Adapting Buildings to meet the Energy Challenge

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Abstract

Heating Ventilation and Air Conditioning (HVAC) systems account for up to 60% of domestic buildings energy consumption [U.S Dept. of Energy, (2009)]. Natural ventilation offers the opportunity to eliminate the mechanical requirements of HVAC systems by using the natural driving forces of external wind and the buoyancy effect from internal heat dissipation. A wind tower was used in traditional architecture originating from the Middle East and captured air at a higher velocity and delivered it through cool sinks to the buildings occupants. Commercial Wind towers have been available in the United Kingdom (UK) for the last forty years; recent rising energy costs have seen their implementation into new and existing building increase. This research details the technological developments of the wind tower system in the UK and Qatar and discusses the barriers to implementation and the ongoing research in this field.

1 Introduction

The way in which energy is produced and consumed has a direct impact on global warming and pollutant emissions. The Kyoto Summit secured a commitment from the majority of countries to establish a global program for CO_2 emissions reduction. The major sectors producing CO_2 in most countries are the power generation sector, the transportation sector and the building sector. According to the World Business Council for Sustainable Development (WBCSD), buildings account for up to 40% of the worlds energy use [WBSCD, (2009)]. Hence, the building sector accounts for a large proportional of primary energy consumption in most countries.

The rapid development of Middle Eastern countries such as Dubai and Qatar has placed them at the top of the global carbon footprint with Qatar producing 55.4 tons of carbon per person, the highest global carbon footprint. In Qatar and other hot climate countries, air conditioning is a major contributor to CO2 emissions. Heating Ventilation and Air Conditioning (HVAC) systems account for up to 60% of domestic buildings energy consumption [U.S Dept. of Energy, (2009)].

Clearly any technology which reduces the HVAC consumption will have a dramatic effect on the overall energy performance of the building. Natural ventilation offers the opportunity to eliminate the mechanical requirements of HVAC systems by using the natural driving forces of external wind and the buoyancy effect from internal heat dissipation. This can be achieved through careful placement of windows and doors and solar gain placement at the design stage [Lomas, (2007)].

Another device which incorporates both wind driven and buoyancy driven forces is the wind tower. The wind tower was used in traditional architecture originating from the Middle East and captured air at a higher velocity and delivered it through cool sinks to the buildings occupants. Commercial Wind towers have been available in the United Kingdom (UK) for the last forty years; recent rising energy costs have seen their implementation into new and existing building increase.

This research details the technological developments of the wind tower system in the UK and discusses the barriers to implementation and the ongoing research in this field. In 2010 the authors formed an international research group to reduce energy consumption in the domestic sector by integrating novel low energy cooling devices in Qatari residences [Ghani and Hughes, (2010)]. Presented here is a detailed insight into the future of advancement of the wind tower system and highlights the vast scope for HVAC savings across both commercial and residential sectors.

2 Previous related work

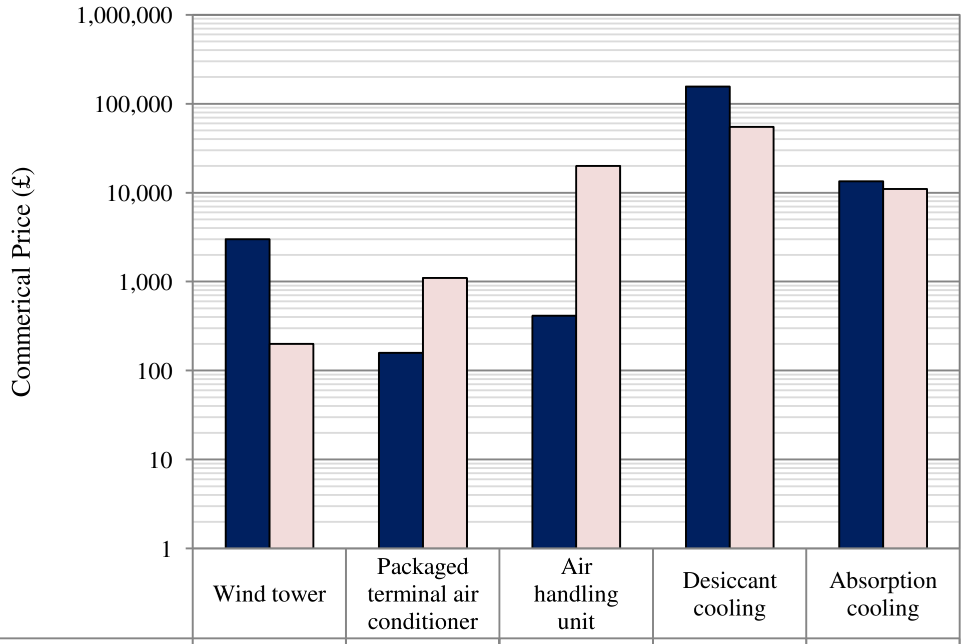
In contemporary wind towers, the principles of passive stack and wind effect are researched in the design of the stack. Hughes and Ghani (2008) carried out work on determining the overall feasibility of sustainable development by decreasing the running expenses of buildings. A passive ventilation device known as windvent was used in the computational fluid dynamics based numerical analysis of wind velocities ranging between 1-5 m/s. The investigation confirmed that even at low wind velocities, the windvent was able to provide the desired rate of fresh air supply into the building, hence concluding that the device is suitable for sustainable ventilation systems.

Further study by Hughes and Ghani (2008) included the performance analysis of the Windvent device by shifting the external angle of the louvre between 0 and 45 degrees in order to determine the point of highest efficiency in terms of pressure and velocity. The work incorporated a CFD based numerical code with the inlet wind velocity of 4.5 m/s. The results confirmed that an angle of 35 degrees was required for optimized Windvent louvre performance for the input parameters. The study also revealed that there is an increase in velocity of a given space for a reduction in trailing edge stall.

Hughes and Ghani (2009) studied the consequences on the indoor environment with the usage of windvent dampers which work on the principle of difference in pressure gradient. The investigation was based on highlighting the optimum operating conditions for this passive ventilation device. Computational fluid dynamics was used for numerical analysis for damper angle range between 0 and 90 degrees. The results displayed that the best operation occurs between the range of 45-55 degrees for mean U.K. wind velocities.

Hughes and Ghani (2011) further calculated the capability of a passive windcatcher device to achieve the required delivery rates of fresh air intake. The numerical model was based on CFD code and included a standard passive stack device along with simulated low-voltage axial fan. The results established that a low-power fan is mandatory to provide the British Standard requirements of 20Pa for the minimum ventilation rates. The location of the fan was found to be top position by doing the CFD analysis. The computational work was compared with experimental testing for the confirmation of the investigation.

Hughes *et al.* (2011) carried out a comprehensive review of sustainable heating, ventilation and air-conditioning technologies in modern day dwellings. The study focused on comparing various cooling techniques used to condition the air in buildings ranging from natural ventilation to the advanced cyclic loops involving desiccant cooling processes based on their energy consumption and relative expenditure requirements (Figure 1). The work revealed that modern wind towers require minimum external power consumption for its method of operation respectively.



	Wind tower	Packaged terminal air conditioner	Air handling unit	Desiccant cooling	Absorption cooling
Price (£)	3,000	158	414	155,767	13,380
Power Consumption (W)	200	1,100	20,000	55,000	11,000

Figure 1 Comparison of power consumption and financial cost on the log scale (Hughes et al., 2011)

Hughes et al. (2012) further highlighted the different cooling techniques integrated with wind tower systems to improve its thermal performance. Key parameters including the ventilation rates and temperature were evaluated in order to determine the viability of implementing the devices for their respective use. The results showed that the highest temperature reductions were achieved from incorporating evaporative cooling techniques into the wind tower such as wetted column (clay conduits) and wetted surface (cooling pads). The temperature reduction are found to be in the range of 12 –15 K. The study also highlighted the effect of the addition of the cooling devices inside the device which reduces the air flow rates and reduces the overall efficiency of the wind tower.

Calautit et al. (2012) re-designed a traditional row house to be adapted to the hot and arid climate of the Middle East. The vernacular design features include a number of cooling devices such as an open courtyard, wind towers and heat-storing building materials to reduce overheating during the summer months. The study investigated the performance of a wind tower incorporated into the row house to replace the traditional ventilation devices using computational fluid dynamics (CFD) modelling. The study highlighted the ways in which the resulting natural air flows in the house operated using the ANSYS Fluent CFD tool to develop a numerical model of an optimized wind tower system. Achieved ventilation rates and temperature distribution inside the structure were investigated. The results demonstrated that the proposed wind tower configuration was able to increase the average indoor air velocity by 63%. An improved airflow distribution is observed inside the modified row housing model.

3 Technological development of wind towers

Wind towers have been in existence in various forms for centuries as a non mechanical means of providing indoor ventilation, energy prices and climate change agendas have refocused engineers and researchers on the low carbon credentials of modern equivalents. Conventional and modern wind towers architecture can be integrated into the designs of new buildings, to provide thermal comfort without the use of electrical energy. Figure 2 illustrates ventilation through a four-sided wind tower device. The wind tower is divided by partitions to create different shafts. One of the shafts functions as inlet to supply the wind and the other shafts works as outlet to extract the warm and stale air out of the living space. The temperature difference between the micro and macro climate creates different pressures and result in air currents (Cheuk-Ming and Hughes, 2011).

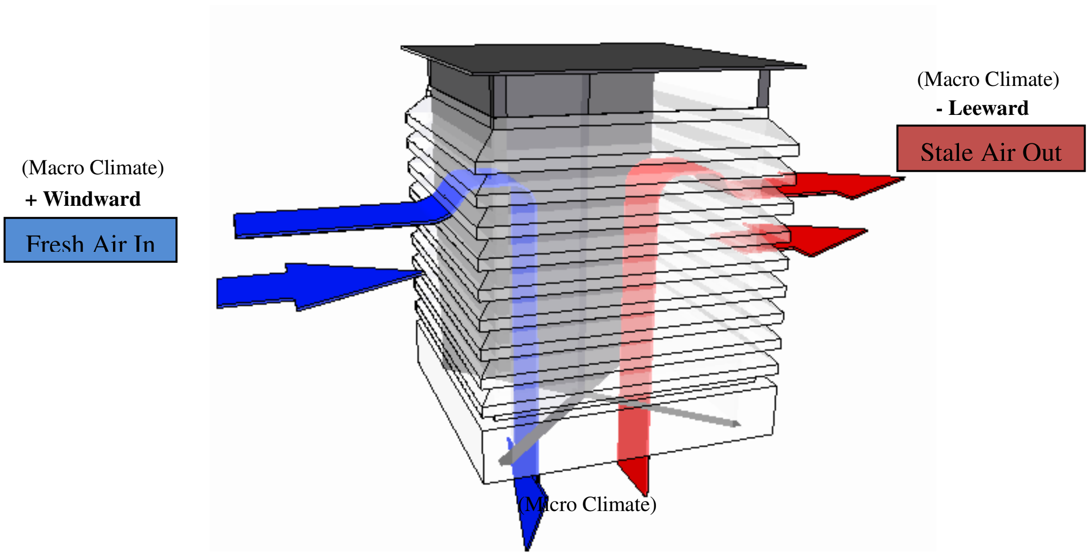


Figure 2 A flow diagram representing ventilation through a multi-direction wind tower device

The design of wind tower system has been traditionally based on the topography, climatic conditions, personal experience of architects, social position of the occupants and variation in height, cross-section of air channel, number of openings, size and positioning of openings, form, construction materials, and placement of the tower with respect to the building. The efficiency of wind towers is reliant upon creating the maximum pressure difference between the air inlet openings and exhaust of the passive device (Elizalde and Mumovic, 2008). The air movement around the structure will determine the size, location and form of the wind tower and its openings, so as to maximise the pressure differential. Figure 3 illustrates different configurations of traditional wind tower systems in Yazd, Iran.

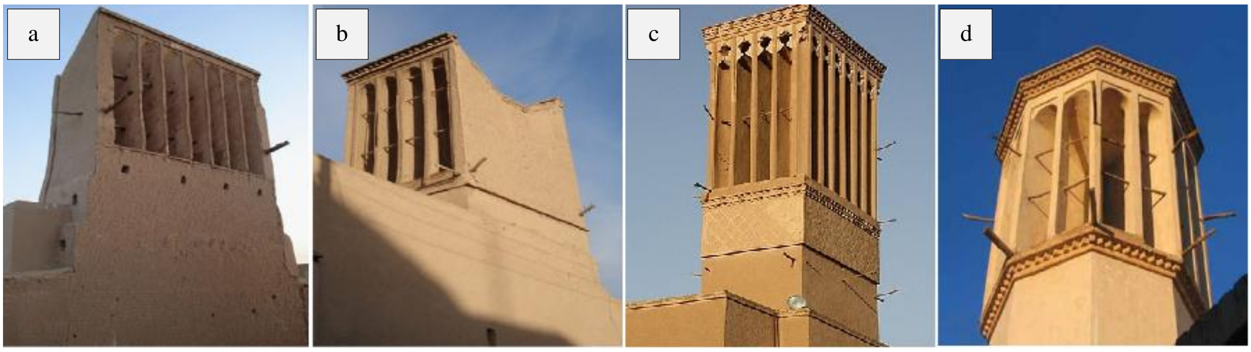


Figure 3 Traditional wind towers with different number of openings (a) one-sided, (b) two-sided, (c) four-sided, (d) octahedral (Hughes et al., 2012)

Naturally ventilated buildings do not require additional energy to move the airflow within a structure. However, the cooling capabilities of conventional wind towers which depend on the structure design itself are limited. Therefore it is essential to cool the air in order to improve the thermal comfort of its occupants (Hughes et al., 2012). Figure 4 shows a concept design of a wind tower system integrated with cooling devices. Evaporative cooling pads sit at the top of a wind tower with pump re-circulating water over them. Hot air is passed through these pads and cooled by the water evaporation. Cool moist air is denser than ambient air and sinks down the tower and into the enclosed space. In order for the cool air to flow in, hot air must be released. Solar chimney is located directly opposite the wind tower to establish effective cross-flow ventilation inside the structure and exhaust the stored hot air using buoyancy-driven forces.

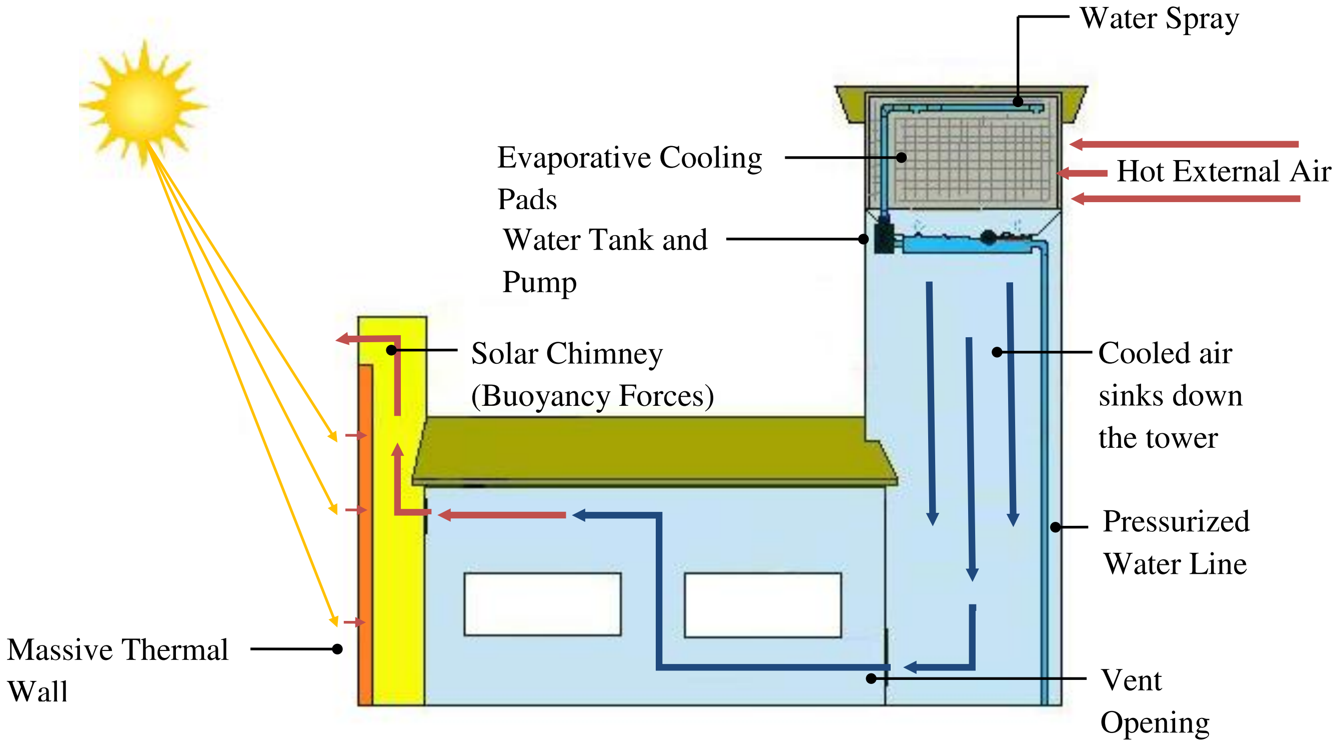


Figure 4 Concept design of a passive wind tower integrated with different cooling devices (Hughes et al., 2012)

Modern architects and engineers integrated the principles of traditional wind tower with modern technology as helpful devices to increase the quality and efficiency of the supplied air. Modern wind towers provide natural ventilation and light to any space in a building. Commercial wind tower systems as a top-down roof mounted, multi directional device used for naturally ventilating buildings further enhances the portability of the device in comparison to its traditional counterpart (Hughes and Ghani, 2008). Modern wind towers are usually compact and smaller in size compared to the traditional wind towers as shown in Figure 5.

The device extends out from the top of a structure to catch the wind at roof level and channels fresh air through a series of louvers into the enclosed space under the action of air pressure, and simultaneously the negative *pressure* extracts stale air out of the room. Unlike the traditional wind tower systems, air is supplied to the enclosed space through the diffusers located at ceiling level. Hence, more free space is available for ventilation on the ceiling than on the corresponding floor of equal area.

Figure 5 Modern roof mounted circular and square wind tower systems (Hughes et al., 2012)

In order to augment the airflow from the current practices involving wind towers, extensive research has recommended that a passive-assisted natural ventilation system may be employed to provide continuous supply of fresh air without affecting the energy requirements of the wind tower (Hughes and Ghani, 2011). The hybrid system incorporates a low-powered fan installed inside the wind tower with the fan functioning when required to assist the flow of air between the building exterior and interior via the ventilator. The solar driven fan also functions as an exhaust device for extracting stale air out of the building. It provides a constant supply of ventilation air, even when there is no wind. Zero energy solution is guaranteed, allowing the building natural ventilation design to be optimized and ensuring a low energy natural ventilation strategy to be maintained. Figure 6 shows a windvent device incorporating solar powered internal fans. The solar fan can be used to overcome excessive heat gains and boost the air movement through the wind tower when extra ventilation is required.

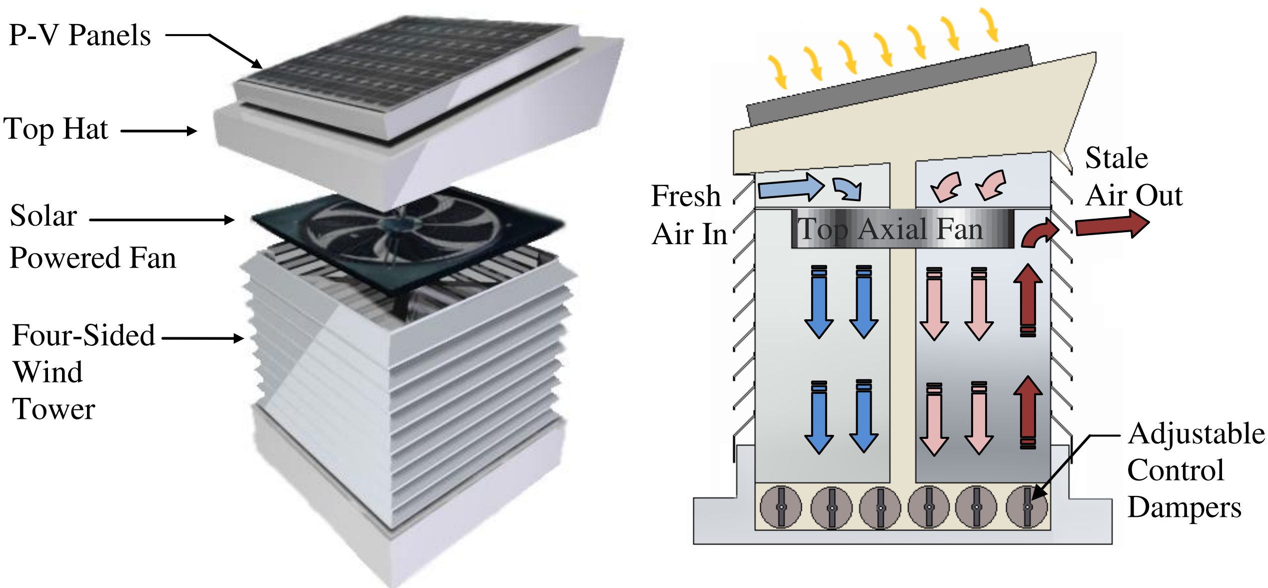


Figure 6 Schematic of a wind tower system integrated with a solar powered fan (Hughes et al., 2012)

Furthermore, by integrating heat transfer devices within the actual wind tower systems, the overall energy consumption levels can be reduced. The cyclic process operates by inducing warm air is passed through cooling tubes, which allows for cooling of the air stream. Heat transfer devices are installed inside the passive terminal of the wind tower unit, highlighting the potential to achieve minimal restriction in the external air flow stream while ensuring maximum contact time, thus optimsing the cooling duty of the device (Figure 7).

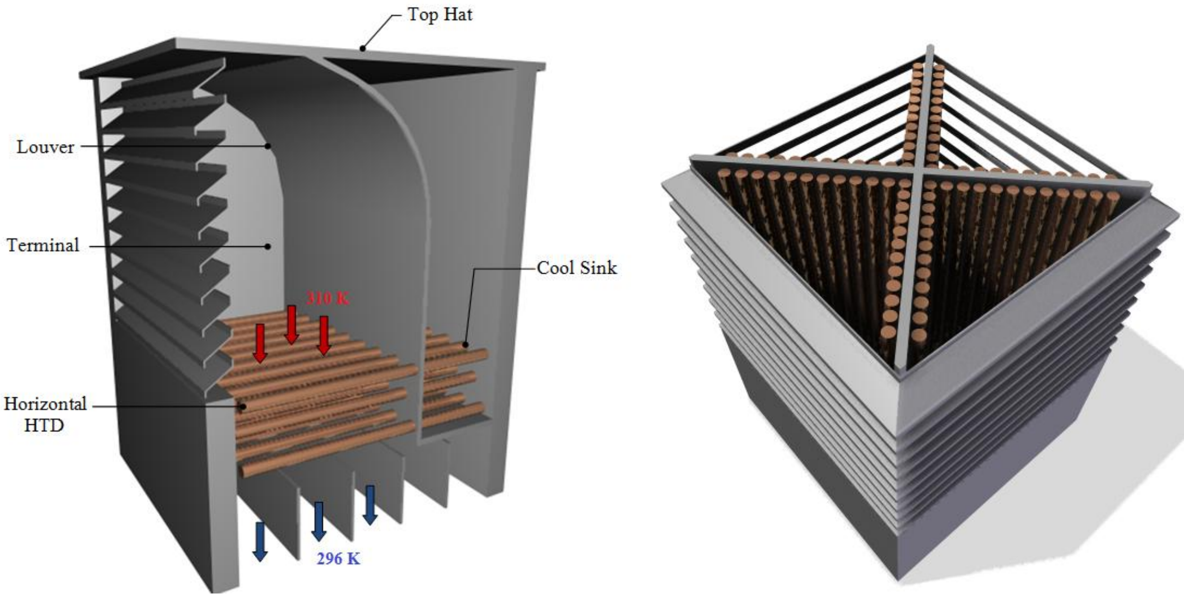


Figure 7 Schematic of the circular wind tower model with the proposed horizontal and vertical heat pipe configurations.

4 Results and Discussion

The preliminary studies comprised of a heat exchanger system integrated within the control volume of a modern 4x4 wind tower device in order to depict the thermal performance of the system. A horizontal profile plane constructed at immediate downstream of the horizontal heat pipes (using pure water as the working fluid) control volume within the wind tower structure to analyse the air temperature differential confirmed the performance of the transfer pattern of heat as an air temperature reduction of 14K was obtained (Figure 8) from the source temperature of 315K respectively.

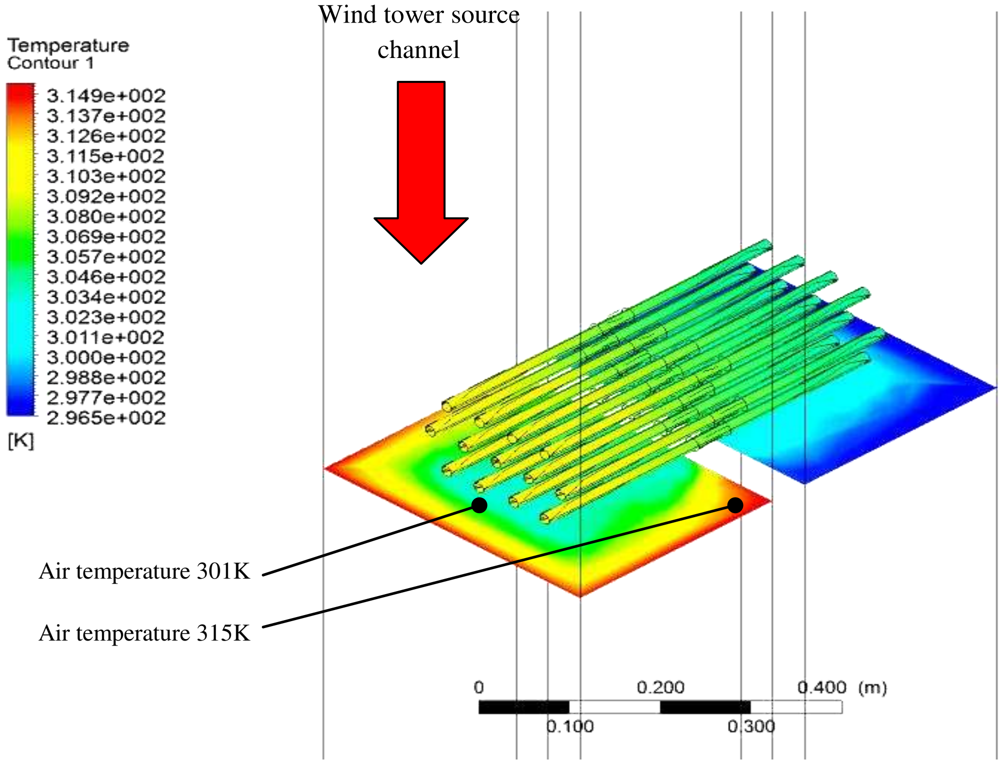


Figure 8 Cross-section of the wind tower source channel temperature differential

Figure 9 illustrates the velocity streamlines of a middle plane in the test room model integrated with a wind tower device. From the diagram it is seen that the air flow is entering from the right side of the enclosure (velocity inlet). The airflow splits at the wind ward side of the structure with the air entering the wind tower openings and the remaining flow shearing across the structure and exiting to right side of the enclosure (pressure outlet). Air-short circuiting is observed, some of the air flow exits the leeward quadrant without entering the microclimate

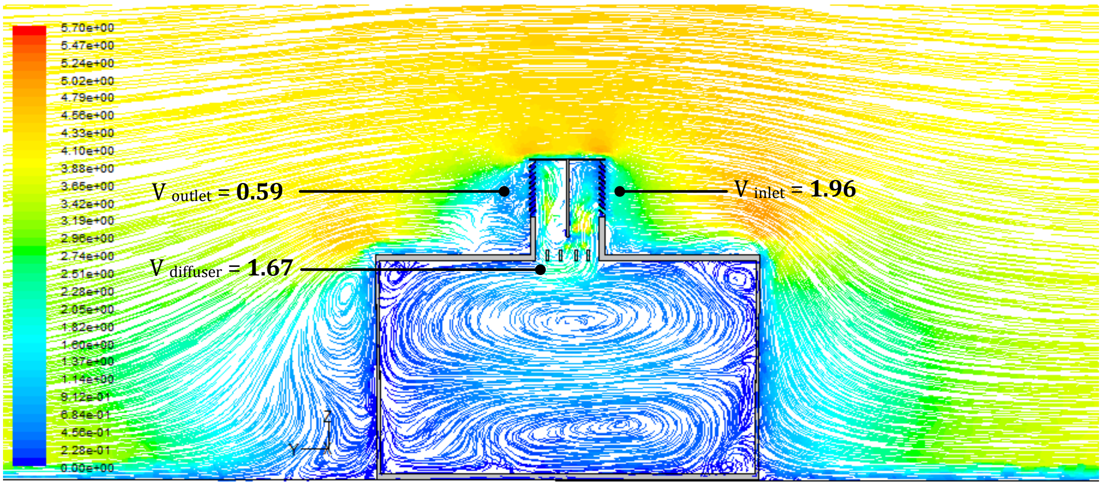


Figure 9 Velocity streamlines of a cross sectional plane in the test room with an inlet velocity of 4 m/s (Modern wind tower)

Figure 10 compares the calculated results for the achieved air supply rates for the different wind tower configurations. It is observed that the benchmark and vertical arrangement model barely supplied the minimum rate at external wind speed of 1 m/s. It was found that the one-sided wind tower incorporated with the horizontal heat pipe arrangement delivered the most amount of air supply into the room at zero air incidence angles. However, the ventilation performance of the device is significantly reduced as the incident wind blows away from the direction of its design range.

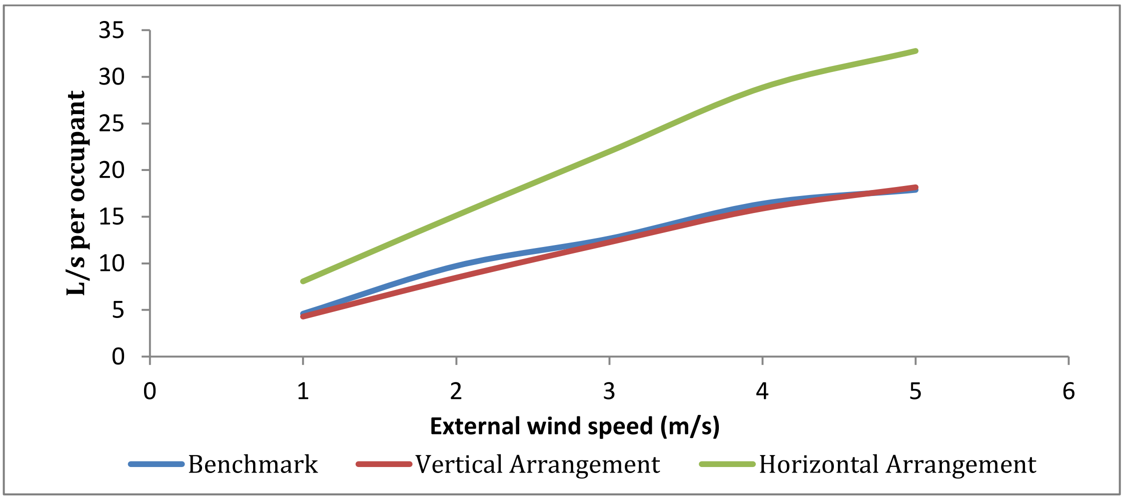


Figure 10 Comparison of the air supply rates of the different configurations at different wind speeds.

Figure 11 shows a comparison between the thermal performances of traditional evaporative cooling and heat transfer devices inside a test channel (controlled test). From the illustration (Figure 11a) it is seen that there is a sufficient decrease in air temperature. This is due to the absorption of heat in the evaporative cooling. The water is sprayed at the top section of the channel (h = 9 m), temperature decrease very fast and slightly increases due to the walls of the wind tower. From Figure 11b, the temperature reduction is greater on the left side of the channel where the air velocity is significantly lower which increases the contact time between the heat transfer devices and air stream.

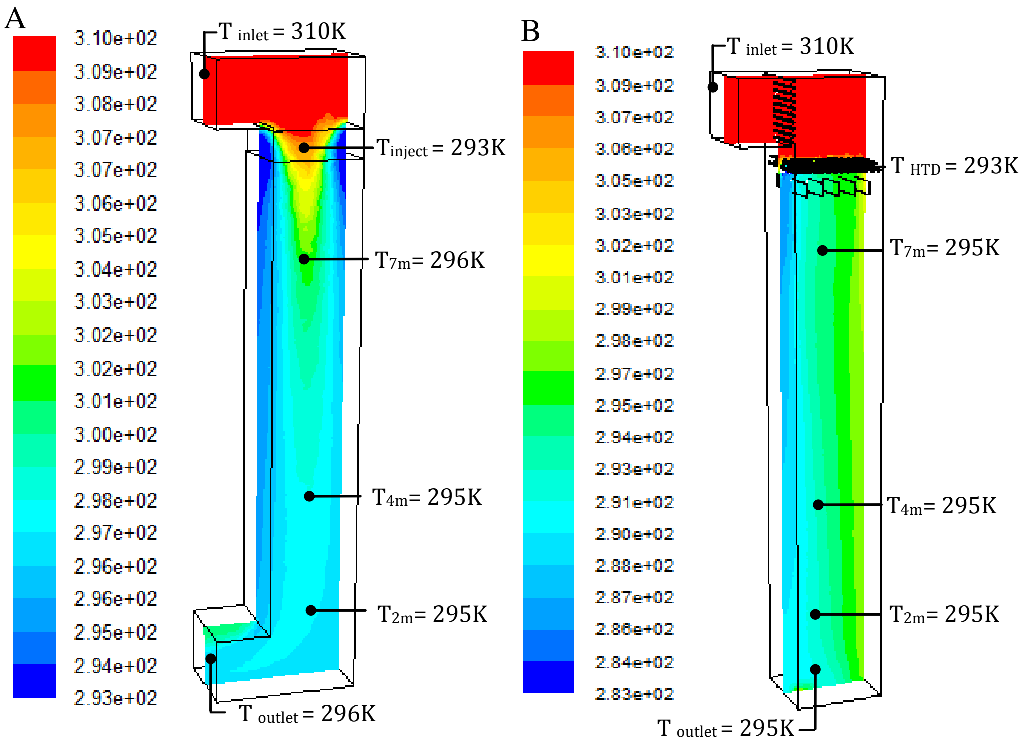


Figure 11 Temperature contour lines of a cross sectional plane in the test channel (controlled test): (a) evaporative cooling (b) heat transfer devices

Figure 12 compares the thermal performance of a wind tower system incorporated with evaporative cooling and heat transfer devices.

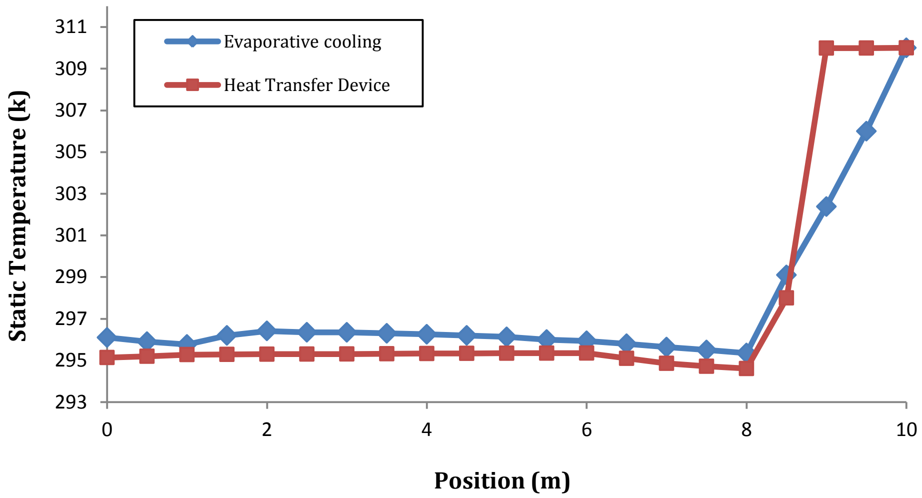


Figure 12 Comparison of the variation of temperature of airflow from entering to exiting.

Figure 13 illustrates temperature distribution inside a test room integrated with a modern wind tower device. It is observed that the temperature is reduced as it approaches the cross-dividers with the vertical HTD arrangement. The average temperatures inside the microclimate are 296.2 K and 295.8 K with the macro climate temperature set at 310 K.

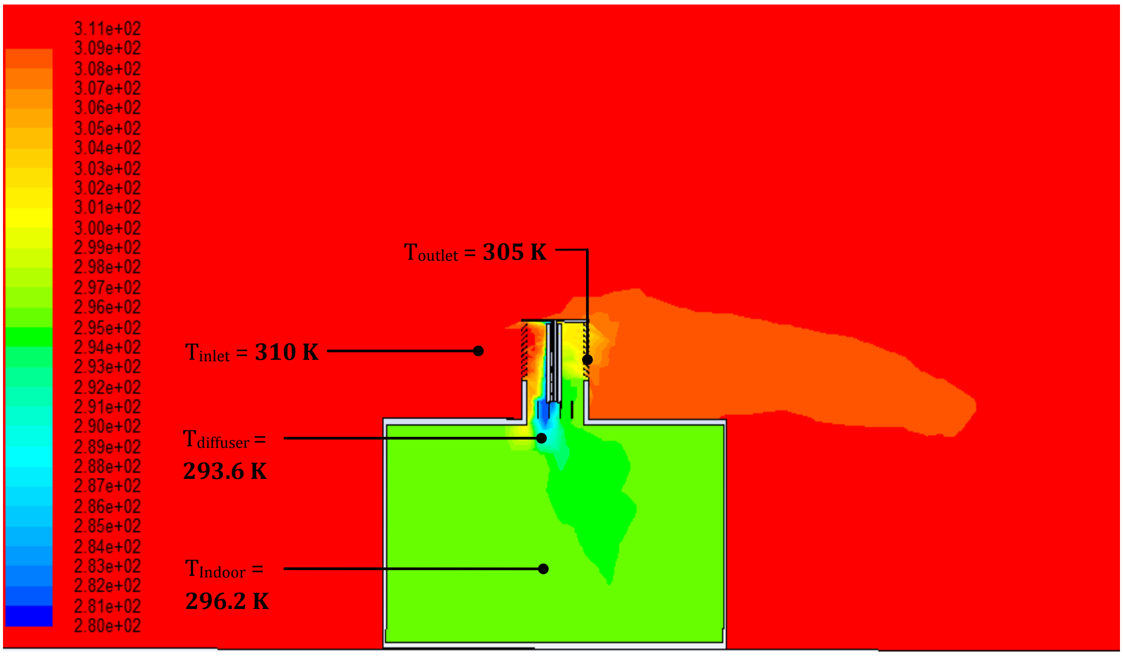


Figure 13 Temperature distributions inside the test room with a modern wind tower incorporating the vertical HTD arrangement

Figure 14 illustrates temperature distribution inside the test room integrated with a one-sided wind tower device with horizontal HTD arrangement. Air temperature reduction is observed inside the microclimate, average temperature of 295.8 is obtained inside the models with the outdoor temperatures set at 310K.

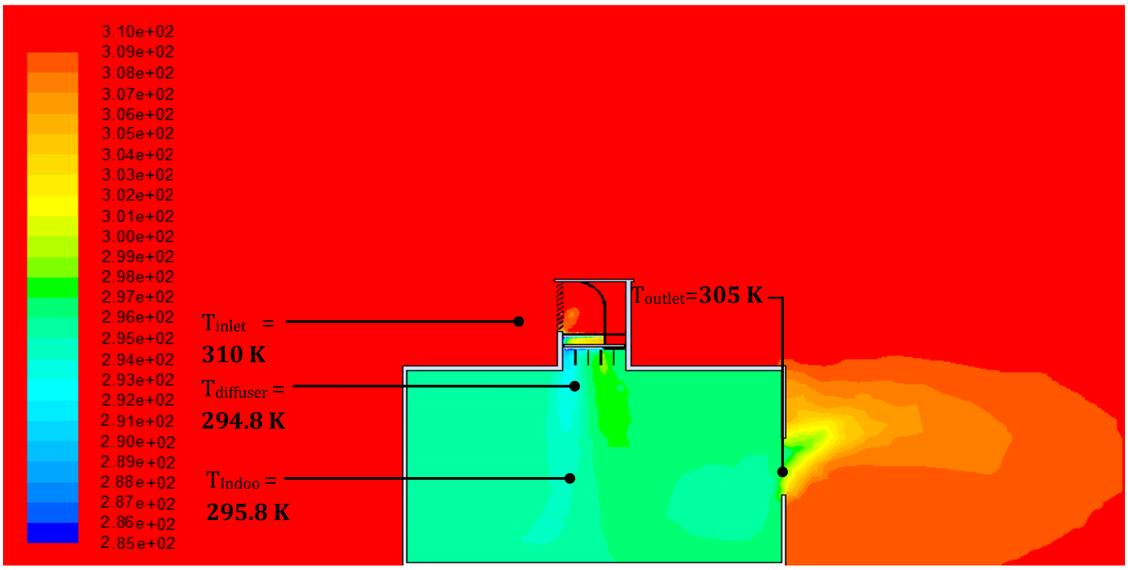


Figure 14 Temperature distributions inside the test room with a modern wind tower incorporating the horizontal HTD arrangement

5 Future work

Currently the developed system is undergoing field trials in the United Arab Emirates. There are two test facilities, one with a conventional wind tower as a benchmark and a second with the cooling integrated system for comparison. The trials will continue throughout the summer to experience the maximum temperature swing and thus validate the findings of the study. To protect the Intellectual Property a UK patent application GB1321709.6 has been filed. Dissemination of the final findings of this study are anticipated for early 2015 and will be disseminated thereafter.

6 Conclusions

The integration of wind towers as a low energy alternative to HVAC systems has vast potential and presented here are the technological advancements to date. The introduction of a low energy cooling towers into Qatar will provide a milestone in the development of advanced natural ventilation technologies. So far this project has attracted global attention, the authors are working closely with the Zayed Future Energy Prize, QNRF and IP Group to bring zero energy cooling to the Middle East.

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