CONTENT

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A novel arrangement of metal fin heat recovery device in a dual channel wind scoop windcatcher system for reducing the building energy demand in temperate climates

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Abstract

The windcatcher, an innovative natural ventilation apparatus, facilitates the provision of fresh air and ensures indoor thermal comfort under suitable external conditions. This research introduces an advanced dual-channel windcatcher system that employs a rotary wind scoop, offering ventilation regardless of wind direction and incorporating passive and low-energy technologies. A cost-effective, low-pressure loss heat recovery design for the rotary scoop windcatcher was devised, featuring stationary fins between the supply and return channels. This design allows for heat recovery in the natural ventilation system, with heat being consistently transferred through the metallic fins. A Computational Fluid Dynamics (CFD) model, corroborated by experimental data, was adapted to assess ventilation performance and heat recovery efficiency. The findings revealed that the windcatcher system, equipped with a heat recovery (HR) unit, maintained over 95% of its initial ventilation rate. Furthermore, a heat recovery efficiency exceeding 15% was attained by utilizing a one-meter-long heat recovery unit in this study.

Keywords: *Windcatcher, CFD, heat recovery, natural ventilation, wind tunnel*

1. Introduction

As energy prices continue to rise and concerns over global warming intensify, researchers are exploring ways to increase energy efficiency across various sectors. One sector that could make a significant contribution to achieving a sustainable energy economy is the built environment. The construction and built environment industries are responsible for over 40% of the direct and indirect global carbon emissions (He, Yang et al. 2014). Heating, Ventilation and Air Conditioning (HVAC) systems are responsible for over half of the energy consumption in buildings, with air conditioning being one of the fastest-growing energy users in the built environment (Pérez-Lombard, Ortiz et al. 2008, Liu, Justo Alonso et al. 2022). This places a significant burden on the electricity grid in many parts of the world. Therefore, researchers are seeking sustainable and cost-effective solutions that provide good indoor thermal comfort and air quality to building occupants while minimizing the use of air-conditioning (Jomehzadeh, Hussen et al. 2020).

Natural ventilation is an attractive solution and has been the focus of many research studies. But natural ventilation is typically insufficient to provide the required indoor thermal comfort in unfavourable hot and cold climatic conditions. Thus, researchers are looking for sustainable and economical solutions to provide building occupants with good indoor thermal comfort and air quality while minimizing the use of air-conditioners, such as combining natural ventilation with other passive/low-energy strategies, including solar heating, heat recovery, cooling and dehumidification (Jomehzadeh, Hussen et al. 2020, Zhang, Yang et al. 2021, Bamdad, Matour et al. 2022).

Heat recovery systems were proposed in the ventilation system but mainly in mechanically ventilated buildings. In the natural ventilation system, the windcatcher is a suitable natural ventilation device for heat recovery integrations with both supply and return channels. Much research investigated the heat recovery system in windcatcher systems using heat pipes (Calautit, O'Connor et al. 2016, Chaudhry, Calautit et al. 2017, Calautit, Tien et al. 2020, Barreto, Qu et al. 2022), solid tubes (Liu, Jimenez-Bescos et al. 2022) and thermal mass wheels (Calautit, O'Connor et al. 2019, Calautit, O'Connor et al. 2020). Heat pipes are suitable for low-resistance systems driven by wind, increasing room temperatures by 2.8°C (Mahon, Friedrich et al. 2022). However, the high price of the heat pipes would result in a high capital cost and maintenance cost. A case study in the UK demonstrated that integrating heat recovery into natural ventilation systems can effectively provide fresh air with minimal energy use (Dorizas, Samuel et al. 2018). Moreover, the pressure loss through the system results in a low ventilation rate in natural wind conditions and additional fans are necessary for the system.

In addition, the traditional multidirectional ventilation device can not provide a stable heat recovery, because the heat exchange between supply and return channels was not always stable (Mahon, Friedrich et al. 2022). The heat recovery in a conventional four-sided windcatcher was investigated, but the frequent switching of inlet and outlet would decrease the heat recovery efficiency (Liu, Jimenez-Bescos et al. 2022, Mahon, Friedrich et al. 2022).

The supply-to-return area ratio in the traditional four-sided windcatcher is not constant which might be switched between 1 and 3. At the condition with a supply-to-return area ratio of 3, the heat recovery between the supply and return channels is not balanced and the recovery efficiency was not maximized. As shown in Figure 1, the varying wind direction would also cause reverse flow and the heat recovery performance will be decreased (Khan, Su et al. 2008). Moreover, the channels on the opposite sides were not adjacent which further limited the efficiency of heat recovery. Thus, although effective heat recovery with so many limitations is something better than nothing, investigating a suitable design to overcome the limitation of traditional passive heat recovery is necessary for low-carbon natural ventilation in buildings and industries.

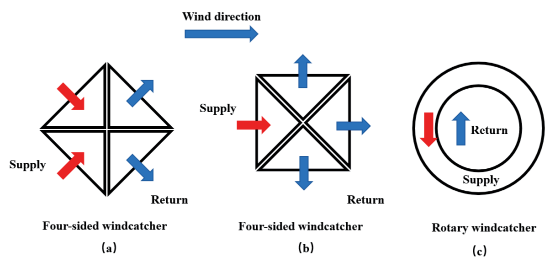


Fig. 1. Comparison of the ventilation airflow direction in a typical multi-directional windcatcher and the proposed rotary windcatcher (a) wind direction from an edge in four-sided windcatcher (45° from the face) (b) wind direction from a face in four-sided windcatcher (c) in rotary scoop windcatcher

Heat recovery systems are vital for energy conservation in buildings, capturing and reusing waste heat to enhance thermal efficiency and significantly reduce energy consumption (Calautit, O'Connor et al. 2020). A case study in the UK demonstrated that integrating heat recovery into natural ventilation systems can effectively provide fresh air with minimal energy use (Dorizas, Samuel et al. 2018). In windcatcher natural ventilation systems, common heat recovery technologies include heat pipes (Calautit, O'Connor et al. 2016, Liu, Jimenez-Bescos et al. 2022, Mahon, Friedrich et al. 2022) and thermal wheels (Calautit, O'Connor et al. 2019, Calautit, O'Connor et al. 2020). Heat pipes are suitable for low-resistance systems driven by wind (Barreto, Qu et al. 2022), increasing room temperatures by 4.5°C (Calautit, O'Connor et al. 2016) and 2.8°C (Mahon, Friedrich et al. 2022).

The aim of this study is to advance the development of a heat recovery unit within the rotary scoop windcatcher with low-pressure loss. This aim will be achieved through the utilization of Computational Fluid Dynamic (CFD) simulations. This research will encompass three distinct yet interconnected objectives: (1) experimental validation of the model; (2) evaluation of the ventilation performance of the windcatcher, with integrated heat recovery unit; and (3) assessment of the overall heat recovery performance of the unit.

To achieve the first objective, experimental validation will be conducted to ensure the accuracy and reliability of the model. Subsequently, the performance of the integrated windcatcher with a heat recovery unit will be evaluated. Lastly, the heat recovery unit's overall performance will be assessed, taking into account various factors such as the rate of heat recovery, temperature efficiency, and pressure loss. This research will advance the understanding of heat recovery units within rotary scoop windcatchers, providing insights into their performance and limitations.

2. Method

This section discussed the method which included numerical CFD modelling using ANSYS Fluent software and experimental wind tunnel testing to validate the model. The data obtained from the simulations and experiments were used to evaluate the ventilation performance and heat recovery efficiency of the device.

2.1. Proposed system model and prototype

In prior research, the potential for heat recovery integration in building natural ventilation was explored through the proposal of a novel windcatcher design (Figure 2). This innovative design offers independent ventilation, irrespective of the prevailing wind direction (Li, Calautit et al. 2023). The windcatcher design incorporates a rotary wind scoop and a concentric tube arrangement that ensures fixed supply and return channels. Consequently, the impact of fluctuating wind directions is effectively eliminated.

The unique characteristics of this windcatcher design make it suitable for the application of a passive heat recovery device. This device, which utilizes metal fins to capture heat from the return duct, can be seamlessly integrated into the windcatcher structure to provide efficient, low-cost heat recovery. The metal fins enable the transfer of heat from the outgoing air to the incoming air, thereby recovering heat that would otherwise be lost.

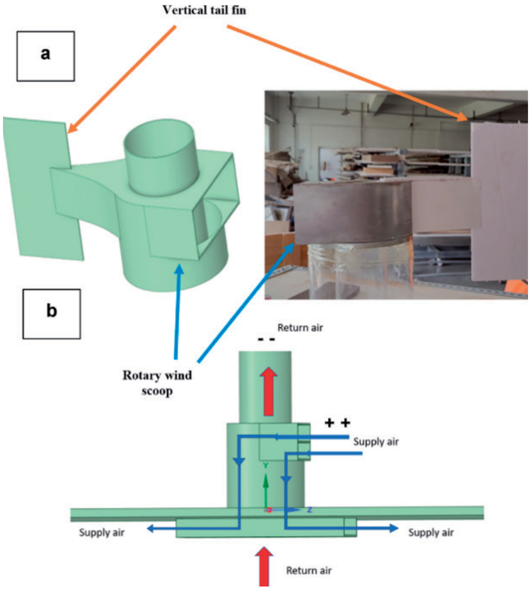


Fig. 2. (a) Proposed rotary scoop windcatcher for passive heat recovery integration (Li, Calautit et al. 2023) and (b) operation

In the initial windcatcher design, the supply and return channels were separated by the internal tube. However, the limited contact surface area posed a challenge to achieving efficient heat recovery. To address this issue, metal fins were inserted into the internal tube to increase the contact area, resulting in the creation of a heat recovery unit (Figure 3).

The heat recovery unit was fabricated using aluminium fins with a thickness of 1 mm. The fins had a length of 95 mm, with 62mm on the supply side and 32mm on the return side. The fins were arranged at an angle of 12 degrees, and a total of 72 fins were used. To simulate the heat transfer process, aluminium panels with a thickness of 1mm were employed in the numerical simulations. The use of aluminium panels was favoured due to their superior strength, lower thermal conductivity than steel, and lower cost than copper. After decreasing the thickness of the metal panels to approximately 1mm, the thermal resistance of the panels was negligible, and the heat transfer efficiency was primarily influenced by the convection heat transfer coefficient between the air and the metal panels. The height of the fins was varied between 0.5m and 1m for evaluating the heat recovery efficiency.

The validated windcatcher tubes had external and internal diameters of 450mm and 300mm, respectively. The ventilation performance of the windcatcher was previously validated in research (Li, Calautit et al. 2023), and this study focused on evaluating the performance of the heat recovery unit.

The incorporation of the metal fins heat recovery unit in the windcatcher system offers a promising approach for reducing the building energy demand. The results of this study could have significant implications for sustainable building design, particularly in temperate climates, where natural ventilation is commonly used, and efficient heat recovery systems are in high demand.

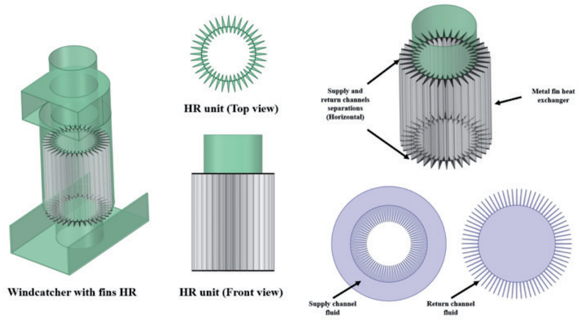


Fig. 3. Windcatcher with metal fins heat recovery unit and the supply & return air channels

2.2. Experimental wind tunnel testing

To evaluate the performance of the windcatcher prototype, a test room cube with the dimensions 1.2m x 1.2m was constructed, using 50mm thick insulation board to ensure thermal insulation (Figure 4). To prevent airflow short-circuiting and ensure good air circulation inside the test room, two L-shape anti-short circuit devices (ASCD) were installed, as per previous research (Li, Calautit et al. 2023). The windcatcher prototype was placed in the centre of the test room.

A 4m long open wind tunnel (Figure 4) was constructed for testing the windcatcher ventilation rate. The wind tunnel was equipped with a contraction section, screen mesh, and honeycomb flow conditioners, as described in previous research (Li, Calautit et al. 2023). The screen mesh and flow conditioners were used to establish a turbulent flow from the industrial fans, creating a stable airflow suitable for evaluating the CFD model, as reported in previous research (Li, Calautit et al. 2023).

The wind speed profiles measured from the outlet of the wind tunnel were used as the inlet boundary conditions for the CFD simulations, providing a reliable representation of the actual airflow conditions. The resulting data were used to evaluate the ventilation performance of the windcatcher and to optimize its design for maximum efficiency.

The use of a dedicated test room and wind tunnel facility allowed for controlled experimental conditions and provided valuable insights into the performance of the windcatcher prototype. The results of this study have significant implications for sustainable building design, offering a promising approach to reducing energy consumption and associated greenhouse gas emissions.

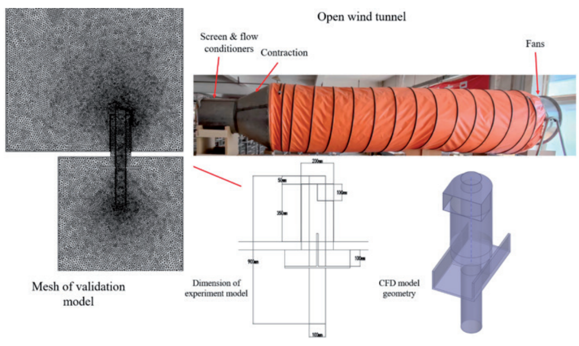


Fig. 4. Wind tunnel and CFD model set-up and the dimension of the model

2.3. CFD modelling

In this research, the performance of the suggested system is assessed through the implementation of Computational Fluid Dynamics (CFD) simulations. The commercial software, FLUENT, is employed for conducting the airflow simulations. Concurrently, the three-dimensional model is developed utilizing Spaceclaim, which is integrated into the Ansys Workbench software environment.

The mass, momentum and energy equations are solved for the airflow within this model. The Reynolds-averaged Navier-Stokes and k-epsilon equations are applied, in accordance with previous research (Li, Calautit et al. 2023). A second-order upwind scheme is utilized to discretize all transport equations. The widely adopted Semi-implicit Method for Pressure-Linked Equations (SIMPLE) segregated pressure-based algorithm solver is implemented for turbulent airflow simulations. The governing equations for mass (eqn.1), momentum (eqn.2), and k and epsilon (eqn.3 and 4) are incorporated within the model. The detailed parameters in the simulation model were presented in Table 1.

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho u) = 0 \quad (1)$$

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho u u) = -\nabla p + \rho g + \nabla \cdot (u \nabla u) - \nabla \cdot \tau_t \quad (2)$$

$$\frac{\partial (\rho k)}{\partial t} + \nabla \cdot (\rho u k) = \nabla \times [(\mu + \frac{\mu_t}{\sigma_k}) \nabla k] + P_k - \rho\varepsilon \quad (3)$$

$$\frac{\partial (\rho \varepsilon)}{\partial t} + \nabla \cdot (\rho u \varepsilon) = \nabla \cdot [(\mu + \frac{\mu_t}{\sigma_\varepsilon}) \nabla \varepsilon] + \frac{c_{1\varepsilon} P_k}{k} \varepsilon - C_{2\varepsilon} \rho \frac{\varepsilon^2}{k} \quad (4)$$

In order to test the heat recovery potential of the windcatcher, the governing energy equation (5) was added to the CFD simulation method.

$$\frac{\partial (\rho e)}{\partial t} + \nabla \cdot (\rho e u) = \nabla \cdot (k_{eff} \nabla T) - \nabla \cdot (\sum_i h_i j_i) \quad (5)$$

where: is velocity (m/s), t is time (s), ρ is density (kg/s), g is gravitational acceleration (m/s²), p is pressure (Pa), τt is stress tensor of the turbulence stresses (Pa), μ is dynamic molecular viscosity (Pa·s), μ_t is turbulent viscosity (Pa·s), is turbulent production of kinetic energy ($kg \cdot m^{-1} \cdot s^{-3}$), e is specific internal energy (J/kg), $C_{1\varepsilon}$ and $C_{2\varepsilon}$ are empirical constants (dimensionless), keff is effective heat conductivity (W/(m·K)), hi is specific enthalpy of fluid (J/kg), T is air temperature (K), ji is mass flux (kg/(m²·s))

To simplify, the heat recovery efficiency of the windcatcher and the ventilation performance of the windcatcher were evaluated separately. The mesh element number of the heat recovery simulation of a 0.5m and 1m long heat recovery unit were 2.16 million and 3.42 million, respectively. The mesh elements of the windcatcher with and without a heat recovery unit were 12.6 million and 4.22 million, respectively. Three different models with elements of 0.22 million, 0.88 million and 4.22 million were used for the mesh sensitivity analysis and the ventilation performance difference between the three mesh sizes was ignorable, with an average difference of 0.5%. However, the model with highest mesh number, 4.22 million, was selected in this research with higher resolution for a better visulization performance.

Table 1. CFD settings and boundary conditions in accordance with previous research (Li, Calautit et al. 2023).

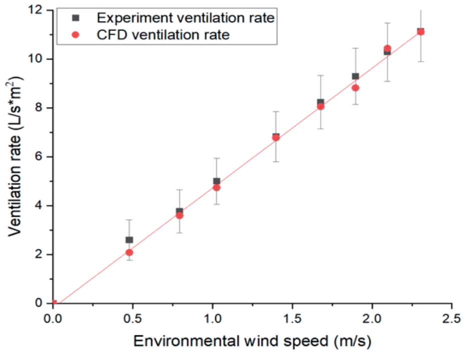
Term	Value and settings
Inlet	
Velocity (m/s)	0-3 (profiled wind speed for validation) 1-7 (constant wind speed for optimizations)
Initial Gauge Pressure (Pa)	0
Specification Method	k-epsilon RNG
Outlet	
Gauge Pressure (Pa)	0 (atmospheric)
Wall	
Shear Condition	No slip
Roughness Models	Standard
Roughness Height	0
Roughness Constant	0.5
Converged residuals	
Continuity / k / Epsilon	0.001
X/Y/Z velocity	0.0001

In the heat recovery evaluation, the external supply air temperature was 0°C (273 K) and the internal return air temperature was 27°C (300 K). The heat recovery efficiency was evaluated by the internal energy difference between the supply and return air and heat flux through the metal fins.

3. Results and discussion

3.1. Model validation

The experimental validation results, together with the velocity contour, are depicted in Figure 5. In the case of the scaled prototype, fresh air was supplied at rates ranging from 1.7 L/s/m² to 9.18 L/s/m², taking into account outdoor wind speeds varying between 0.5 m/s and 2.5 m/s. The mean discrepancy in the ventilation rate between the Computational Fluid Dynamics (CFD) simulation and the experimental data was 0.156 L/s/m², with an average variance of 4.5%. An observed linear relationship emerged between the average wind speed and the ventilation rate. The investigation showed that the difference in ventilation rate between the CFD model, which integrated profiled wind from the open wind tunnel, and the homogeneous environment wind under comparable average wind speeds was insignificant.



(c)

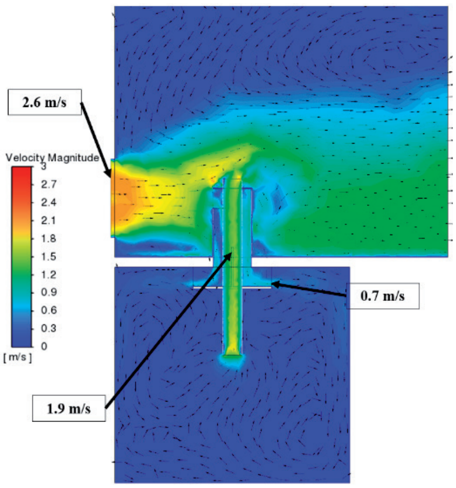


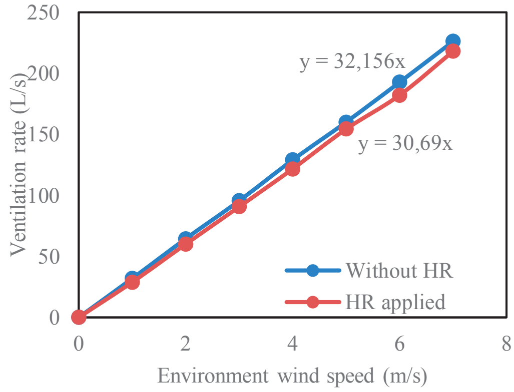
Fig. 5. Experimental and CFD results comparison and the velocity contour of the validation model

3.2. Ventilation performance

The ventilation performance of the windcatcher model without the HR unit and the model with a 0.5m long HR unit are shown in Figure 6. Similar linear relationships between the ventilation rate and the environment were achieved, and the HR unit only decreased 4.5% of the total ventilation rate. As the fins only increased the contact surface area without affecting the section area in the long channel, the overall ventilation rate was not significantly affected (Figure 6). The high ventilation rate of the initial windcatcher remained for a sufficient fresh air supply, and a low-pressure loss increment in the 0.5m long HR unit provides the potential of installing a longer HR unit in the windcatcher system.

3.3. Heat transfer efficiency

The heat transfer rate and efficiency of the 0.5m HR unit are shown in Figure 7. and the HR efficiency of HR units with different lengths is shown in Figure 9. With the increase of mass flow rate, the heat transfer rate increased steadily, but the HR efficiency was slightly decreased. A higher airflow velocity around the heat recovery surface increased the convectional heat transfer coefficient but the convectional heat transfer coefficient was not proportional to the airflow velocity and the increase of the convectional heat transfer coefficient was decreased with the increase of airflow velocity. Thus, the HR efficiency was decreased from 10% to 6.5%. HR efficiency of about 15% was achieved in a windcatcher with a 1m long HR unit which would decrease to 14% at a higher ventilation rate condition. However, in most cases, the ventilation rate of the ventilation system would not be increased to over 300 L/s which requires an environment wind speed of over 10 m/s. Thus, the heat recovery efficiency would remain at a higher level.



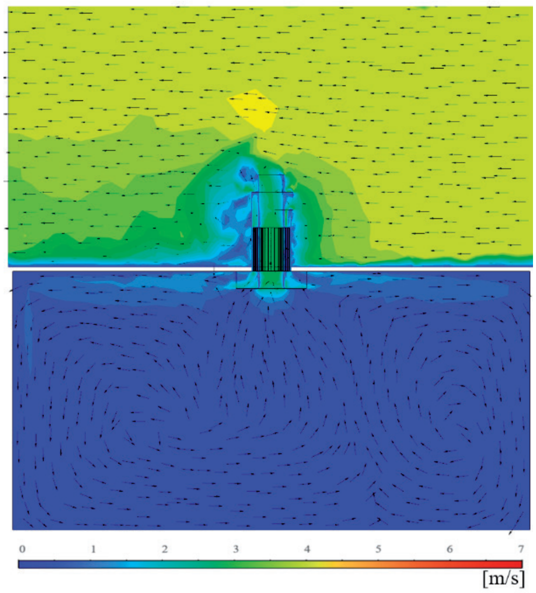


Fig. 6. *Ventilation performance and velocity contour of the windcatcher model with and without HR unit (0.5m long fins)*

The temperature contour with a 27 temperature difference between supply and return air in the 1m heat recovery unit and the velocity contour under a high airflow rate are shown in Figure 8. A heat recovery unit with an efficiency of 15%, could increase the supply air temperature by 4 under a 27temperature difference between supply and return air. This temperature increase is higher than a windcatcher heat recovery system using heat pipes, increasing room temperatures by 2.8°C (Mahon, Friedrich et al. 2022), and the cost of flat metal panels is much lower than the cost of heat pipes which the heat recovery windcatchers in this research commercially viable. The airflow velocity between the fins was decreased, and the pressure loss of the system was increased, which decreased the total ventilation rate of the windcatcher.

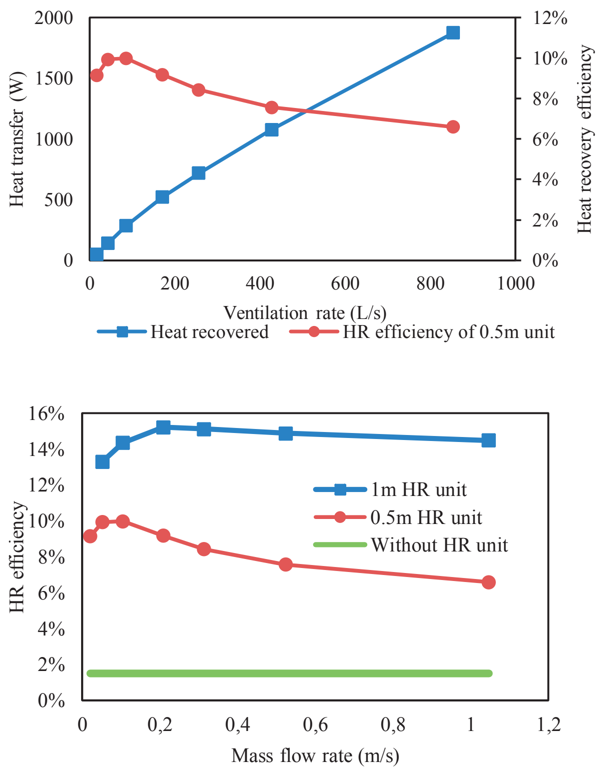


Fig. 7. *Heat transferred through metal fins and the heat recovery efficiency of a 0.5m heat recovery unit after increasing the ventilation rate, and heat recovery efficiency of 0.5m and 1m heat recovery units*

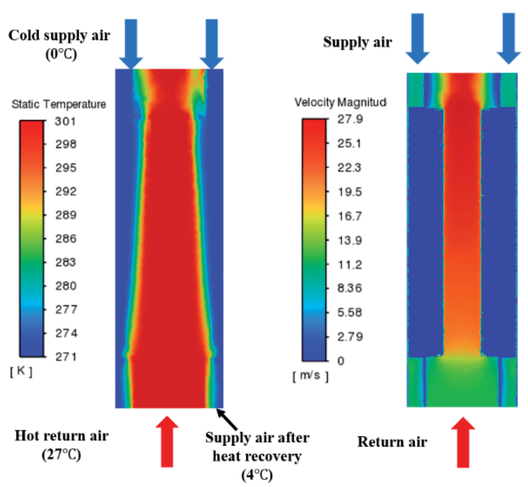


Fig. 8. Temperature and velocity contour in the 1m heat recovery unit

4. Conclusion

In this study, a passive heat recovery system utilizing low-pressure loss metal fins was proposed for integration into a rotary scoop windcatcher. The initial scaled windcatcher model was assessed through wind tunnel experiments and Computational Fluid Dynamics (CFD) simulations. Subsequently, a full-scale windcatcher model was optimized based on the scaled model, with the heat recovery unit applied to the full-scale configuration. Ventilation performance and heat recovery efficiency were evaluated using CFD simulations.

The full-scale windcatcher demonstrated a ventilation rate exceeding 160 L/s when subjected to an outdoor wind speed of 5 m/s. The ventilation rate loss incurred by a 0.5 m heat recovery unit amounted to a mere 4.5%, maintaining a high ventilation rate of over 150 L/s under the same outdoor wind speed. The heat recovery efficiency of 0.5 m and 1 m heat recovery units approximated 9% and 15%, respectively, with the potential for further enhancement by employing longer heat recovery units. A 4°C increase in supply air temperature was achieved by a windcatcher with a 1 m heat recovery unit under a 27°C temperature differential.

In this preliminary investigation, a simple design and operation principle were employed for the heat recovery system. Heat recovery efficiency was intentionally limited to preserve high ventilation efficiency. The contact surface-to-volume ratio in the channels can be further augmented by increasing the number of fins and obstructing the space beyond the fins. Given that ventilation efficiency was not significantly impacted by the heat recovery unit, the unit's length can be extended to attain higher heat recovery efficiency without compromising ventilation efficiency. Furthermore, the windcatcher's height is typically elevated to capture wind at higher speeds and minimize interference with the building's edge. Sufficient space for a heat recovery unit is available, allowing for an overall heat recovery efficiency increase that satisfies both designers and occupants.

Future research should evaluate the metal fins heat recovery device using wind tunnel experiments. Additionally, optimizing the metal fins and windcatcher geometry will be essential for attaining higher ventilation rates and heat recovery efficiency. The windcatcher used in this research has a diameter of about 0.5m. In the further application of this windcatcher, the dimensions of the windcatcher should range from 0.2m to 1m, which is similar to the application of a wind turbine with different sizes based on the ventilation demand. The passive solar heating, passive cooling using evaporative cooling, and passive dehumidification design in the windcatcher system should also be investigated in further research.

5. Nomenclature

e	Specific internal energy (J/kg K)
Gb	Generation of turbulence kinetic energy due to buoyancy
Gk	Generation of turbulence kinetic energy due to mean velocity gradients
h_i	Specific enthalpy of fluid (J/kg)
j_i	Mass flux (kg/s)
k_{eff}	Effective heat conductivity (W/m K)
m	Mass of fluid(kg)
p	Pressure (Pa)
P_k	Turbulent production of kinetic energy
ΔQ	Heat flux through the heat recovery unit (W)
σ_k	Turbulence model constant of k
σ_ε	Turbulence model constant of ε
t	Time (s)
T	Air temperature (K)
u	Velocity (m/s)
$\bar{V}$	Average airflow velocity in the return duct (m/s)
V_c	Airflow velocity in the centre of the return duct (m/s)
αk	Inverse effective Prandtl numbers for k
α_ε	Inverse effective Prandtl numbers for ε
μ	Dynamic molecular viscosity (Pa s)
μ_t	Turbulent viscosity(m^2/s)
ρ	Density (kg/m^3)
τ_t	Divergence of the turbulence stress
ASCD	Anti-short circuit device
CFD	Computational Fluid Dynamic
HVAC	Heating, ventilation and air-conditioning
HR	Heat Recovery

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