The University of
Nottingham

UNITED KINGDOM · CHINA · MALAYSIA

Calautit, John Kaiser and Aquino, Angelo I. and Shahzad, Sally and Nasir, Diana S.N.M. and Hughes, Ben Richard (2017) Thermal comfort and indoor air quality analysis of a low-energy cooling windcatcher. Energy Procedia, 105 . 2865 - 2870. ISSN 1876-6102

Access from the University of Nottingham repository:
http://eprints.nottingham.ac.uk/44932/1/1-s2.0-S1876610217306884-main.pdf

Copyright and reuse:

A note on versions:

The 8th International Conference on Applied Energy – ICAE2016

Thermal comfort and indoor air quality analysis of a low-energy cooling windcatcher

John Kaiser Calautit[a],*, Angelo I. Aquino[a], Sally Shahzad[b], Diana SNM Nasir[a], Ben Richard Hughes[a]

[a]Department of Mechanical Engineering, University of Sheffield, Sheffield S10 2TN, United Kingdom
[b]School of Engineering and Technology, University of Derby, Derby, DE22 3AW, UK

Abstract

The aim of this work was to investigate the performance of a roof-mounted cooling windcatcher integrated with heat pipes using Computational Fluid Dynamics (CFD) and field test analysis. The windcatcher model was incorporated to a 5m x 5m x3 m test room model. The study employed the CFD code FLUENT 15 with the standard k-ε model to conduct the steady-state RANS simulation. The numerical model provided detailed analysis of the airflow and temperature distribution inside the test room. The CO_2 concentration analysis showed that the system was capable of delivering fresh air inside the space and lowering the CO_2 levels. The thermal comfort was calculated using the Predicted Mean Vote (PMV) method. The PMV values ranged between +0.48 to +0.99 and the average was +0.85 (slightly warm). Field test measurements were carried out in the Ras-Al-Khaimah (RAK), UAE during the month of September. Numerical model was validated using experimental data and good agreement was observed between both methods of analysis.

Keywords: Built Environment; Computational Fluid Dynamics (CFD); Cooling; Energy; Natural Ventilation

1. Introduction and Literature Review

The windcatcher dates back to 1,500 years ago. Their usage was spread to Middle East countries such as Iran, Egypt and the UAE. Natural ventilation and passive cooling of the airflow without electrical power are the most important features of windcatchers [1]. In the UAE, windcatchers can be seen in the town of Bastakiya and signified a remarkable effort to attain comfortable living in a hot climate. Coles *et al.* [2] studied the effectiveness of UAE's Bastakiya windcatchers by carrying out measurement of temperatures, wind tunnel modelling and interviews with previous residents. Recently, McCabe and Roaf [3] performed dynamic thermal modelling of a Bastakiya house centered on the windcatcher ventilation system using historical climate data. The study analysed the potential of traditional windcatchers to increase the comfort by varying the height and cross-sectional area. To this end, most of the studies on windcatchers in the UAE are mainly based on the traditional systems and many of these historic buildings

have been demolished to make way for new developments [2]. The use of modern air-conditioning technology and cheap energy due to government supports have contributed to the diminishing of functional windcatchers. Nowadays, windcatchers can be seen in new developments in the UAE which are exaggerated in scale and have no functional purpose. Though the "non-functional" wind towers are copies of the ones in historic Bastakiya district, it still shows that there is an awareness of its heritage value. As energy becomes less affordable, energy security decreases and as people become more aware of the environmental impact, the ability to passively cool buildings becomes more important.

Many researchers [1] have attempted to improve the effectiveness of windcatchers by increasing the ventilation rates and operation time. Several studies [1,4] focused on the aerodynamics design and ventilation performance of windcatchers. Recently, several works [5,6] have integrated heat pipes in windcatchers to improve its cooling performance in hot countries. The numerical analysis [5] showed that the temperature reduction of the supply air reached up to 12°C while still providing the fresh air requirements. Figure 1 shows the operation of the cooling windcatcher with heat pipes. The hot outdoor air enters the windcatcher through the louvers. The airflow is driven downwards and passed through a series of heat pipes which absorbs the heat from the airflow (evaporator) and transfers it to a parallel cool sink (condenser). Adjustable dampers are mounted at the bottom of the deviceto control the delivery rate of the outdoor air, as fluctuations in external wind speed greatly influence the air movement rate within the occupied space. The cooled air is supplied to the room beneath the channel via ceiling diffusers. The current work expands on previous research [5,6] by investigating the capabilities of the system to provide good thermal comfort and indoor air quality in buildings.
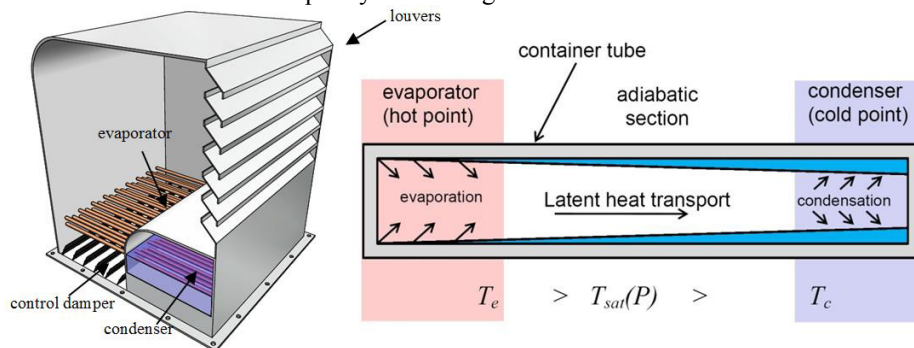

Fig. 1. Schematic of (a) windcatcher cooling system; (b) heat pipe heat transfer

2. Research Methodology

2.1. Computational modelling

ANSYS FLUENT 15 software was used to conduct the steady-state Reynolds averaged Navier–Stokes equation (RANS simulation) which employed a control-volume-based technique for solving the flow equations. The standard k-ε turbulence model was used, which is a well-established method in research on windcatcher natural ventilation [1]. Second-order upwind scheme was used to discretised all the transport equations. The numerical code used the semi-Implicit method for pressure-linked equations (SIMPLE) algorithm for the velocity-pressure coupling of the computation. The governing equations are not repeated here but available in the ANSYS FLUENT guide.

The windcatcher (Figure 1) was created using commercial CAD modeller. The CAD solid data was imported into ANSYS DesignModeller (pre-processor) to generate a fluid domain. The domain (Figure 2a) was separated into three parts: the windcatcher, indoor and outdoor environment. The windcatcher was incorporated to the indoor domain with the dimensions of 5m x 5m and 3m, representing a small room. It was assumed that the windcatcher was supplying airflow at 100% (fully open), therefore dampers were not modeled in the system. The dimension (20 mm outer diameter) and spacing (50mm horizontal

and 20mm vertical) of the heat pipes located downstream of the windcatcher channel were based on earlier work [5-7]. The cool sink was not included in the modelling for simplification [5]. Figure 2a shows the computational domain used for the analysis of the room with a windcatcher. The domain was sufficiently large to prevent artificial acceleration of the flow. The length of the up-stream domain was kept short, 5 times the height of the test room, to avoid the unintended existence of stream-wise gradients while satisfying the recommendations. The length of the down-stream domain was 15 times the height of test room, sufficiently long to allow the wake region development behind test room, which was important for the simulation of exhaust flow from the leeward opening [8].
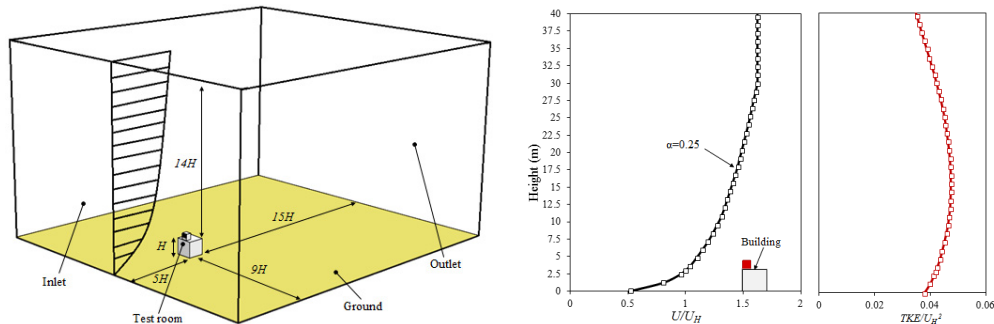

Fig. 2. (a) computational domain; (b) ABL flow profiles for wind velocity and turbulence kinetic energy [8]

Due to the complex geometry of the windcatcher model, an unstructured-grid technique was employed to discretise the domain. The advanced size function in ANSYS Meshing was used to precisely capture the geometry while maintain a smooth growth rate between regions of curvature. In order to capture accurately the flow-fields near the critical areas of interest (i.e. louvers and heat pipes) in the simulation, size functions were applied in those surfaces. The total number of the grid elements was 5.6 million. The selected resolution of the grid was based on the grid sensitivity analysis and convergence analysis on several grids (4.6 to 9.2 million).

The boundary conditions were set using the guidelines highlighted by [8] for the simulation of flows in the urban environment. The vertical profiles of the airflow velocity and turbulence kinetic energy were imposed on the inlet as shown in Figure 2b, based on the measurement data of [8]. The mean velocity of the approach flow obeyed a power-law with $\alpha = 0.25$, which corresponds to a sub-urban terrain. The top and side boundaries were defined as symmetry and the outlet surfaces of the domain was set as zero-static pressure. All the test room surfaces were set as smooth non-slip walls. The standard wall functions were prescribed to the wall boundaries [8]. The wall functions for the ground surface were modified to reflect the effect of roughness of the ground using the equivalent sand-grain roughness height and roughness constant. The inlet temperature was set to 36°C and relative humidity was set to 50% which are typical average in Ras-Al-Khaimah (RAK) during September. The wall temperature of the heat pipes was set to 20°C [5,6].

For the CO_2 distribution simulation, the room was filled with 12 occupants (equally distributed inside the room. A simplified exhalation (constant exhalation) model [9] was used for the analysis. The model of the occupant was simplified to a 1.80m x 0.30m x 0.17m cuboid shape. The area for the mouth opening is equal to 0.13m x 0.10m [9]. Average value of 6 l/min of exhaled air was assumed for the simulation [9].

2.2. Experimental field testing

Field testing measurements were carried out in RAK, which is situated in the northern part of the United Arab Emirates (UAE), located at latitude 25.67 ˚N and longitude 55.78 ˚E with and elevation of 8.00 m. The climate of RAK can be characterised as a hot-desert climate with very hot summers and mild winters. High temperatures can be expected from June to August, with a mean temperature ranging between 37-40 ˚C. The tests were carried out during the month of September (Sept. 17 – 18, 2014)

between 11AM to 4PM. The prevailing winds in RAK are from the northern direction (N-NNW-NW) and therefore, the opening of the windcatcher was positioned to face the predominant wind. The average wind speed in RAK is between 3.6 m/s-4.6 m/s but during the days of test wind speeds went up to about 5.7-6.0 m/s. A 1 m x 1 m prototype of the cooling windcatcher was manufactured (Figure 3a) and installed on top of a 3 m x 3 m x 3 m test room as displayed in Figure 3b. Similarly, the 20mm heat pipes were arranged inside the downstream of windcatcher channel as described in Section 2.1. The cool sink was fed by water at approximately 20 ˚C. The walls and roof of the room was built using insulated studwork. A small cut-out at the back of the room serves as an outlet. The temperature was measured using type-k thermocouple: outdoor, supply air (3 equally-spaced thermocouples downstream of windcatcher channel) and heat pipe wall (1 on surface). The thermocouples were connected to a data logger to monitor and collect the data. The uncertainty associated with the measurement tool was ±0.6 °C at a temperature of 50 °C and ±0.5 °C at 0 °C. The measurement device recorded the temperature every second.

Fig. 3. (a) Full scale windcatcher prototype; (b) windcatcher installation; (c) measurement of supply air

3. Numerical Results

Figure 4a illustrates the contours of velocity in the vertical plane drawn from the middle of the room which is aligned with the direction of the flow and contains the centre of the windcatcher. The airflow that entered the windcatcher via the 45˚ louvers was deflected upwards while the lower side of the flow was in reverse which formed a small recirculation region. The flow slightly accelerated (up to 1.02 m/s) as it turns sharply inside the 90° corner. Reduction in speed was observed downstream of the heat pipes (0.9 to 0.45 m/s). A column of fast moving air enters the space, where the airstream hit the floor of the room and moves toward the opening on the right wall. Figure 4b shows the CO_2 distribution inside the room with 12 occupants (CO_2 source). As observed, fresh outdoor air (assumed to be 382ppm) ventilates the room and dilutes the CO_2. Figure 5a shows the contours of static temperature in the vertical mid-plane which is aligned with the flow direction. The numerical model predicted the indoor temperature to be around 25 °C (closer to the air jet) to 29 °C (closer to outlet). A greater temperature reduction was obtained at the immediate downstream of the heat pipes with a supply air temperature between 24°C- 27 °C, a reduction of upto 12 °C. Figure 6a displays the calculated thermal comfort for the plotted points inside the room (Figure 5b). The thermal comfort was calculated using the Predicted Mean Vote (PMV) method which refers to a thermal scale that runs from Cold (-3) to Hot (+3). The values for metabolic rate and clothing were assumed and set as 1met (sitting) and 0.4 (summer clothing). As observed, the calculated PMV values ranged between +0.48 to +0.99 and the average was +0.85 (slightly warm), which was above the recommended acceptable PMV value in the ASHRAE Standard 55-2013. The percentage of occupants that will be dissatisfied with the indoor conditions were between 10-28.2%. It should be noted that the calculation was only based on steady state conditions and a transient model (varying indoor and outdoor conditions) should be used for a more detailed analysis.
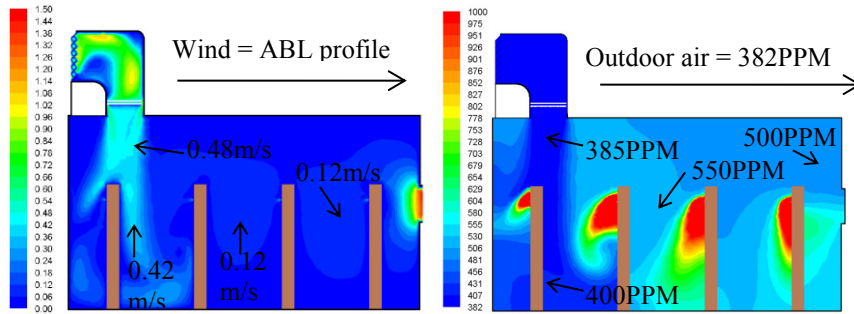
Fig. 4. Cross-sectional contour of (a) velocity magnitude (m/s); (b) CO_2 concentration (ppm)
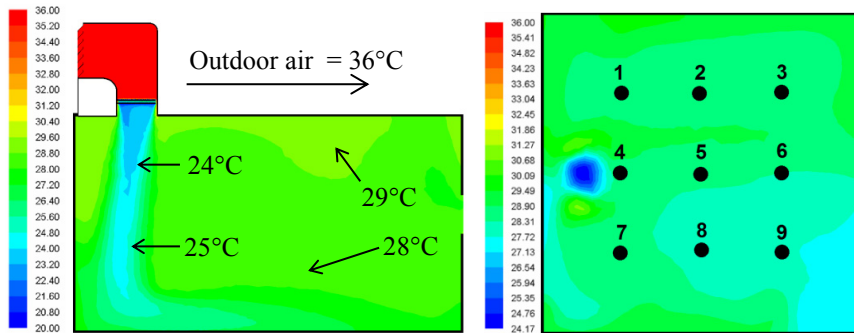

Fig. 5. Cross-sectional contour of air temperature (˚C); (a) side view; (b) top view (1.1m height)
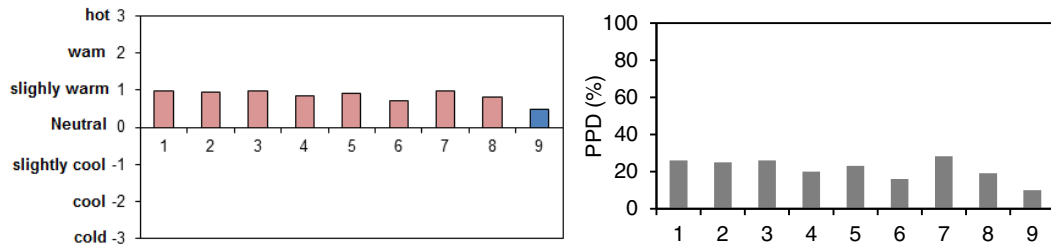

Fig.6. Calculated thermal comfort; (a) Predicted Mean Vote (PMV); (b) Predicted Percentage of Dissatisfied (PPD)

4. Experimental Results and Method Validation

Figure 7a displays the measurements of outdoor air temperature, supply air temperature at the three positions downstream of the windcatcher and heat pipe surface temperature during the 5-hour testing on (09/18/14) from 11 AM to 4 PM The windcatcher began to deliver airflow into the test room at 11:30 and the temperature drop ranged between 3 ˚C-4 ˚C during this period. When the wind started to blow consistently within the ±40° wind angle from 1 PM to 4PM and the temperature drop ranged between 3 ˚C–11.5 ˚C during this period. Figure 7b shows a detailed view of the temperature measurements from 3 PM to 4 PM. The temperature measurements taken during several periods (03:05, 03:16, 03:30, 03:37, 03:48 and 03:58) were used for the validation of the steady-numerical model. It is worth noting that for this numerical model, the test room size was reduced to 3m x 3m x 3m so it will be similar to the field test. Predicted supply temperatures are added to the chart for comparison with the measured results. As observed, the numerical model in most cases under-predicted the supply temperature, however a similar trend between both methods was observed. The average error between the results was 3.15%.
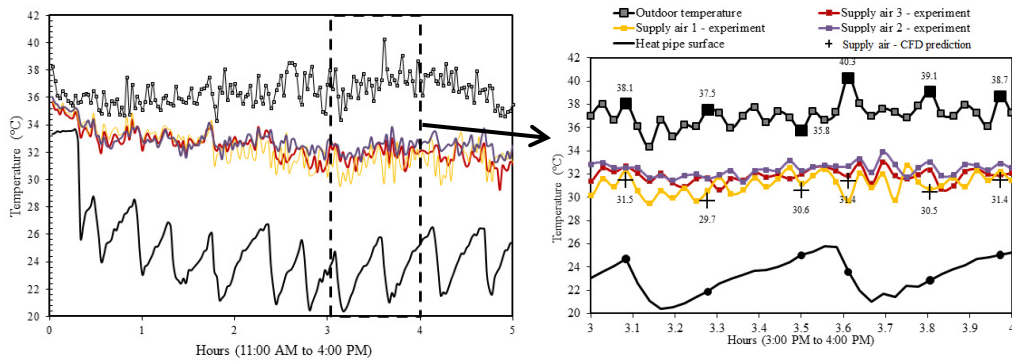
Fig. 7. (a) field test measurements; (b) validation of numerical modelling

5. Conclusions and Future Work

A numerical and experimental investigation was carried out to investigate the ventilation and thermal comfort performance of a passive cooling windcatcher integrated with heat pipes. The study employed the CFD code FLUENT 14.5 to conduct the steady-state RANS simulation which employed the FVM approach. The numerical model provided detailed analysis of the airflow and temperature distribution inside the test room. For the indoor CO_2 concentration analysis, a simplified exhalation (constant exhalation) model was used and the room was filled with 12 occupants. The analysis showed that the system was capable of delivering fresh air inside the space and lowering the CO_2 levels. The thermal comfort was calculated using the Predicted Mean Vote (PMV) method and Predicted Percentage of Dissatisfied (PPD). The calculated PMV values ranged between +0.48 to +0.99 and the average was +0.85 (slightly warm). It should be noted that the calculation was only based on steady state conditions and a transient model should be used for a more detailed analysis. Field testing measurements conducted in the Ras-Al-Khaimah (RAK) during the month of September demonstrated the positive effect of the integration of heat pipes on the cooling performance

References

[1] Hughes BR, Calautit JK, Ghani SA, The Development of Commercial Wind Towers for Natural Ventilation: a review. *Applied Energy* 2012;**92**:606-27.

[2] Coles A, Jackson P, Jones I. How wind towers work: A study of the effectiveness in Dubai's Bastakiya, International Committee of Vernacular Architecture Conference, Al Ain, 2012.

[3] Ciaran M, Roaf S. The wind towers of Bastakiya: assessing the role of the towers in the whole house ventilation system using dynamic thermal modelling. *Architectural Science Review* 2013;**56**:183-194.

[4] Calautit JK, Hughes BR. Wind tunnel and CFD study of the natural ventilation performance of a commercial multi-directional wind tower. *Building and Environment* 2014;**80**:71-83.

[5] Calautit JK, O'Connor D, Sofotasiou P, Hughes BR. CFD Simulation and Optimisation of a Low Energy Ventilation and Cooling System. *Computation* 2015;**3**:128-149.

[6] Calautit JK, Chaudhry HN, Hughes BR, Ghani SA. Comparison between evaporative cooling and heat pipe assisted thermal loop for a commercial wind tower in hot and dry climatic conditions, *Applied Energy* 2013; **101**:740-755.

[7] Calautit JK, Hughes BR, Shahzad SS.CFD and wind tunnel study of the performance of a uni-directional wind catcher with heat transfer devices. *Renewable Energy* 2015;**83**:85-99.

[8] Tominaga Y, Akabayashi S, Kitahara TA, Arinami Y. Air flow around isolated gable-roof buildings with different roof pitches: Wind tunnel experiments and CFD simulations. *Building and Environment* 2015;**84**:204-213.

[9] Calautit JK, O'Connor D, Hughes BR. Determining the optimum spacing and arrangement for commercial wind towers for ventilation performance. *Building and Enviornment* 2014;**82**:274-287.

Biography

Dr Calautit is a Research Associate in the University of Sheffield. He received his Mechanical Engineering degree from Heriot-Watt University and his PhD from the University of Leeds. His PhD study focused on numerical and experimental techniques to design and investigate performance of passive cooling windcatchers.