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Energy modeling and air flow simulation of an ancient wind catcher in Yazd

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Abstract

Wind catchers (wind towers) are one component of the traditional sustainable buildings with a central courtyard in the hot regions of Iran. In this research a most common type of the wind tower – the four sided wind catcher- was evaluated both experimentally and numerically. The tower of the Mortaz house in the city center of Yazd was equipped with temperature, wind, air velocity and solar sensors. Monitoring took place over a three months winter period. A series of 3D steady CFD simulations was carried out using OpenFOAM. The airflow pattern through the wind catcher model was simulated to predict and monitor the air flow behavior in the four equipped shafts for prevailing wind directions. Finally the validation of the CFD numerical simulation results with the onsite measurements data is discussed. The goal of this research is developing a method of informing the design decision for new wind catchers and the renovation of traditional wind catchers in early design stage using CFD simulation tools and energy modeling in sustainable buildings.

Key words: Traditional sustainable buildings, Wind catcher, CFD simulation, Energy modeling, Experimental measurements

1. Introduction

Wind catchers as natural ventilation components were widely used in Iranian traditional housing to provide acceptable thermal comfort in central courtyard houses. The major advantage of wind catchers is that they work with the renewable energy of the wind, requiring no other energy sources for operation. These sustainable ventilation systems have become an increasingly attractive method for reducing energy consumption and energy costs in building sector. Many researchers have been studied the functional behavior of the wind catchers in Iran. Bahadori [1,4], performed full analysis of the design of wind catchers in several locations such as Yazd city in summer time and presented two new designs of wind catchers. Saffari et al. [9] studied a numerical simulation of evaporative cooling in a wind tower. They used the partitions as surfaces that inject water droplet in very low speed normal to the surface for simulating evaporative cooling. The interaction between the airflow – as continues phase – and water droplets – as discrete phase – was described. Several parameters such as the diameter of the droplet, the injection rate per square meter of the surface, and the speed of the injection were separately studied. The results were compared with some analytic
data and showed a good agreement with them. In addition it was suggested that using evaporative cooling has a great increase in wind catchers performance. Montazeri et al. [6-8] also investigated the effects of the numbers of openings by modeling a circular cross section wind tower that has several openings at equal angles. The results show that the number of openings is a main factor in the performance of wind tower systems. It also shows that the sensitivity of the performance of different wind catchers to the wind angle decreases by increasing the number of openings. Moreover, when it is compared with a circular wind tower, a rectangular system provides a higher efficiency. The present work studied on a full scale four-sided wind catcher to model the air flow pattern through the tower in the four tower shafts at prevailing wind direction and is validated by comparison with the onsite measurements data. The air velocity values were calculated and analysis in the tower shafts to find the hydrodynamic performance of the wind–induced natural ventilation system. [6-8]

2. EXPERIMENTAL ONSITE MEASUREMENTS

The experimental house - Mortaz house- at the city center of Yazd [ latitude 31°53’50”N ] in Iran was equipped with temperature, wind, air velocity and solar sensors. Monitoring took place over a three month winter period [14]. Fig.1 shows the plan of the experimental house and the wind tower including four equipped shafts. A Wireless Ultrasonic Wind Sensor with USB interface consisting of a receiver and a cable with a USB plug was installed on a mast head as a local weather station (fig.2). The local weather station is installed on the roof of the Mortaz house which is located around 20 meter far away from the wind tower and is free to the wind (fig. 3).

Fig1. Plan of the experimental house and the wind tower including four equipped shafts

To study the airflow pattern through the tower of Mortaz house the data from the wind sensor and air velocity sensors on the warmest day of the measurement period (on 03 Nov. 2014 between 14:00 PM - 16:00 PM ) are selected to analyze [14]. Fig.4 shows a view of the air velocity sensor inside shaft B. The data obtained from the wind sensor with the wind speed range of 0.2-40 m/s, wind direction range of 0-359° and the resolution of one degree. Based on the wind data collection and analysis of the daily wind diagram (fig.5) the prevailing wind is seen as blowing from the North direction. The mean wind velocity of 1.5 m/s is recorded by the wind sensor at the height of 11 m during the warmest hours of the day on 03 Nov. 2014.
Fig 2. Local weather station

Fig 3. Location of air velocity sensors and local weather station

A1: Air velocity sensor in shaft B

A2: Air velocity sensor in shaft D

Fig. 4. Air velocity sensor in shaft B

Fig. 5. Wind rose diagram

Fig. 6 shows the orientation of the experimental house in relation to the prevailing wind. Four air velocity sensors (A4 – A1 – A2 – A3) with the working range of 0-20 m/s was also installed in the middle of four tower shafts (shaft A – B – D – E) in height of 2.00 m above the outlet of the tower (5.35 m from the ground level) respectively.
3. NUMERICAL SIMULATION

According to the range of wind velocity, the flow can be considered incompressible and the temperature variations are considered constant in this simulation. The 3D steady RANS equations were solved in combination with the realizable $k-\varepsilon$ turbulence model. The governing equations are:

\[ \nabla \cdot (\bar{U}) = 0 \]  

\[ \frac{\partial (\bar{U})}{\partial t} + \nabla \cdot (\bar{U} \bar{U}) - \nabla \cdot ((\mu_t) \nabla \bar{U}) = -\nabla p \]  

where $\mu_t$ is turbulent viscosity. It is determined from kinetic energy ($k$) and dissipation energy ($\varepsilon$) based on Boussinesq eddy viscosity assumptions [15].

The Open source Field Operation and Manipulation (Open FOAM) C++ libraries are used for numerical simulation [13]. It is supplied with numerous pre-configured solvers, utilities, and libraries. It is open, not only in terms of source code, but also in its structure and hierarchical design, so that its solvers, utilities and libraries are fully extensible. A full scale model (50 × 25 × 7 m$^3$) of the experimental house with wind-driven natural ventilation tower (6.05 × 3.45 × 14 m$^3$) was built and used in simpleFoam solver in OpenFOAM 2.3.0 for simulation. The dimensions of the computational domain were chosen based on the CFD guidelines by Franke et al. [10] and Tominaga et al. [11]. The resulting dimensions of the domain were 500 × 500 × 80 m$^3$. The computational grid was created using snappyHexMesh and blockMeshDict as mesh generation tools in OpenFOAM. Hexahedral cells are dominant in the present grid. The surface mesh view has shown in Fig.7. For wind direction $\theta=0^\circ$, the inlet boundary conditions (mean velocity U, turbulent kinetic energy k and turbulence dissipation rate) were initialized based on the measured mean wind speed of 1.5 m/s from the local weather station. The turbulent intensity set to 0.02. For the ground surface, the standard wall functions were used. The simulation results are used to validate against the onsite measurement results of air velocity fields. The governing equations are discretized with the finite volume method. Second order upwind discretization schemes were imposed on all the transport equations solved and the SIMPLE is adopted as pressure-velocity solution algorithm.

![Fig 7.Surface mesh view generated using snappyHexMesh](image-url)
4. Discussion and results

1-4- Experimental Results

Fig.8 shows the average air velocity variations in four equipped shafts of A, B, D and E on 03 Nov.2014. The graphs follow the sinusoidal pattern which occurs in nature phenomenon (like breathing system). The indoor air velocity fluctuates between 0.25 m/s and 2.8 m/s. Fig.8 also reveals that the indoor average air velocity is low between midnight and early morning and increases in the afternoon. The maximum average air velocity of 2.8 m/s is recorded in shaft A with the maximum fluctuation in the afternoon. As mentioned before, the difference between the CFD results and experimental data in shaft A can be explained due to the fluctuations in this shaft in the afternoon. The high air velocity is caused by lighter air density due to higher air temperature in the afternoon.

![Average air velocity in four equipped shafts](image)

2-4- Numerical Results

Fig.9 shows the streamlines of the turbulent airflow through and around the tower for an inlet velocity of 1.5 m/s at zero direction. The velocity field in four equipped shafts presented in Fig.10. The results show that the air flow direction in shaft A and B (inlet shafts) is downward with the negative values while the velocity fields is upward in outlet shafts of E and D.
Fig 9. CFD simulation of the air flow around and inside the wind tower

Fig 10. Velocity field in four tower shafts

3-4- Validation of CFD simulations against experimental data analysis

Fig. 11 shows the comparison between the empirical mean air velocity and CFD results. The root mean square deviation (RMSD) between empirical data and CFD simulation results is 10.8%. The tabulation of the RMSD is shown in Table 1. The RMSD reveals that CFD
simulation has a good agreement with the empirical results in three tower shafts B, D and E with the value of 3.9%. It can be explained by the hydrodynamic behavior of shaft A which is explained in Experimental results section. Table 1 shows that the average air velocity in four equipped shafts is 0.55 m/s for the CFD results while it is 0.50 m/s for the experimental analysis.

<table>
<thead>
<tr>
<th>Sensor Location</th>
<th>CFD</th>
<th>Experimental data</th>
<th>Absolute deviation X (%)</th>
<th>$X^2$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1 - Shaft B</td>
<td>0.37</td>
<td>0.37</td>
<td>0.0</td>
<td>0.0</td>
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<tr>
<td>A2 - Shaft D</td>
<td>0.70</td>
<td>0.75</td>
<td>6.6</td>
<td>43.5</td>
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<tr>
<td>A3 - Shaft E</td>
<td>0.50</td>
<td>0.51</td>
<td>1.9</td>
<td>3.6</td>
</tr>
<tr>
<td>A4 - Shaft A</td>
<td>0.46</td>
<td>0.58</td>
<td>20.6</td>
<td>424</td>
</tr>
<tr>
<td>Root mean square deviation</td>
<td></td>
<td></td>
<td></td>
<td>10.8</td>
</tr>
</tbody>
</table>

Table 1. The root mean square deviation between experimental data and CFD simulation

Fig11. Comparison between the experimental mean air velocity and OpenFOAM CFD simulation
5. CONCLUSION

Energy modeling and CFD simulation is an important and interesting method to study and research on performance analysis of wind catchers as sustainable architecture components, providing valuable information in a much shorter time than when carrying out onsite measurements. The present work has shown the possibility of simulating a real case with the wind-driven natural ventilation tower in Yazd. The simulated values of air velocity has shown the functional behavior of air flow in four shafts of the wind catcher. Although the comparison between the under controlled conditions for CFD simulation and un-controlled onsite measurements should be considered. The validation results are more accurate since appropriated information is given as boundary conditions, simplification hypothesis and geometric mesh. This paper aims to investigate the use of building performance simulation tools as a method of informing the design decision of sustainable buildings.

References


