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NUMERICAL AND EXPERIMENTAL ANALYSIS OF A NOVEL PASSIVE HEAT RECOVERY WINDCATCHER (PHRW)

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ABSTRACT

This work proposes a novel design incorporating a passive heat recovery device into a windcatcher and investigates its performance using numerical and experimental analysis. Numerical modelling and experimental testing were used to characterise the radial blade design of the heat recovery rotary wheel in terms of performance. Two configurations of the radial blades provide data that can be used to assess how air velocity is affected by the design, the pressure drop across the device and the heat transfer capabilities of the radial blades. To further assess the potential of the proposed devices, it was incorporated into a multi-directional windcatcher ventilating a small room. Despite the blockage of the rotary heat recovery wheel, it was able 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 0.5-4K depending on the indoor/outdoor conditions, this passive recovery has the potential to reduce demand on space heating systems.

Keywords: Built environment, CFD, heat recovery, natural 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 [4] and their commercialisation had increased over the years [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

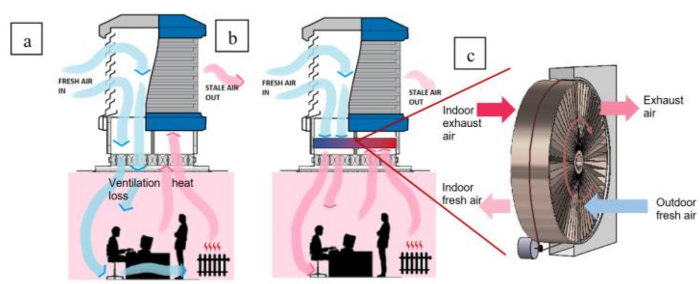

Fig 1 (a) standard windcatcher (b) passive heat recovery windcatcher (c) proposed passive heat recovery wheel

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

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concentration of pollutants have been seen to rise above the accepted guideline levels, which can lead to poor mental performance [5] and ill health [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].

Though windcatcher cooling has had more attention in the past [10 -12], little work has been carried out in the area of heat recovery [13] or heating incoming air in windcatchers. Shao et al. [14] noted that passive stack systems are designed without heat recovery which leads to large amounts of wasted heat. Woods et al. [15] 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. Younis and Shoukry [16] and Calay and Wang [17] examined the use of rotary thermal wheels for residential building applications. These studies indicate that a rotary thermal wheel may be applicable for heat exchange in ventilation, both for summer and winter conditions. However, both studies used forced ventilation in order to overcome the expected pressure drop across the rotary wheel which leads to the energy implication of the fans. 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. METHOD

2.1 *Numerical modelling*

The commercial CFD tool FLUENT within ANSYS Workbench is used to carry out the numerical modelling of the passive heat recovery device. The equations detailed here relate to those utilised in FLUENTv18, adapted from the ANSYS Theory Guide. It should be noted that the governing equations are not altered in this study. The mass and momentum equations are solved for all flow types. Due to the heat transfer involved in the study, the energy equation is required. As the model flow will be turbulent, the Reynolds-averaged Navier-Stokes and the k-epsilon equations are essential which are well-established methods in the research on natural ventilation flows [6, 12]. Second-order upwind scheme is employed to discretise all the transport

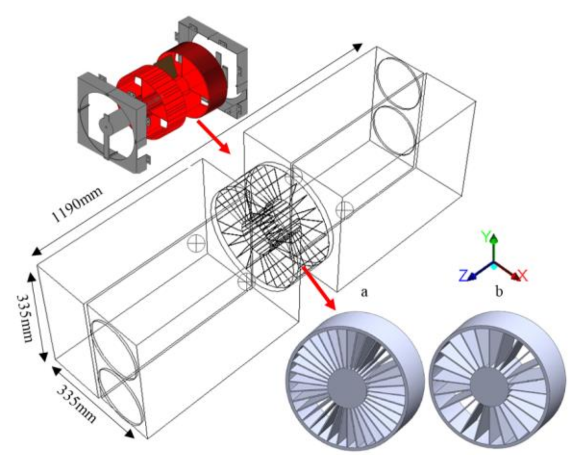

Fig 2 Computational model of the two-way cross-flow duct used for evaluating the performance of (a) 32- and (b) 20-radial blade arrangement

equations. The most commonly used Semi-implicit method for pressure-linked equations segregated pressure-based algorithm solver is used in this study.

For processing using ANSYS CFD, geometry is created in SolidWorks a commercial 3D CAD software and imported for flow analysis. The present study requires the modelling of separate components that are assembled into an integrated system which can be done in Solidworks. The geometry generated in CAD is imported to ANSYS Design Modeler which requires further modification to define the computational fluid domain required for the CFD simulations. Two types of radial blade rotary wheel configurations are produced for numerical investigation (Figure 3). The angle of separation between radial blades is varied between 10° (32 radial blades) and 15° (20 radial blades).

In order to examine the device performance under controlled conditions, it is decided that two adjacent airflow streams flowing in opposite directions would be used. To make computation quicker, the complexity of the ductwork and heat recovery device is reduced. In the full experimental tests, two airflow streams flowing in opposite directions with the heat recovery device rotating and transferring heat between the airflow streams. To simplify the CFD simulations, it is decided that one airflow channel would be modelled at a time. Since the geometry modelled in CFD is to be the identical size as the experimental model, the limitation of the rapid prototyping equipment is taken into consideration. Limitations of the 3D printing size resulted in a heat recovery wheel with a diameter of 0.3m and depth of 0.105m. The 2mm rotary blades are made of and copper and had a dimension of 0.100x0.100m^2. Each channel has a fluid volume of 0.160x0.325x0.490m^3. The channels included a pressure inlet (15Pa, 21.4- 23.9ºC) at one end and two circular outlets (15Pa, 24.7-39ºC) on the opposite side. Additional volumes are also imported and added to the solid geometry to model the volumes of copper in the device, located between the radial blades for simplification. The added radial blade volumes are used to set source/sink term functions which is used to modify the flow properties that pass through the fluid volume for example to simulate the transfer of energy

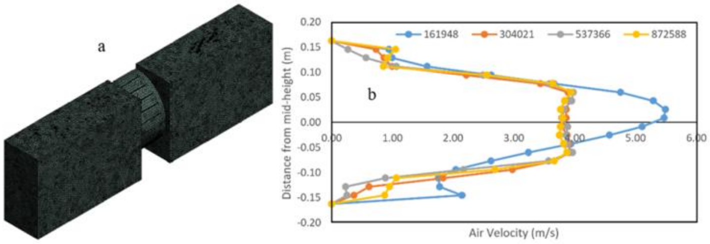

Fig 3 (a) Computational mesh (b) mesh sensitivity analysis

between the incoming (fresh, outdoor air) and outgoing (from the internal environment) airstreams.

Mesh sizing is applied to all geometry surfaces, with 0.0075m element size for all configurations (Figure 3). The number of mesh elements ranged between 526,000 and 872,000, which is due to the differences in geometry

In order to verify the CFD solutions independence from the grid, sensitivity analysis is carried out. The results (vertical air velocity profile taken from duct centreline) of each run is compared as shown in Figure 3b.

Similar tools and methods are used to carry out the modelling of the windcatcher with the passive heat recovery device. Figure 4a displays the computational domain of the windcatcher mounted on top of a small test room. The wind tunnel test section is created as an enclosure which allows the simulation of airflow around the windcatcher model. A velocity flow field is generated by setting one plane as velocity inlet and the other plane as pressure outlet. The study ensured that the numerical modelling boundary conditions. The windcatcher model is based on a modern design which incorporated angled louvres and control dampers. The internal channel of the windcatcher is split by a cross divider which allows the

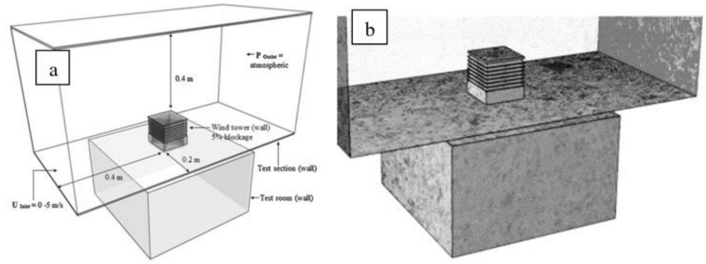

Fig 4 (a) Computational domain (b) mesh around the surfaces of the model arrangement

device to capture airflow from any direction. Unlike the standalone heat recovery wheel simulation, the full passive heat recovery wheel is simulated with the windcatcher. The passive heat recovery device is connected below the windcatcher. Similarly, the heat recovery wheel and its radial blades are explicitly modelled. Figure 4b shows the generated computational mesh around the surfaces of the 3D model of the windcatcher device, test room and enclosure. Grid sensitivity analysis is also carried out to assess the independence of the CFD solution from the mesh size.

The rotating heat recovery device is modelled using rotating frame motion in ANSYS FLUENT. This assumes that the device is steadily, allowing for a steady state solution. The motion of the rotary device is orientated at its mid-point and z-axis direction. The rotation velocity is set to 1.57 rad/sec (15 rpm). The radial blade material is set to copper (density-8978 kg/m3, specific heat-381j/kgK and thermal conductivity-387.6W/mK). The numerical analysis is conducted at various outdoor wind speeds ranging between 1-5 m/s. The pressure outlet is set to 0 Pa. In order to simulate a cold outdoor airflow, the outdoor air temperature is set to 10°C (283K). This is chosen as it represents the average annual air temperature in the UK (UK Met Office). The test room floor is set as a heat flux boundary condition of 75 W/m2 to take into account the heat gains from occupants and equipment.

2.2 *Experimental testing*

The concept of the rotary wheel with radial blades is shown in Figure 5. In order to test the new design, prototypes of the rotary wheel and an appropriate

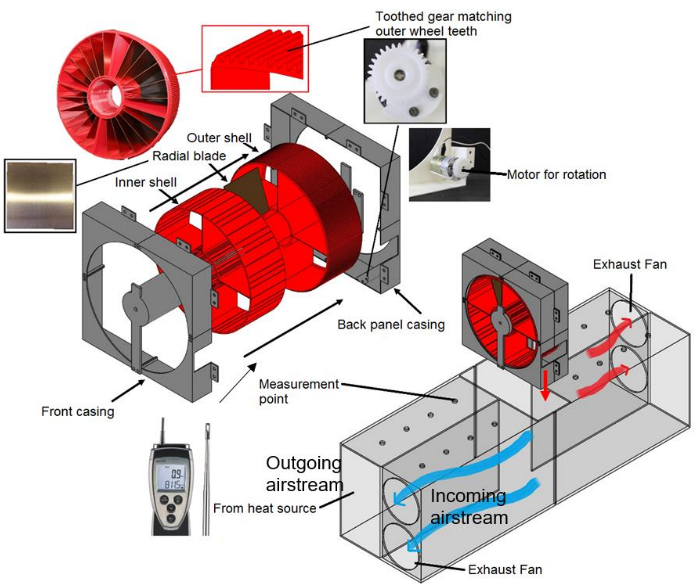

Fig 5 Experimental setup of the passive heat recovery wheel test

covering are built and incorporated into a duct work with two counter current channels (incoming and outgoing airflow as described previously) with varying properties to assess the thermal performance of the device. The flows properties are measured upstream and downstream of the rotary wheel in both channels then its performance is analysed. The measurement points are located at the centre of each channel at 0.1m intervals. The incoming airflow conditions are dictated by the conditions of the laboratory internal space (temperature ranged between 21.4-23.9°C) while the outgoing airstream temperature is conditioned using a heat source (24.7-39.8°C). The rotary wheel is set to constantly rotate at 6rpm, driven by a motor and gear system incorporated within the case of the device as shown in Figure 7. Given the wheel size and the motor available for use, 6rpm is decided as a suitable compromise of rotation speed. Most of the components (the rotary wheel and casing) are non-standard and required the use of 3D printing. Copper plates are used for the heat recovery radial blades with the dimensions 100mmx100mmx1mm. The inner shell of the rotary wheel with 0.145m diameter is designed to house the radial blades. In order to provide the rotation, a toothed gear attached to a small motor is utilised. The outer shell is designed to match the teeth on the gear to allow the smooth rotation of the wheel. 3D printing is used to construct the shell accurately.

In order to investigate the effect of the passive rotary wheel on the supply air temperature measurements are carried out. The air temperature is recorded at the same locations using Testo 176 P1 logger and temperature probe with a measuring range of -20 to 70^{o}C, accuracy of ±0.03°C and resolution of 0.1°C. Simultaneous measurements are made at all data collection points, every 5 seconds for a one-hour period. Carrying out the monitoring over a long period permitted for slow changes in the airflow condition to be observed.

3. RESULTS AND DISCUSSION

The airflow temperature before and after the device is assessed in both the experiments and numerical modelling. Due to the nature of numerical CFD analysis of a problem and experiment setup and measurement, the introduction of uncertainties in the design and errors in the result values is generally unavoidable. Therefore, validation of the CFD models by using the experiment. Figure 6 shows a comparison of the air temperature results from the CFD model and experimental tests. The measurements show the air temperature 100mm after the heat recovery rotary wheel. The different tests represent the changes to the outgoing airstream inlet temperature, ranging from 25-40°C. As observed, a good agreement is observed between both methods, with the average error at 0.16% and 0.07% for the incoming and outgoing airstreams. The expected trend of increased temperature change for both airflow streams as the outgoing airstream inlet temperature increased is observed for both configurations. Although the temperature change increased as the outgoing inlet air temperature increased, the temperature change is not equal between the two airstream. The temperature change in the outgoing airstream (0.2-2.3°C for HR32-1 to HR32-4) is higher than the incoming airstream (014-0.7°C for HR32-1 to HR32-4) which shows that the design of radial blade is effective at conducting heat from the outgoing airflow but less effective at releasing this energy to the incoming airstream. This suggests that significant thermal energy is stored within the radial blades. Increasing the ability of the blades to dissipate the stored thermal energy would increase the performance of the device. It should also be noted that the inlet temperature for the incoming airflow is between 23.1-23.9°C which is not the temperature range the device is designed for. However due to the limitations of the experimental tests, the incoming air is

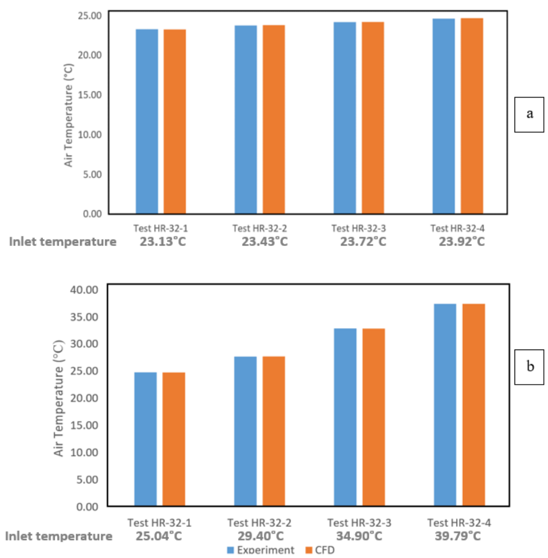

Fig 6 Comparison between experiment and CFD air temperature in the (a) incoming and (b) outgoing airstream after the 32 blade rotary wheel.

not conditioned and dependent on the lab room temperature. Given the relatively high incoming airflow stream inlet temperature, further investigation would be advised. As the heat recovery device is designed for passive ventilation integration, the incoming air temperature should represent the external air conditions and temperature. Common outdoor air temperatures in the UK and northern Europe, areas where device would be most beneficial in winter months, would be significantly lower (8-11°C in the UK) than the temperatures measured in here.

Figure 7a 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. Figure 7b 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

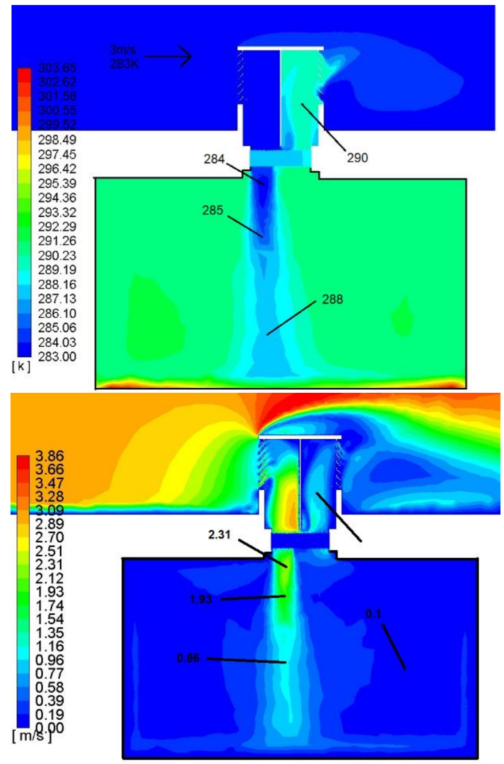

Fig 7 Cross-sectional contour planes of (a) air temperature (b) air velocity with the outdoor wind speed and temperature at 3m/s and 283K

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.

4. CONCLUSION AND FUTURE WORKS

Following the experimental testing and simulations of CFD models, it is necessary to characterise the radial blade design of the heat recovery rotary wheel in terms of performance. These characteristics inform how successful the integration of the design into a passive ventilation system would be. The results from the experiments and CFD testing show that the transfer of heat from the outgoing airstream to the incoming airstream is possible with the radial blade configuration of the rotary wheel. The maximum increase in temperature of the incoming airstream was 0.68°C for the 32-blade configuration when the temperature of the outgoing airstream was 40°C. This is higher than the outgoing air temperature of a standard occupied room and would require additional energy input to increase outgoing air temperature, offsetting any savings of increased incoming air temperature. Given the potential for the radial blade rotary wheel not to impede the flow of air through the system, the development of the radial blade design should focus on increasing the efficiency of heat transfer across the device. The high conductivity of the copper material used in the blades is effective at storing heat in the wheel matrix, effective radiation and convection of the heat to the incoming airstream is required.

To further assess the potential of the proposed devices, it was incorporated into a multi-directional windcatcher ventilating a small room. The air flow through a windcatcher with a rotary heat recovery wheel was also 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 0.5-4 K depending on the outdoor wind conditions. 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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