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Numerical and experimental analysis of a natural ventilation windcatcher with passive heat recovery for mild-cold climates

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Abstract

In this work, a novel design incorporating a passive heat recovery device into a windcatcher was proposed and investigated using numerical and experimental analysis. The proposed system incorporates a rotary thermal heat recovery in the windcatcher channel. Computational Fluid Dynamics (CFD) was used to investigate the effect of the heat recovery device on the performance of the windcatcher, highlighting the capabilities of the system to deliver the required fresh air rates. The windcatcher model was incorporated to a 5m x 5m x 3m test room model representing a small classroom. The study employed the CFD code Fluent18 with the k-epsilon model to conduct the simulations. The numerical model provided detailed analysis of the airflow and temperature distribution inside the test room. A 1:10 scale prototype of the system was created and tested experimentally in a closed-loop subsonic wind tunnel to validate the CFD investigations. Despite the blockage of the rotary t heat recovery wheel, ventilation rates were able to provide adequate ventilation. In addition to sufficient ventilation, the heat in the exhaust airstreams was captured and transferred to the incoming airstream, raising the temperature between 1-4K depending on the indoor/outdoor conditions, this passive recovery has the potential to reduce demand on space heating systems. According to WBCSD, a recovery of 3 K from the exhaust stream to the inlet stream could generate energy savings up to 20% in heating costs. This shows that the concept has significant potential to be developed further, whereby the heat transfer properties of the system can be investigated and tested on a larger scale.

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Keywords: computational fluid dynamics; heat recovery; passive ventilation; windcatcher

1. Introduction and Literature Review

The government policy to reduce UK carbon emissions by at least 80% of the pre-1990 levels by 2050 is a major driving force in reducing the energy demand of the built environment [1]. A large percentage of the energy use is due to space heating which accounts for up to 40% of the total energy demand in both residential and service sector properties and other developed countries [2]. Hence, reducing the energy required to heat buildings domestic and commercial buildings presents one part of a solution to reach the goal of cutting carbon emission. Recently, natural ventilation techniques such as windcatchers were increasingly being employed in buildings for increasing the supply of fresh air and reducing the mechanical ventilation consumption [3]. Windcatchers were utilised in buildings in the Middle East for many centuries and their commercialisation had increased over the years [4, 5]. A windcatcher is divided into quadrants, which allow fresh air to enter as well as stale (used) air to escape irrespective of the prevailing wind direction (Figure 1a). The windcatchers provides fresh air driven by the positive air pressure on the wind-ward side, while exhausting stale air with the assistance of the suction pressure on the leeward side. Windcatchers also operate by a secondary action of the stack effect; the density of air decreases as the temperature increases, causing warmer air to rise and exit the windcatchers. In mild-cold climates such as in the UK, their use is generally limited to the summer, as shown in Figure 1. This is due to the potential for low incoming air temperatures to cause thermal discomfort to the occupants and the use of natural ventilation solutions will increase heat loss and lead to increased energy costs [6]. While by restricting the use of natural ventilation during winter months, the concentration of pollutants have been seen to rise above the accepted guideline levels, which can lead to poor mental performance and ill health [5, 6].

Recently, windcatchers have undergone considerable amount of research to better understand the effect of airflow through and over windcatchers as well as the ventilation rates that can be provided by these systems [7]. Further to this, attempts have been made to improve the thermal comfort that can be provided to occupants [8]. The work has been conducted through the use of CFD modelling as well as scaled wind tunnel testing and in some cases, in situ or field testing in order to understand the effects in a real-world environment [9].

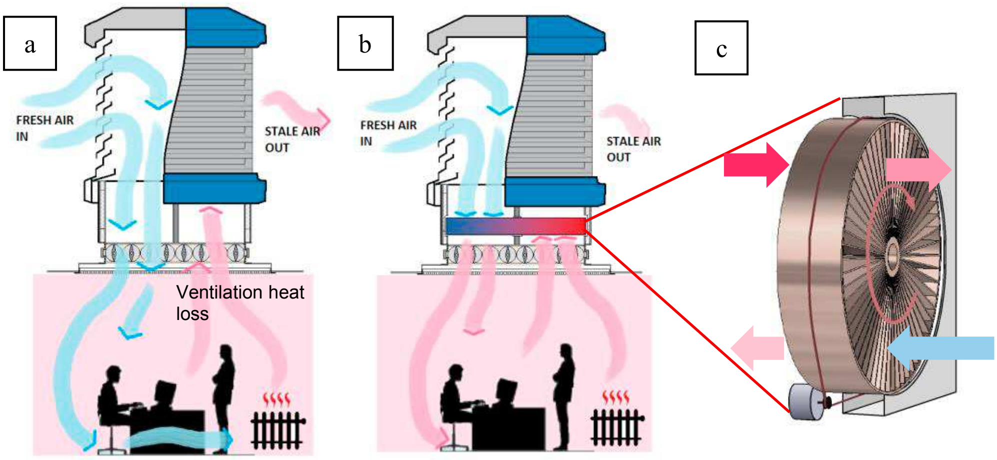

Fig. 1. (a) standard windcatcher (b) passive heat recovery windcatcher (c) proposed passive heat recovery wheel

Though windcatcher cooling [10-12] has had more attention in the past, little work has been carried out in the area of heat recovery or heating incoming air in windcatchers. Shao et al. [13] noted that passive stack systems are designed without heat recovery which leads to large amounts of wasted heat. Woods et al. [14] looked at the use of windcatchers during the winter using air mixing techniques to dilute the incoming cool air with the internal air. This system increased the incoming air temperature, thereby negating the heat demand whilst maintaining adequate pollutant levels but required very strict building design and control systems. Though this area of research is expanding with more teams exploring the potential of heat recovery in passive ventilation systems, little work has been performed on the use of the rotary thermal wheels specifically in natural ventilation. This is due to the high pressure drop across the rotary wheel which can impede the flow of air through the natural ventilation system. Rotary thermal wheels provide heat recovery at a high efficiency, even when compared to other heat recovery technology. The potential for energy savings using a rotary thermal wheel coupled with a passive ventilation system such as a wind tower are high. The lack of current research exploring a system similar to this demonstrates a key gap in existing knowledge.

To improve the year-round capabilities of windcatcher systems to enable consistent use during cooler months, a retrofit heat recovery system is desirable. This study introduces and discusses the potential of this concept using CFD analysis and wind tunnel experimental for validation. The concept is to attach a redesigned rotary heat recovery wheel system at the bottom channel of a windcatcher, as shown in Figure 1b. Using the properties of the thermal wheel as a heat exchanger, the thermal energy in the internal exhaust air is recovered to the incoming air. This concept raises the incoming air temperature. By raising the temperature of the incoming air from the windcatcher, adequate year-round ventilation is maintained and during the heating season, energy demand for heating systems is reduced.

2. Methodology

2.1. Numerical modelling

ANSYS Fluent 18 software was used to conduct the steady-state Reynolds averaged Navier–Stokes equation) which employed a control-volume-based technique for solving the flow equations. The standard k-e turbulence model was used, which is a well-established method in research on windcatcher natural ventilation [4]. Second-order upwind scheme was used to discretised all the transport equations. The numerical code used the semi-Implicit method for pressure-linked equations algorithm for the velocity-pressure coupling of the computation. The governing equations are not repeated here but available in the ANSYS User guide. The flow domain representation of the geometry of the windcatcher and location of set boundary conditions are shown in Figure 2a. A 5 x 5 x 10 m^3 enclosure was created to simulate the velocity of the outdoor wind. Furthermore, the model of the 1 x 1 m^2 windcatcher was integrated to a test room located beneath it. The test room with an internal volume of 3 x 3 x 5 m3 represents a small classroom [7]. windcatcher was modelled with seven louvres angled at 45°. The wind tower was assumed to be supplying at 100% (fully open), therefore the volume control dampers was not added to the model. The rotary heat recovery wheel was connected below the windcatcher as a separate part. Unlike previous works, the rotary heat recovery wheel was modelled explicitly with radial plates instead of using porous zone method. A non-uniform mesh was applied to the volumes of the computational model. The computational mesh of the windcatcher and test room model is shown in Figure 2b. The mesh was refined around critical areas of interests in the simulation. Several meshes were generated to investigate the solution independency from the mesh. The mesh was refined (mesh sizes ranging from 2.8 to 7.4 million elements) until the posterior estimate error became insignificant between the number of elements and the posterior error indicator (supply velocity). The discretisation error was found to be the lowest at over 7.4 million elements.

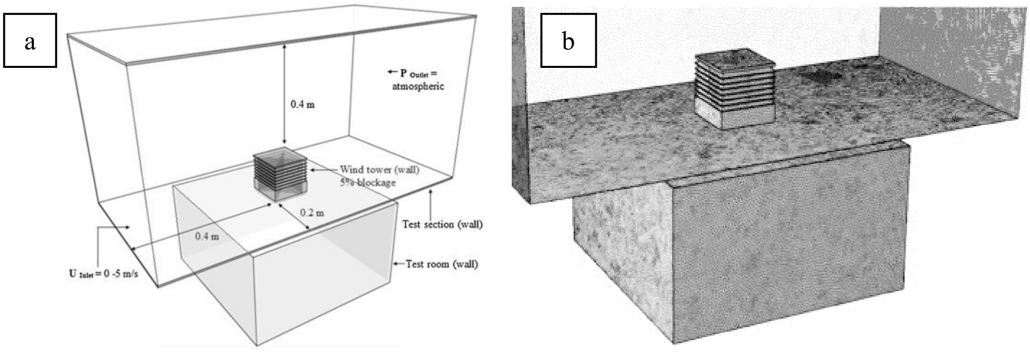

Fig. 2. (a) Computational domain (b) mesh design

The rotation of the rotary heat recovery wheel was modelled using frame motion in ANSYS Fluent. The mesh motion of the rotary heat recovery wheel was orientated at the centre point and vertical axis of the wheel; this ensured that the volume rotated around the centre point at the required speeds of 15rpm (1.57 rads/s). The material of the heat recovery wheel was set to copper. The CFD analysis was performed at various outdoor wind speeds (0 - 5 m/s). The pressure outlet was set to 0 Pa (atmospheric). For the analysis of the windcatcher, the external air temperature was set to 283 K to simulate a cold outdoor environment. This was chosen as it represented the average annual air temperature in the UK according to the UK Met Office. The floor was set as a heat source with a heat flux of 75 W/m2 to simulate the internal heat gains (occupants and equipment) in a teaching space.

2.2. Experimental wind tunnel testing

The experimental investigation was conducted in a closed-loop wind tunnel [15]. The size of the test section was 0.5 x 0.5 m2 and 1m length (Fig 3). A 1:10 scale model of the windcatcher with heat recovery wheel was used in the experimental study. The creation of an accurate scaled model was essential for the study; therefore, the windcatcher was constructed using 3D printing. The scale of the model of the windcatcher was selected to maintain, as close as possible, equality of model and prototype ratios of overall dimensions to the important meteorological lengths of the simulated wind. The rotary heat recovery wheel was designed to be 80mm in diameter with a depth of 20mm and porosity of 70%. The rotary heat recovery wheel was held in place in the casing by using supports which did not interfere with the rotation. In order to achieve the required rotation speed for the wheel, a rotation shaft was fitted through the test section vertically which connected to a DC motor underneath the test section. The rotation shaft was kept as thin as possible in order to prevent the flow being affected. The scale model of the windcatcher produced a maximum wind tunnel blockage of 4.8%. The model of the windcatcher was connected to a 0.5 x 0.5 x 0.3 m^3 test room, mounted underneath the test section.

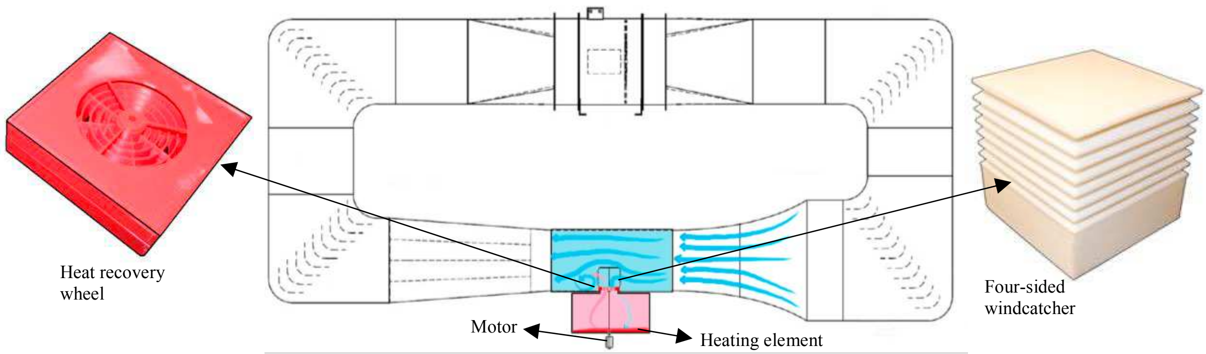

Fig. 3. Experimental wind tunnel testing of the passive heat recovery windcatcher

In order to assess the air flow characteristics through the windcatcher with the rotary heat recovery wheel, nine predetermined points within the room model were used for the measurement of the air velocity (Figure 4b). The nine points within the room model were chosen in order to give an equal spread of measurement points and to ensure that the mixture profile of the air could be monitored. The hot wire probe (Testo 425) gave velocity measurements with uncertainty of ±1.0 % rdg. at speeds lower than 8 m/s.

4. Results and Discussion

To validate the CFD model against the experimental model, the percentage error between the two data sets must be to an acceptable level. In addition to percentage error as an indicator of correlation, identifying equal trends in both sets of data is important to validate the CFD model. To determine the accuracy of the CFD model in relation to the wind tunnel model, first a comparison of the quantitative data was taken to calculate the numerical accuracy. The air velocity at the building model mid-height was calculated at each of the nine measurement points for the three different external air velocities. Figure 4a shows a comparison between the experimental and CFD results of the velocity measurements. This comparison showed a low difference range and the trends were to be in a good agreement. Average error across the points was 7.46%. It should be noted that the boundary conditions in the CFD model were kept as similar as possible to those in the experiment, minimising the error which could be caused.

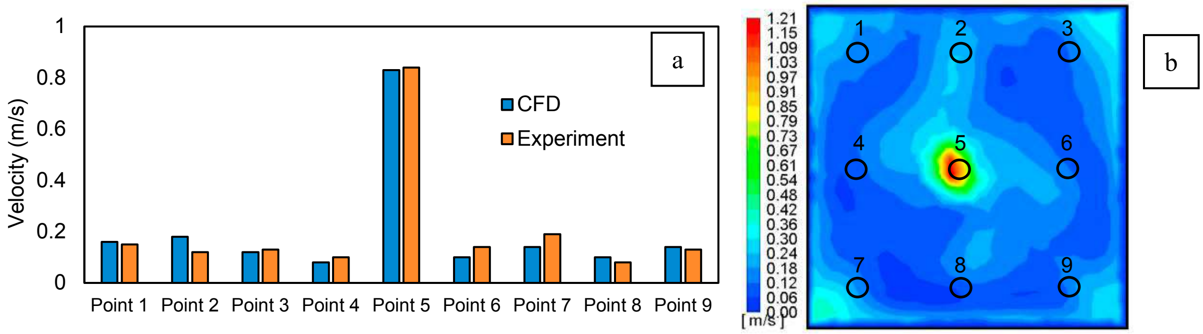

Fig. 4. (a) Comparison between CFD and experiment values of air velocity (b) measurement points at a height of 150mm in the test room.

Figure 5a shows the temperature contours of the cross-sectional plane in the test room model. As observed, the addition of heat recovery had a positive effect on the indoor air temperature, raising the incoming fresh air to 284-285K when the outdoor wind speed and temperature are 3m/s and 283K. It is worth noting that the temperature difference seen in the inflow and outflow of the wind tower. On the inlet stream of the wheel, the air temperature is at 283 K. On the outlet stream of the wheel, the air temperature is 290 K due to the heating effect of the floor area. This suggests that if the increased temperature in the outlet stream can be recovered and transferred to the inlet stream, the inlet temperature would reduce the demand on any heating system used. Further to this, the inlet air temperature was set at 283 K which is higher than average winter outdoor air temperature during the recorded in the UK between 1981 and 2010 of 277–279 K, meaning that the exhaust stream temperature would be even higher than the inlet stream temperature, giving great potential for thermal energy recovery and transfer.

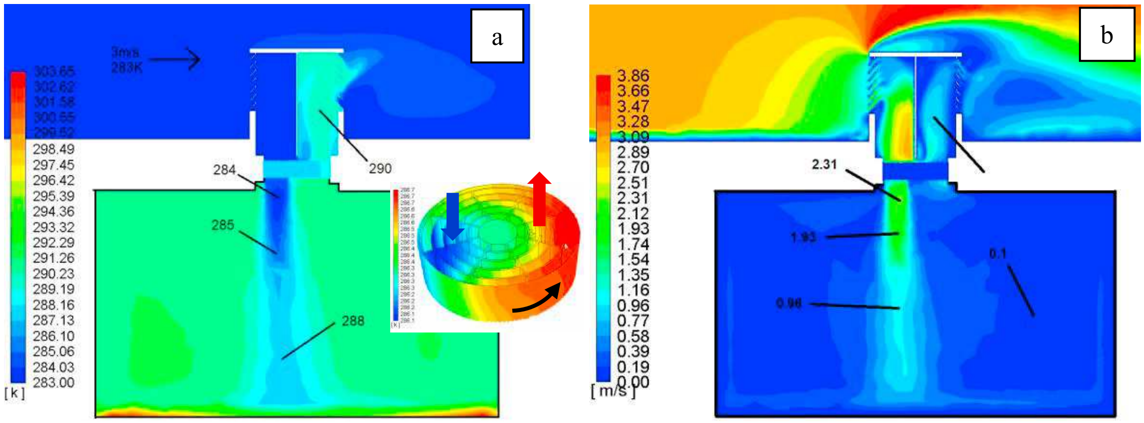

Fig. 5. Cross-sectional contour planes of (a) air temperature (b) air velocity with the outdoor wind speed and temperature at 3m/s and 283K

Figure 5b 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 as it turns sharply inside the 90° corner. Although reduction in speed was observed downstream of the heat recovery device, it did not impede the ventilation rate of the wind catcher. A column of fast moving air enters the space, where the airstream hit the floor of the room and circulated inside the structure and exited the wind catcher exhaust. Large recirculation region was observed at the leeward side of the wind tower. Figure 6a shows the effect of varying the outdoor wind speed on the indoor air temperature for standard windcatcher and windcatcher with heat recovery. As expected, the higher the outdoor wind speed, the lower resultant air temperature inside the room. The rate at which the internal temperature falls as the inlet velocity increases was of significance. A more substantial temperature increase was seen from 2 m/s to 3 m/s (2-4 K supply air temperature reduction) outdoor wind speed, than from 3 m/s to 5 m/s (1-2 K supply air temperature reduction). Figure 6b shows the effect of varying the outdoor wind speed on the average indoor air velocity.

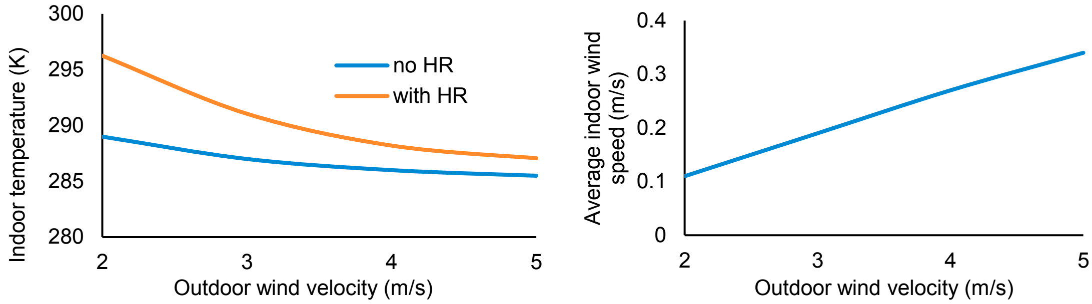

Fig. 6. Effect of varying external wind speeds on average (a) indoor temperature (b) indoor velocity

5. Conclusion and Future Work

In this study, the air flow through a windcatcher with a rotary heat recovery wheel was investigated using CFD modelling. It has been shown in previous work that windcatchers are capable of delivering the guideline levels of ventilation into a room, therefore the rotary wheel should not reduce the air supply rate to unsuitable levels to provide adequate ventilation to be an effective system. The numerical modelling was validated against experimental models tested in a closed-loop wind tunnel. The comparison between the CFD and experimental model showed a good correlation between the two sets of data. Results showed that the addition of heat recovery had a positive effect on the indoor air temperature, raising the temperature between 1-4 K depending on the outdoor wind conditions. According to WBCSD [2], a recovery of 3 K from the exhaust stream to the inlet stream could generate energy savings up to 20% in heating costs. This shows that the concept has significant potential to be developed further, whereby the heat transfer properties of the system can be investigated and tested on a larger scale.

Acknowledgement

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