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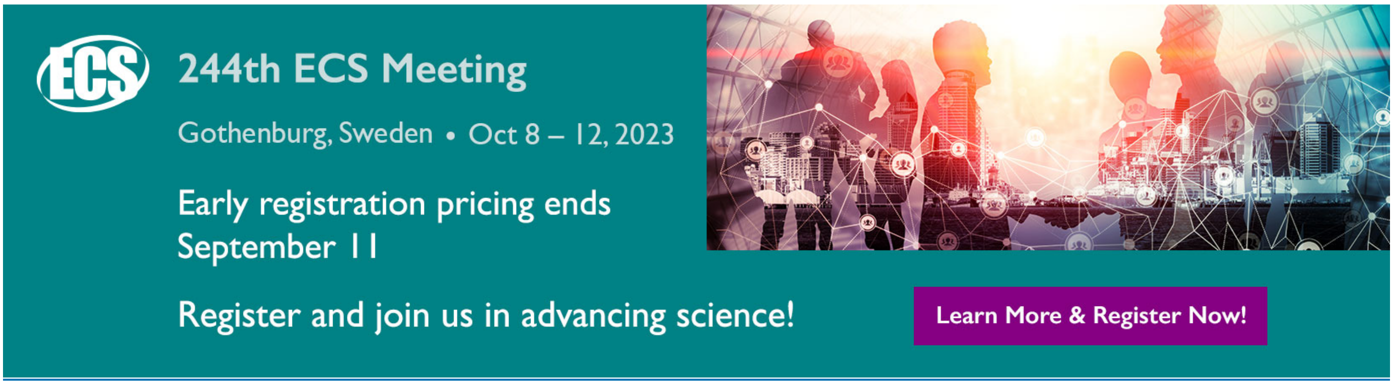

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Analysis of a rotary passive heat recovery device for natural ventilation windcatcher

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Abstract

Based on the design of traditional architecture, windcatchers are devices which provides passive ventilation by manipulating pressure differentials around buildings induced by the movement of wind and difference in temperature. In temperature climates, it is effective in providing passive cooling during summer months. However, during winter months, the low air temperature supplied to the space can cause further thermal discomfort and increase heat loss which lead to higher energy consumption. This limits the capabilities of windcatchers to provide ventilation all year round. To address this issue, the present study proposes incorporating a rotary thermal heat recovery device into the windcatcher channel and investigate its performance using numerical modelling and experimental tests. The study focused on characterizing the design and performance of the copper radial blades of the proposed heat recovery device. The predicted results of the airflow and temperature showed good agreement with the experimental tests. Two types of radial blade designs were assessed in terms of the airflow velocity and distribution, the pressure drop and the heat recovery performance.

Keywords: built environment, CFD, heat recovery, natural ventilation

1. Introduction

The commitment of UK government in minimizing greenhouse gas emission by at least eighty percent of 1990 levels in the year 2050 has been the greatest drive in reduction of energy use within the built environment [1]. A huge portion of energy consumption comes from space heating which records forty percent of the overall energy use in service and residential sector [2]. Therefore, minimizing the energy demand to heat commercial and domestic buildings can contribute in providing solutions to achieve the aim of reducing carbon emissions. Nowadays, the use of natural ventilation methods is now being recognized and installed in buildings for reducing the mechanical ventilation use and increasing the supply of fresh air [3]. Windcatchers are normally used in Middle Eastern countries and currently increasing its presence in the market [4,5].

Figure 1a shows the structure and function of a windcatcher. This type of system provides fresh air driven by the air pressure on the wind ward area, while exhausting stale air assisted with suction pressure on the leeward area. Moreover, it can also function using the stack effect method; the air mass reduces when the temperature rises, resulting warmer air to go up and depart the windcatcher's openings. In countries with temperate climate like the United Kingdom, their operation is limited during summer. This is due to the low temperature of the incoming or supply air that can lead to thermal discomfort within the occupied space and increase heat loss [6]. While when the use of natural ventilation is restricted, the mixture of contaminants has been observed to increase more than the recognised guidance levels, that can result to illness and poor mental performance [5,6].

Several researches were already carried out on wind catchers. The main goal is to improve the understanding on the effect of airflow over and through wind catchers and the ventilation level that devices can offer [7]. Moreover, these studies have been conducted to enhance the thermal comfort which can be offered to occupiers [8]. This study will use scaled wind tunnel testing, CFD modelling, and also field or situ testing to recognize the effects in a real-world setting [9].

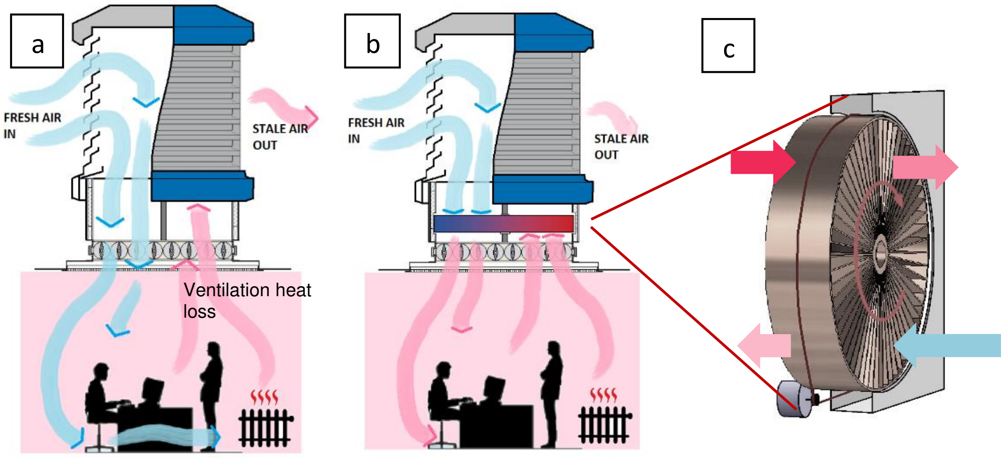

Figure 1. a) standard windcatcher b) wind catcher with heat recovery wheel c) rotary wheel with radial blades

It has been observed that there are several studies on wind catcher cooling, but few on heating incoming air or heat recovery in wind catchers [10-12]. In Shao et al. [13] study, it was revealed that passive stack system design without heat recovery resulted in a huge amount of wasted heat. Woods et al. [14] investigated the application of wind catchers during the winter with the assistance of air mixing methods to dilute the incoming cool air with the indoor air. The wind catcher increased the incoming air temperature, thus reducing the heat demand and at the same time keeping enough level of contaminants, however it required strict control methods. Even though this topic of research is growing with more researchers investigating the performance of heat recovery in passive ventilation techniques, there are still few works carried out in the application of the rotary thermal wheels in natural ventilation. This is due to the high pressure drop across the rotary wheel that can hinder the air flow through the natural ventilation device. This type of device offers heat recovery at a high efficiency, even if compared to other heat recovery device. The energy saving potential of utilizing rotary wheel incorporated with a passive ventilation device like wind tower are high.

In order to enhance the performance of wind catcher devices to allow continuous usage in heating season, integration of a passive heat recovery device is required. This research will assess the performance of the proposed device using numerical modelling and experimental tests for validation. A redesigned rotary heat recovery wheel device will be installed below the wind catcher's channel. Utilizing the components of the thermal wheel as a heat exchanger, thermal energy in the indoor exhaust air is recovered to the incoming air. This technique increases the incoming air temperature. Through increasing the incoming air temperature from the wind catcher, sufficient year around ventilation is maintained during winter, the demand of energy for heating devices will be minimized.

2. Methodology

2.1. Numerical modelling

This study used numerical analysis and experimental testing to examine the potential of the heat recovery and validated the results, as demonstrated in Figure 2. Fluent CFD will be used for numerical modelling, while a combination of wind tunnel testing and full-scale laboratory examination for experimental testing.

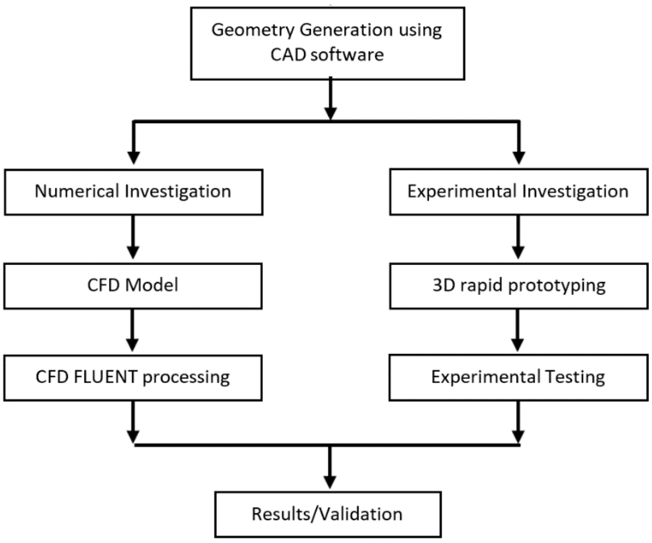

Figure 2. Numerical and experimental methodology

The ANSYS Fluent software was used to investigate the numerical modelling of the passive heat recovery system. 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 [15-18]. Second-order upwind scheme is employed to discretised all the transport equations. The most commonly used Semi-implicit method for pressure-linked equations segregated pressure-based algorithm solver is used in this study [19-20].

By using ANSYS CFD, geometry was formed in SolidWorks and imported for flow examination. The geometry created in CAD was transferred to ANSYS Design Modeler that needs further adjustment to identify the domain needed for the CFD modelling. There are two kinds of radial blade rotary wheel arrangements created for this study, as shown in Figure 3. The angular separation among radial blades differ between 15° (20 radial blades) and 10° (32 radial blades).

In order to ensure that the numerical results compared to the experimental data are as close as possible, the simulation should reflect similar conditions as in the experimental tests. For the computational demands to be reduced, the geometry for the CFD models was simplified. In order for the computation to be faster, the intricacy of the heat recovery device and ductwork were decreased, as demonstrated in Figure 3. The 2 mm rotary blades used in this study had 0.100 x 0.100m^2 dimensions and these are made of copper. Every channel has a fluid volume of 0.160 x 0.325 x 0.490m$^{3.}$ The channel consisted an inlet at one end and two circular outlets on the opposite area. During the test, fans were installed at the outlets to direct the flow to the passageways. 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.

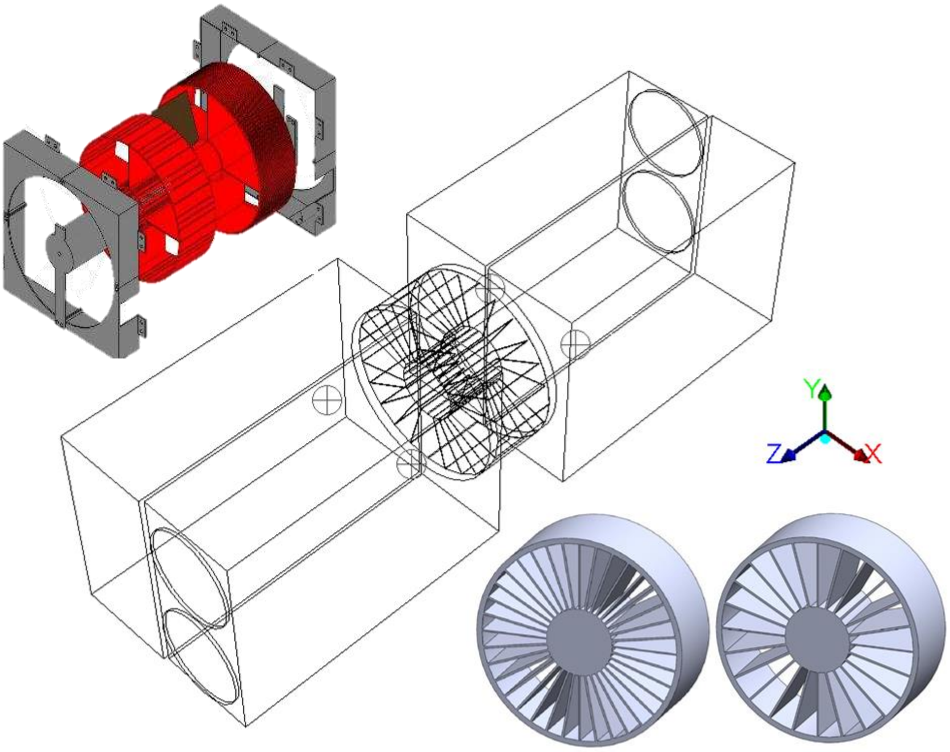

Figure 3. CFD model of the two way cross-flow duct utilised for evaluation.

Since there are variations with the geometry of different arrangements, each needed a single mesh to be created. Mesh sizing was used for the entire geometry surfaces, with element size of 0.0075m for all the arrangements. The volume of mesh elements were approximately 526,000 to 872,000, and this is because of variations in geometry. To validate the CFD grid independence solutions, sensitivity assessment was used. This is done through generating several different mesh sizes with geometries configuration and simulating the model using similar boundary conditions. Table 1 shows the values for the boundary conditions gathered from the calculations during the examinations.

Table 1. Overview of boundary conditions.

Input Condition	Value	
	Supply Air	Exhaust Air
Pressure Inlet (Pa)	15	15
Exhaust Fan Outlet (Pa)	2.5	2.5
Inlet Air Temperature (°C)	21.4- 23.9	24.7-39.
Wheel Rotation Speed (rpm)	6	6
Source (W/m^3)	100,000-750,000	-
Sink (W/m^3)	-	200,000-4,800,000

2.2. Experimental testing

The concept of the rotary wheel with radial blades is shown in Figure 4. To assess the performance of the new design, models of the rotary wheel and suitable covering are created and integrated to the duct work with two counter current passageways (exhaust and supply air flow) with varying material properties to evaluate the thermal performance of the system. The flow properties were measured downstream and upstream of the rotary wheel for each passageway then its potential was evaluated. The measurement points were positioned at the center of every passageway at 0.1 m intervals. The supply air flow settings were ordered through the situations of the lab indoor space (temperature around 21.4-23.9 °C) whereas the departing air stream temperature was conditioned using a heat source (24.7-39.8°C) [21]. The purpose of the experiment was to examine the potential of recovery and thus sufficient continuous supply air flow stream and controlled exhaust air flow stream temperature was useful. The wheel was set to continuously rotate at 6rpm, assisted with motor and gear device integrated inside the case of the system, as demonstrated in Figure 4. With the available motor and given wheel size, 6rpm was decided as the appropriate rotation speed.

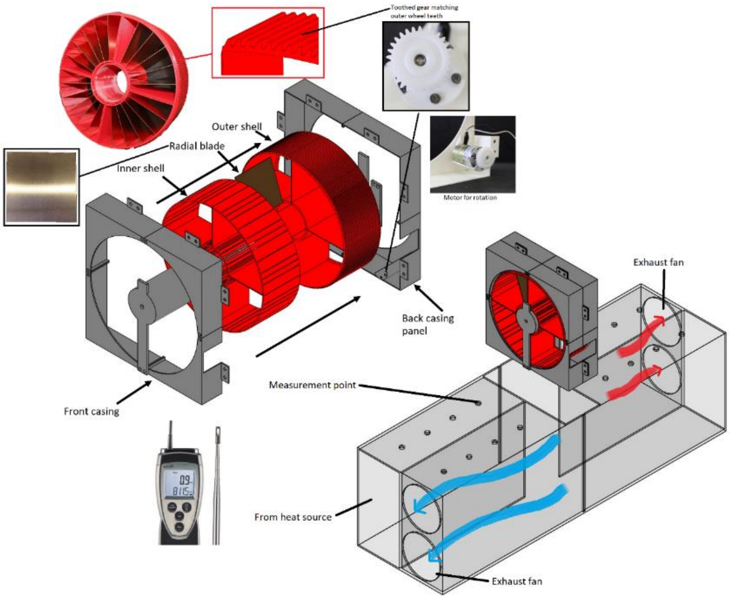

Figure 4. Arrangement of the passive heat recovery wheel experiment.

Four regulated similar axial fans were incorporated at every channel to drive the air flow. Air is drawn from the duct inlets through the channel by the axial fans (suction driven flow). This arrangement showed the greatest uniform velocity profile in the channels. Many of the elements such as casing and rotary wheel were nonstandard and needed the use of 3D printing. Figure 4 demonstrates the total dimension of the ductwork with 5 mm acrylic Perspex material. Casing of the heat recovery system sit flush in the ductwork and any air gaps were closed at the time of experimental testing such as measurement points that are unused. The copper plates were applied for the heat recovery radial blades having 100 mm x 100 mm x 1mm dimensions. The rotary wheel's inner shell with diameter 0.145 m was built to house the radial blades. For the system to rotate, a toothed gear incorporated to a small motor was used. While for the outer shell, it was built to match the teeth on the gear to let the wheel rotate smoothly. In order to build the shell accurately, 3D printing was utilized. To examine the response of the passive rotary wheel on the supply air ventilation level, air flow velocity measurements were conducted. As mentioned in the previous section, low pressure drop over the system was required to make sure that the needed ventilation levels will be reached even at low wind speeds. Velocity measurements were conducted through utilising Testo 425 hot wire anemometer with resolution of 0.01m/s and an accuracy of 0.03 m/s +5%rdg. In every calculation area, the air velocity was calculated for twenty seconds and the mean velocity rate was recorded. The measurement was conducted three times for every area. Air temperature was taken at similar areas with the use of Testo 176 P1 logger, resolution of 0.1°C, and accuracy of 0.03°C. Simultaneous measurements were used for the entire data collection points, every five seconds for one hour. Monitoring was carried out in a long period of time with slow alterations in the air flow setting.

3. Results and Discussion

The numerical simulation is validated to ensure the confidence in the predicted result. The velocity and temperature experimental data are utilised for the validation of each of the configurations of the rotary heat recovery wheel. The contours of the air velocity distribution in the supply or incominh air channel for the 32-blade rotary wheel is shown in Figure 5a. It can be observed that the airflow upstream of the rotary wheel had a uniform air velocity profile and speeding up from 2.15m/s to 3.76m/s as it approaches the surface of the wheel. The airflow speed further accelerates (up to 5m/s) as it enters the wheel and flows between the narrow spaces between the radial blades. As the airflow exits the device, it is still moving at a higher speed than the upstream side. Flow separations are observed downstream of the channel which is expected given the channel shape and the presence of the passive recovery wheel. The airflow velocity measurements 0.1m upstream and downstream of the rotary wheel are shown in Figure 5b and c. As observed, a good agreement can be observed between the two methods. The average error for the upstream and downstream air velocity are 12.5% and 24.6%. For the 20-blade arrangement, the CFD model overestimated the measurement values for the upstream airflow velocity (36% error average) while the downstream values are underestimated (27% error average). Although the error is higher than that of the 32-blade arrangement, the trends of the data are similar enough to compensate for the higher error percentage.

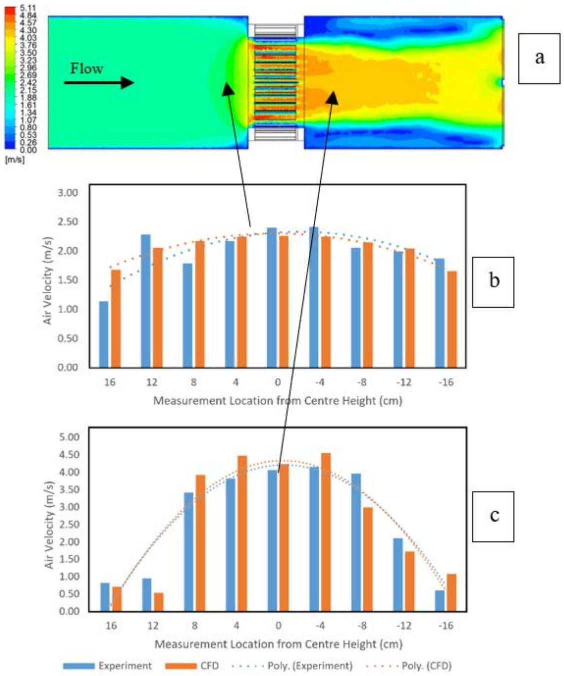

Figure 5. (a) Cross sectional contours of the airflow velocity. Comparison between experiment and CFD air velocity in the supply airstream (b) before and (c) after the 32 blade rotary wheel.

The airflow temperature before and after the device is another parameter assessed in both the experiments and numerical modelling. Validation of the numerical models using airflow temperature is noteworthy given the device purpose is to increase the supply airstream temperature, accurateness of the numerical modelling will support the further development of the proposed concept. Figure 6 and 7 shows a comparison of the air temperature results from the CFD model and experimental tests. As observed, a good agreement is observed between both methods, with the average error at 0.16% and 0.07% for the supply and exhaust airstreams. As the exhaust airstream inlet temperature increased, an increased in temperature change is observed for both airflow streams and configurations. However, the temperature change is not equal between the two airstreams. The temperature change in the exhaust airstream (0.2-2.3°C for HR32-1 to HR32-4) is higher than the supply 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 exhaust airflow but not as effective at releasing this energy to the supply 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 supply 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 supply air is not conditioned and dependent on the lab room temperature. Given the relatively high supply airflow stream inlet temperature, further investigation would be advised. As the heat recovery device is designed for passive ventilation integration, the supplyg air temperature should represent the outdoor air conditions. Common outdoor air temperatures in the UK, areas where device would be most useful in winter months, would be lower (8-11°C in the UK) than the temperatures measured in here.

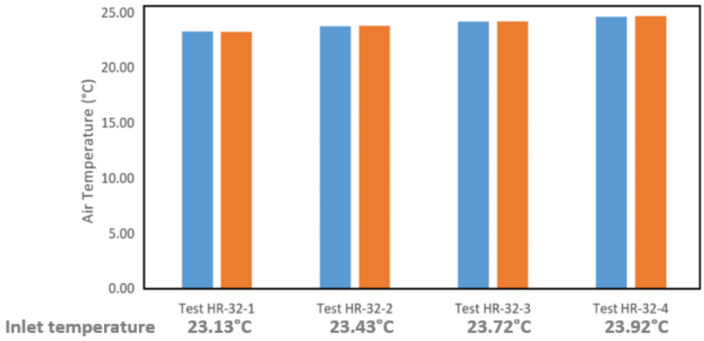

Figure 6. Comparison between experimental and numerical results of air temperature in the supply airstream after the rotary wheel with 32-blades.

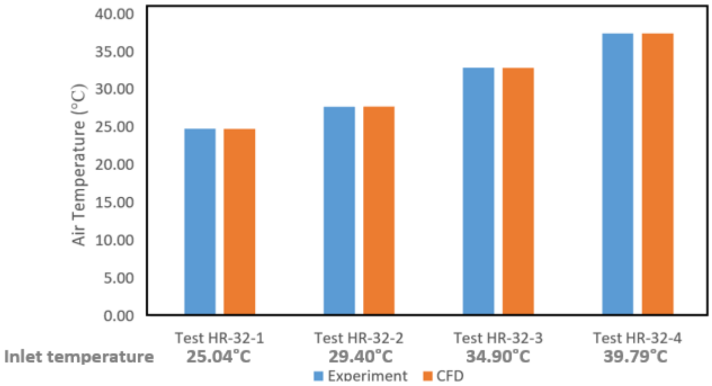

Figure 7. Comparison between experimental and numerical results of air temperature in the exhaust airstream after the rotary wheel with 32-blades.

4. Conclusions

The present study used numerical modelling and experimental tests to investigate the performance of a rotary heat recovery device for a natural ventilation windcatcher. The study focused on characterizing the design and performance of the copper radial blades of the proposed heat recovery device. The predicted results of the airflow and temperature showed good agreement with the experimental tests. Two types of radial blade designs were assessed in terms of the airflow velocity and distribution, the pressure drop and the heat recovery performance. The results showed that although the required pressure drop of 2Pa was not reached, the analysis of the air velocity and pressure upstream and downstream of the device suggested that the it had minimal effect on the airflow rate. The supply rate was 141L/s through the wheel would be suitable to provide fresh air up to 17 occupants. Initial CFD and experimental results showed that the radial blade configurations were able to recover and transfer the heat from the exhaust to the supply airstream. Although, the reduction in temperature of the exhaust air was much higher than the temperature increases of the supply airflow which indicated that the heat conducted by the radial blades is stored and not effectively released to the supply stream. Hence, future studies should focus on further developing the design of the radial blades and increase the heat transfer efficiency considering its potential not to impede the natural ventilation airflow.

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