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Evaluation of airflow and thermal comfort in buildings ventilated with wind catchers: Simulation of conditions in Yazd City, Iran

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ABSTRACT

The usage of passive cooling systems such as wind catchers can reduce the energy usage in buildings and provide natural ventilation and comfort to its occupants, particularly in hot and dry regions of Iran and neighboring countries where it was traditionally used. The purpose of this study was to investigate the airflow and thermal comfort in six different designs of wind catchers using computational fluid dynamics (CFD) technique. Simulations of airflow in the wind catcher and the building were done under steady state and turbulent flow regime with boundary conditions based on typical conditions found in Yazd city, Iran. Several commonly used turbulence models were evaluated to assess the accuracy of the simulation. First, the proposed CFD model was validated through comparison of wind tunnel data available in the literature, and then the model was used for design purposes. It was found that the $k-\omega$ turbulence model can accurately predict the airflow velocity in the range of parameters studied. The design and performance of wind catcher were evaluated based on the thermal comfort levels using the Center for the Built Environment (CBE) thermal comfort tool and numerical data. Width and height of the wind catcher were varied in the simulations and optimal values were determined. It was found that varying the width of the wind catcher had the greatest impact on the airflow speed and distribution inside the room. Reducing the width from 2.5 m to 2 m showed that airflow velocity in the middle area was increased up to 34%. While reducing the width from 2 m to 1.5 m showed an entirely different flow pattern inside the building and also increase airflow speed in the middle area up to 50%. The addition of curved wall at the bottom of the inlet channel showed that it could increase the airflow speed of the inflow stream, however, it also caused the airflow to be directed towards the lower levels of the room and very large rotating flows in the upper levels. Finally, the results showed that the wind catcher may be optimized for improving comfort for various climates using the tools presented in this work.

Introduction

Traditional architectural design in certain hot and dry climates, such as that of Iran, includes wind catchers to promote comfort through passive temperature control and ventilation. Studies have indicated that the four-sided wind catcher is the most used wind catcher in the Middle East and Asian countries such as Iran (Mahnaz and Shemirani, 2009). Fig. 1 presents a typical four-sided wind catcher that is currently used in the city of Yazd (Iran). As shown in Fig. 2, a wind catcher provides natural ventilation by taking advantage of the pressure differences surrounding the building. Therefore, it is essential that the device is positioned to maximize the pressure differential between the inlet and outlet (Hughes et al., 2012).

The computational fluid dynamics (CFD) has emerged as an effective tool for predicting the air ventilation and indoor and outdoor air quality improvement (Nielsen, 2015; Roache, 1998; Versteeg and Malalasekera, 2007; Wilcox, 1998). Montazeri et al. (2010) evaluated the performance of a two-sided wind catcher using wind tunnel testing, smoke visualization, CFD, and analytical models and reported acceptable agreements between different methods. Montazeri (2011) also studied the natural ventilation of different multi-opening wind catchers, both experimentally and computationally. Recently, Kazemi Esfeh et al. (2012) carried out some smoke visualization tests to determine the airflow characteristics in one-sided wind catchers with flat, inclined and curved roofs. In a similar research, Reyes et al. (2013) studied airflow distribution, heat transfer and thermal comfort for five different types of two-sided wind

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Fig. 1. A four-sided wind catcher with rectangle cross section.

catchers in two dimensional geometries for dry and semi-dry areas of Mexico region using the CFD code FLUENT. However, they did not study design parameters such as width and height of the wind catcher that affects the wind catcher performance.

Bahadori et al. (2008) examined two new designs of wind catchers, experimentally and compared their performance with a conventional wind catcher in the city of Yazd, Iran, in terms of air temperature leaving the tower and airflow rate. Dehghan et al. (2013) studied the influence of wind velocity and its direction on the natural ventilation of one-sided wind catchers using analytical modeling and wind tunnel experiments. Elmualim and Awbi (2002) performed a similar experimental analysis but chose to compare the ventilation performance of square and circular wind catchers. Furthermore, Saffari and Hosseinnia (2009) and Kleiven (2003) developed mathematical models to calculate the performance of wind catcher.

There are a few works published in the literature that investigated the detailed thermal conditions and indoor air quality of rooms employing the wind catcher system. Bouchahm et al. (2011), Da Silva (2005), and Badran (2003) performed theoretical analysis of the thermal performance of a wind catcher system incorporating evaporative cooling methods. Bahadori (1978) used far field experimental testing to evaluate the thermal performance of a cooling tower. The wind pressure coefficients at openings of a four-sided wind catcher were measured in a wind tunnel by Karakatsanis et al. (1986). Su et al. (2008) choose unconventional type of wind catcher with circular cross section and four openings to evaluate the net flow rate. Hughes and Ghani (2009) investigated the capability of four-sided wind catcher to ventilate a small classroom. Jones and Kirb (2009) presented an alternative semi-empirical approach in order to provide a fast but accurate estimate of wind catcher performance. Moreover, in the Givoni (1992) work, various methods of creating human comfort conditions in different climates based on their available meteorological data have been studied and compared. However, there was no information regarding the thermal comfort in buildings with wind for hot and dry climate such as Yazd, thus, this issue is evaluated in the present study using numerical modeling. Additional studies of the airflow in the wind catchers may be found in the other researches (Ghadiri et al., 2011; Lo et al., 2013; Rahimi Gorji et al., 2015; Feng et al., 2014; Soni and Aliabadi, 2013; Yang et al., 2015; Tanasic et al., 2011; Taghinia et al., 2015; Zhang et al., 2014; Calautit et al., 2013, 2015, 2016; Abouseba and Khodakarami, 2014; Bouchahm et al., 2011; Aflaki et al., 2015; Reyes et al., 2015).

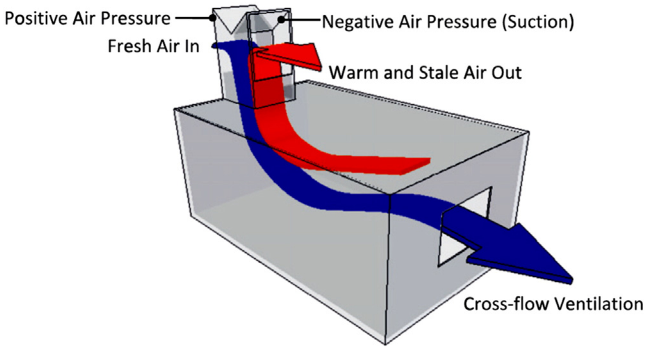

Fig. 2. A flow diagram representing ventilation through a room with a wind tower.

Although there are many works available in the literature on the design of the wind catchers and also their ventilation performance, the thermal comfort variable is usually not investigated. In fact, review of the available literature reveals the existence of a gap related to the impact of architectural design of the wind catcher (width, height, openings, and details geometry) and the way that these variables can optimize airflow and human comfort conditions in the climate of Yazd city. The main contribution of the work is the thermal comfort modeling of a building or space naturally ventilated with a wind catcher. The accuracy of different turbulence models such as k–ε Standard, k–ε RNG, k–ε Realizable, k–ω SST, and k–ω Standard model for wind catcher simulations is also investigated. Thermal comfort in different locations of the building is calculated and assessed using the CBE tool.

Computational method

The present computational method is divided into a number of steps. For the first step, the computational models of various wind catcher designs are developed and imported into the ANSYS FLUENT (version 15.0) code. Then appropriate boundary conditions and turbulence model are set, and the airflow in the wind catcher and in the main room is evaluated. In the next step, the occupants' thermal comfort is studied and improved by varying the wind catcher geometry. Finally, an optimized wind catcher design is obtained based on the comfort of occupants for each zone using the center for the built environment (CBE) thermal comfort zone tool for evaluating comfort according to ASHRAE Standard 55. This standard specifies the combination of indoor thermal environmental and personal factors that produce thermal environmental conditions acceptable to a majority of the occupants within the space.

CFD modeling

A computational model assuming steady incompressible flow under turbulent flow regime is used to investigate the airflow and thermal condition in a pseudo four-sided wind catcher for the climate conditions of the city of Yazd (Iran).

CFD governing equations

In the CFD analysis of the wind catcher, momentum and energy equations are solved by the finite volume method (Fluent, 2012).