Applied Energy xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Climatic analysis of a passive cooling technology for the built environment in hot countries

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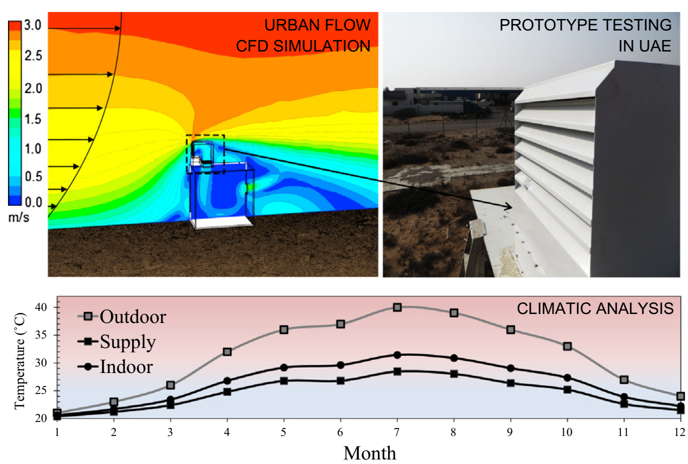
HIGHLIGHTS

- Sub-urban flow simulation was carried out for the analysis of the cooling windcatcher.
- Relevant history and previous works on windcatchers in the UAE were discussed.
- Boundary conditions were varied for each month as per the available climatic data.
- Results of the field testing in RAK carried out in September 2014 were discussed.
- Validation of numerical model using field data showed good agreement.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 14 January 2016
Received in revised form 11 May 2016
Accepted 14 May 2016
Available online xxxx

Keywords:
Building
Computational modelling
Field testing
Heat pipe
Natural ventilation

ABSTRACT

The aim of this work was to determine the ventilation and cooling potential of a passive cooling windcatcher operating under hot climatic conditions by replicating the monthly wind velocity, wind direction, temperature and relative humidity (RH) observed in a hot-desert city. The city of Ras-Al-Khaimah (RAK), UAE was used as the location of the case-study and available climatic data was used as inlet boundary conditions for the numerical analysis. The study employed the CFD code FLUENT 14.5 with the standard k–ε model to conduct the steady-state RANS simulation. The windcatcher model was incorporated to a $3 \times 3 \times 3$ m^3 test room model, which was identical to the one used in the field test. Unlike most numerical simulation of windcatchers, the work will simulate wind flows found in sub-urban environment. The numerical model provided detailed analysis of the pressure, airflow and temperature distributions inside the windcatcher and test room model. Temperature and velocity profiles indicated an induced, cooler airflow inside the room; outside air was cooled from 38 °C to 26–28 °C, while the average induced airflow speed was 0.59 m/s (15% lower compared to a windcatcher w/out heat pipes). Field testing measurements were carried out in the Jazira Hamra area of RAK during the month of September. The test demonstrated the positive effect of the integration of heat pipes on the cooling performance but also highlighted several issues. The comparison between the measured and predicted supply temperatures were in good agreement, with an average error of 3.15%.

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http://dx.doi.org/10.1016/j.apenergy.2016.05.096
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Nomenclature

U	velocity magnitude (m/s)
T	air temperature (°C)
X, Y, Z	cartesian co-ordinates (m)
Re	Reynolds number
ρ	air density (kg/m^3)
μ	kinematic viscosity (m^2/s)
Q	volume flow rate (m^3/s)
g	gravitational acceleration (m/s^2)
A	cross-sectional area (m^2)
ΔP	total pressure loss (Pa)
P	pressure (Pa)
P_o	total pressure (Pa)
P_s	static pressure (Pa)
L	length (m)
W	width (m)
H	height (m)
t	time
e	specific internal energy (J/kg)
k_{eff}	effective heat conductivity (W/m K)
h_i	specific enthalpy of fluid
j_i	mass flux (kg s^{-1} m^{-2})
G_b	source of turbulent kinetic energy due to buoyancy force
α_k	turbulent Prandtl numbers
k	turbulence kinetic energy (m^2/s^2)
ε	turbulence dissipation rate (m^2/s^3)
α	power law coefficient
ABL	atmospheric boundary layer
AC	air-conditioning
CAD	computer-aided design
CFD	computational fluid dynamics
CIBSE	chartered institution of building services engineers
FVM	Finite Volume Method
GHG	greenhouse gas
RAK	Ras-Al-Khaimah
RANS	Reynolds averaged Navier–Stokes
RH	relative humidity
SIMPLE	semi-implicit method for pressure-linked equations
TKE	turbulence kinetic energy
UAE	United Arab Emirates
UK	United Kingdom

1. Introduction

Driven by an ever increasing global demand for energy across all aspects of life and industry, carbon emissions have increased at an alarming rate. Governments have been bound to statutory requirements to cut emissions from pre-1990 levels by 80% by the year 2050 [1]. Therefore, a societal movement away from energy intensive processes and the use of new technologies to reduce the energy consumption must be the key focus. The building sector in particular is one of the main end users of energy [2,3]. Energy consumption for the buildings sector worldwide is expected to grow by 45% in the 2002–2025 period [4]. In rapidly developing Middle Eastern countries such as UAE and Qatar, air-conditioning (AC) is a key contributor to greenhouse gas (GHG) emissions [5]. The extreme conditions of local climate, affordable energy and increased demand for high-levels of comfort had led to the use of energy-intensive AC in nearly all buildings [5]. A study in 2005 [6] indicated that the average consumption per person in Gulf countries was almost 4 times higher than global average.

In addition, the steadily increasing global temperature and decreasing energy security could render the future operation of the built environment un-economical in hot climates, particularly in the Middle East [7]. This could place buildings at risk of overheating and not habitable during extremely hot periods. It is crucial for buildings to adapt to such situations without the additional energy-intensive mechanical cooling. The answer to the issue, however, might be closer to the Gulf than previously thought. Researchers, engineers and architects are now looking at traditional architecture as a way of providing low-energy cooling [8,9]. An example of this is the windcatcher or wind tower (Fig. 1a), which was used by several Middle East countries for many centuries to capture wind and provide a comfortable indoor environment without using energy [10,11]. Nowadays, modern version of windcatchers has been implemented in the UK, particularly in schools and offices spaces [12].

The device provides natural ventilation to buildings through wind-driven airflow and thermal effects (buoyancy flows) [13]. Traditionally, wind tower were tall structures which captures wind at higher altitude and wetted clothes were located inside to cool the air supplied to the space below [10]. A different version of a wind tower with evaporative cooling is shown in Fig. 1b, which used clay conduits and water spray to cool the air [10]. During night-time, the wind tower can also provide cooling by "night-flushing" or removing the stored heat in the building fabric. Recently, several studies [14–16] have proposed the addition of heat pipes in windcatchers to enhance its cooling operation and address the issues associated with evaporative cooling method which are detailed in [15]. Fig. 2 shows a schematic of the windcatcher with horizontally-arranged heat pipes inside its channel. The system operates by capturing hot outdoor airflow and passing it through one side of the heat pipe arrangement (evaporator), which absorbs the heat and transfer it to a parallel cool sink (condenser). The thermal energy is transferred to the heat pipes in the windcatcher channel where they are cooled as the thermal energy is transferred to the passing airflow. The heat pipe system is based on the continuous cycle of evaporation and condensation process. When heat is applied to the external surface of the heat pipe, the liquid inside the tube boils and vaporises into a gas that moves through the tube seeking a cooler location where it condenses, giving off its latent heat [15]. This will maintain the operating conditions and repeat the cyclic operation of the heat pipe. Adjustable dampers are mounted at the bottom of the unit to control the delivery rate of outdoor air, as fluctuations in external wind speed greatly affect the air movement rate within the occupied space. The heated air is supplied to the room below the channel via the ceiling diffusers. Dampers located downstream of the windcatcher controls the delivery rate of airflow, as fluctuations in outdoor wind greatly influence the supply airflow velocity and temperature [14,15]. The cooled air is supplied to the room beneath the channel via the ceiling diffusers.

The objective of this work are two-folds: first, to determine the ventilation and cooling potential of the windcatcher operating under hot climatic conditions by replicating the monthly wind velocity, wind direction, temperature and relative humidity (RH) observed in a hot-desert city such as Ras-Al-Khaimah (RAK), UAE. In our earlier works [14,15,17], we've assessed the performance of the windcatcher system based on extreme outdoor conditions (*i.e.* very high outdoor temperature), therefore this study aims to investigate its operation in response to various outdoor conditions. In [14], the authors compared the ventilation and thermal