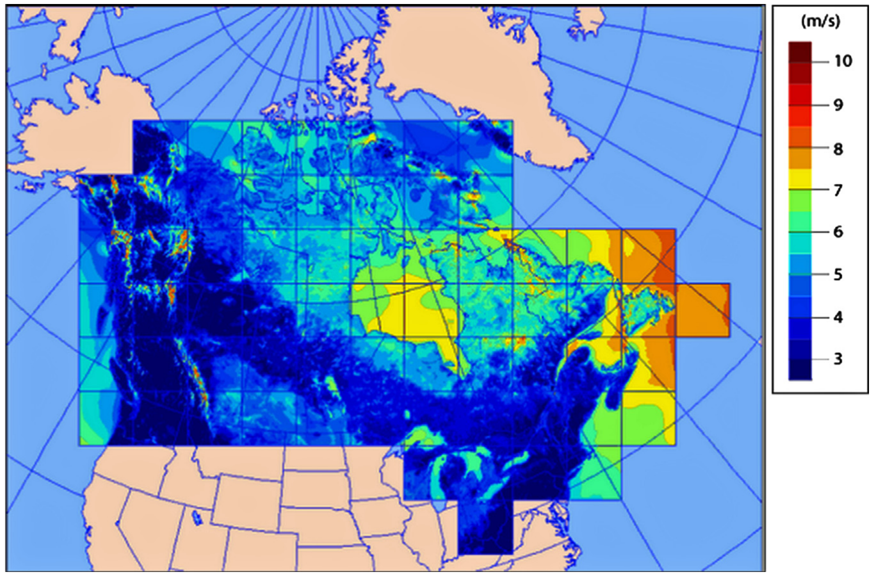

Fig. 25. Numerical simulation of the Mean Wind Speed at height of 30 m above ground during summer across Canada [49].

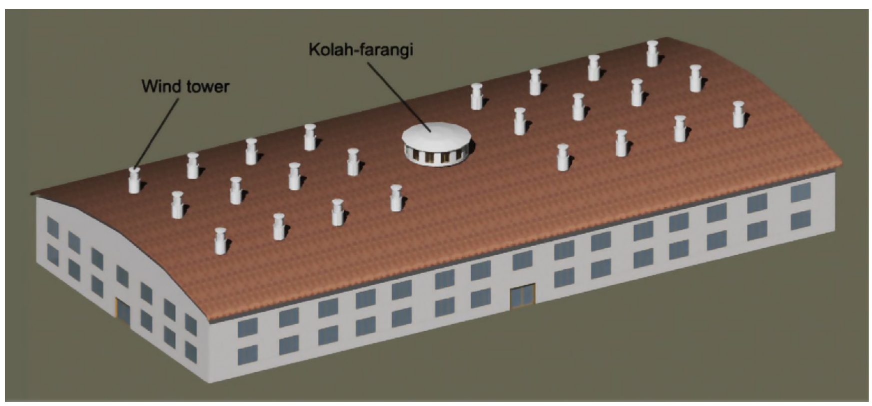

Fig. 26. Application of the proposed wind towers in a commercial building.

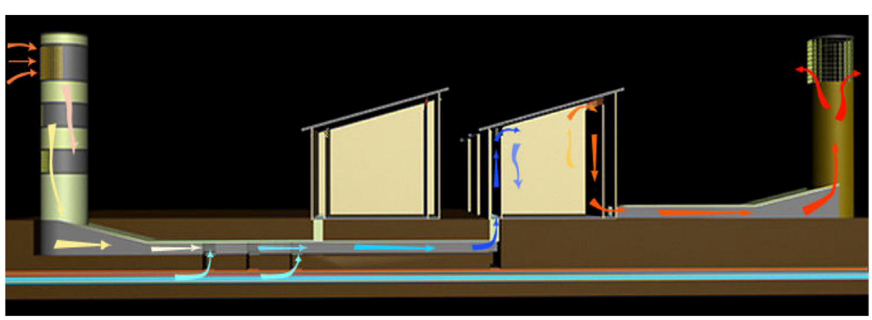

Fig. 27. Air moves in a building through wind tower, underground canal and solar chimney [50].

hot and arid regions [1]. More work is needed to develop such modern wind towers. Future studies should consider: (1) simulation and computational fluid dynamic (CFD) modeling for analyzing fluid and thermal, (2) experimental wind tunnel and smoke visualization approach for comparing the experimental and numerical results, (3) building and installing the newly designed wind towers on actual buildings to evaluate their practicality, and (4) analyzing the newly designed wind towers to improve their performance and examine their other potential applications.

Other alternatives and applications of wind towers, e.g. the use of a combined wind tower and subterranean canal (Fig. 27) should also be examined.

Finally, different countries have to use passive technologies like new designs of wind towers. These technologies can solve the world's energy crisis and global warming. Wind towers can be employed as a green architectural feature in the future building generation.

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