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Numerical and experimental analysis of a multi-directional wind tower integrated with vertically-arranged heat transfer devices (VHTD)

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HIGHLIGHTS

- Potential of integrating heat transfer devices into a wind tower was explored.
- Achieved indoor air speed was reduced by 8–17% following the integration of VHTD.
- CFD model was validated using wind tunnel test and good correlation was observed.
- Impact of varying arrangement of VHTD on ventilation and cooling was studied.
- Effect of ABL flows on wind tower ventilation performance was investigated.

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ABSTRACT

The aim of this work was to investigate the performance of a multi-directional wind tower integrated with vertically-arranged heat transfer devices (VHTD) using Computational Fluid Dynamics (CFD) and wind tunnel analysis. An experimental scale model was created using 3D printing. The scale model was tested in a uniform flow closed-loop wind tunnel to validate the CFD data. Numerical results of the supply airflow were compared with experimental data. Good agreement was observed between both methods of analysis. The Grid Convergence Method (GCI) method was used to estimate the uncertainty due to discretisation. Results have indicated that the achieved indoor air speed was reduced by 8–17% following the integration of the VHTD. The integration of VHTD had a positive effect on cooling performance of the wind tower, it reduced the incoming fresh air by up to 12 K. The effect of varying the number of VHTD rows (1–3 rows) on the system's performance were also investigated. Additional simulations were also conducted to investigate the effect of atmospheric boundary layer (ABL) flows on the wind tower ventilation performance and also compare it with the results of uniform flow wind tunnel study.

1. Introduction

The building sector has substantial scope to reduce the energy use associated with the operation and maintenance of buildings worldwide. Presently, the building sector contributes 30–40% of the global energy demand and more than 60% of this total energy demand is consumed by the Heating, Ventilation and Air-conditioning (HVAC) [1]. This is due to the increasing thermal comfort demands of occupants, regulations for adequate ventilation supply rates and current HVAC technology that is commonly used. Addressing the significant energy requirements of mechanical HVAC services has the potential to significantly reduce the energy demands of buildings heavily reliant on such systems such as commercial buildings, schools and office spaces [2].

Passive ventilation strategies are becoming more commonly used to ventilate and cool buildings [3]. These strategies are able to reduce the energy consumption of buildings with regards to the energy required for ventilation by using the forces of wind driven flow and air buoyancy. Pressure differences created by obstructions in the path of wind flow force air through a building via a combination of driving and suction forces. Air buoyancy due is due to the varying density of air at different temperatures [4]. By controlling this process, buildings can be ventilated with little energy requirement. The two driving forces are combined in a wind tower [5], commercial wind towers have been in existence in the UK for the last 40 years in various forms, and their development over that period has been the subject of much research both in the UK and internationally [6].

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Nomenclature

u	velocity magnitude (m/s)	ΔP	total pressure loss (Pa)
X, Y, Z	Cartesian co-ordinates (m)	P	pressure (Pa)
Re	Reynolds number	P_o	total pressure (Pa)
ρ	air density (kg/m^3)	P_s	static pressure (Pa)
μ	kinematic viscosity (m^2/s)	L	length (m)
Q	volume flow rate (m^3/s)	W	width (m)
g	gravitational acceleration (m/s^2)	H	height (m)
A	cross-sectional area (m^2)	t	time (s)

Wind towers are passive ventilation systems, based on the traditional vernacular design of baud-geer [7]. Baud-geer have been utilised for centuries, predominantly in Middle East, as a method of delivering ventilation to buildings [7]. Though reducing energy demand through the use of passive ventilation is one solution in cutting greenhouse gases as a result of HVAC systems, the key area for reduction is the conditioning of the air. Unlike air-conditioning, wind towers are ineffective at reducing the temperature of supply air. This places a limit on the application of natural ventilation systems in hot climates [8,9]. Therefore, additional technologies should be incorporated with the wind tower to cool the airflow. Fig. 1a shows a wind tower with evaporative cooling technology. The outdoor airflow entering the wind tower top entrance is passed though evaporative cooling pads, evaporating the water in the process and reducing the airflow temperature. However, there are few issues associated with the method such as high operation and maintenance cost [10]. In addition, evaporative coolers use a substantial amount of water to run. Other drawbacks associated with evaporative cooling are discussed in [10].

In this study, heat transfer devices (HTDs) were incorporated into the internal domain of a multi-directional wind tower to reduce the temperature of supply air. As shown in Fig. 1b, the hot outdoor air (1) enters the wind tower through the louvers, which are used to deflect the impact of weather and direct sunshine from entering the device. The airflow is passed through a series of vertically arranged-HTDs (2), which absorbs heat from the airstream and transfers it into a parallel closed-circuit cool sink (3). Volume control dampers are located at the bottom of the unit to control the delivery rate (5). The cooled air is supplied to the room beneath the channel via ceiling diffusers (6). The primary force provides fresh air driven by the positive air pressure on the wind-ward side (1), while exhausting stale air with the assistance of the suction pressure on the leeward side (7).

In our earlier works, we've used numerical modelling to compare the ventilation and thermal performance of a traditional wind tower incorporating evaporative cooling and HTDs [10]. The study showed that the wind tower with HTDs was capable of reducing the air temperature by up to 12–15 K while supplying the recommended fresh air rates. In a more recent work [11], we've explored the integration of horizontally-arranged HTDs into a commercial uni-directional wind catcher. The study identified the cooling potential of the proposed system but also showed several limitations when coupled with a uni-directional system i.e. not suitable in areas with variable wind directions [12]. In this study, we will explore the potential of using a multi-directional device with vertically-arranged HTDs to address this limitation. The system will be capable of supplying fresh air and exhausting stale air irrespective of the wind direction. The numerical model will be validated using a uniform flow wind tunnel. In addition, the effect of varying the number of VHTD rows (1–3 rows) on the ventilation and thermal performance will also be investigated. Furthermore, additional simulations were conducted to investigate the effect of ABL flows on the wind tower ventilation performance and also compare it with the uniform flow scenario.

2. Literature review

The development of several aspects of wind towers to improve efficiency and design has been well documented in the following reviews [13,14]. A comprehensive review of wind tower development was conducted by Hughes et al. [15]. The most commonly used technique for development are Computational Fluid Dynamics (CFD) modelling and scaled wind tunnel testing and hence was used in this study. Improvements to traditional wind towers have been investigated in an attempt to increase the effectiveness in

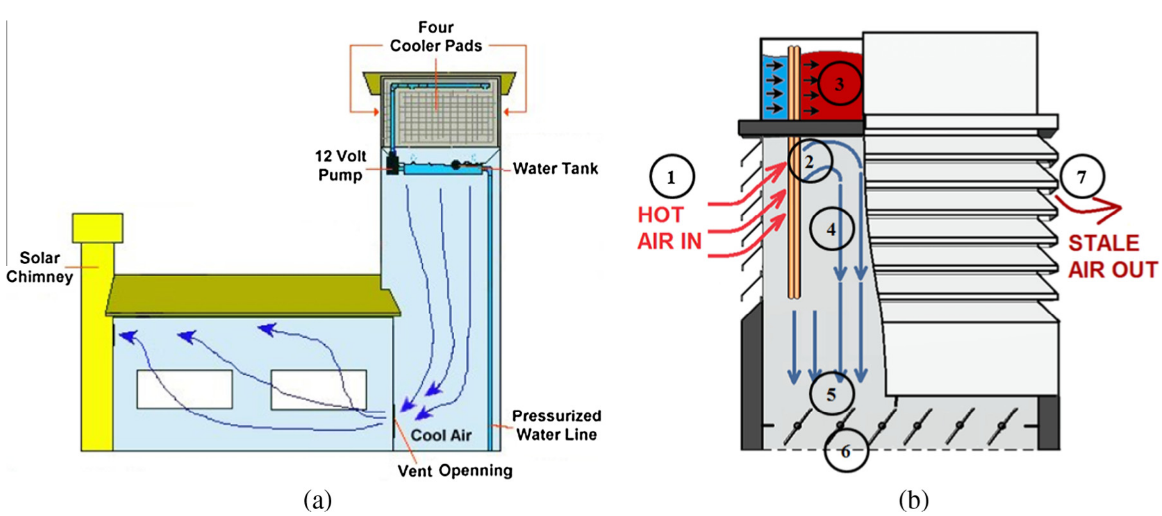

Fig. 1. (a) Wind tower with evaporative cooling and (b) a multi-directional wind tower with VHTDs.

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