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Effect of Rotation Speed of a Rotary Thermal Wheel on Ventilation Supply Rates of Wind Tower System

Dominic O'Connor[a]*, John Calautit[a], Ben Richard Hughes[a]

[a]*School of Civil Engineering, University of Leeds, Leeds, LS2 9JT, United Kingdom*

Abstract

This study explores the integration of a rotary thermal wheel into a wind tower system, specifically the effect of the rotation speed on the ventilation rate and heat recovery. Wind towers are capable of supplying recommended levels of supply air under a range of external conditions, integrating a rotary thermal wheel will cause a reduction in the air supply rates due to the blockage created by the wheel. Using Computational Fluid Dynamics (CFD) analysis, the air supply rate and heat transfer of the rotary thermal wheel have been calculated for a range of rotation speeds between 0rpm – 500rpm.

The recommended air supply rate of 8l/s/p is attained up to a rotation speed of 50rpm; beyond this rotation speed the air supply rate is too low. The maximum temperature recovered across the rotary thermal wheel is measured as 1.77°C at a rotation speed of 20rpm. Using the two results gained from the analysis, an optimum operating range of the rotary thermal wheel can be determined between 5rpm and 20rpm. The technology presented here is subject to an international patent application (PCT/GB2014/052513).

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Keywords: Passive Ventilation; Wind Tower; Heat Recovery; Air Supply Rates;CFD; Rotary Thermal Wheel

1. Introduction

The contribution of the building sector, both construction and operation and maintenance, is estimated to be up to 40% of global energy demand [1]. Of this, 60% of the energy consumption is required for heating, ventilation and air-conditioning (HVAC) [2, 3]. This is a significant amount of energy required to maintain thermal comfort for occupants in buildings using mechanical systems.

* Corresponding author. Tel.: +447857883363.
E-mail address: cn09dbo@leeds.ac.uk

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Commercial wind tower systems offer passive ventilation to buildings with zero energy requirements. Wind towers are modern designs of traditional Baud-geer, traditional wind catchers used in hot, arid countries for ventilation and cooling [4]. Wind towers are capable of providing zero energy ventilation by manipulating pressure differences created by wind forces and the stack (buoyancy) effect [5]. Commercial wind towers are able to supplement mechanical HVAC systems during summer months, when the external air temperature is high enough to be acceptable to be introduced unconditioned into an occupied building, this reduces the energy demand required of the building. However, when the external air temperature falls during winter months, introducing unconditioned air from a wind tower directly into a building would cause significant discomfort to occupants and increasing heating cost.

Integrating a heat recovery device into the ductwork of a wind tower to recover the thermal energy in the exhaust air has been tested using computational fluid dynamics (CFD) and experimental wind tunnel testing in order to determine the viability of the concept. Mardiana *et al.* [6] used a fixed plate heat exchanger as the heat recovery device in wind tunnel experiments and concluded that a heat recovery device is capable of increasing the air temperature of incoming external air in a wind tower system. O'Connor *et al.* [7] proposed the use of a rotary thermal wheel as the heat recovery device due to the more compact nature of the device and ability to transfer heat across multiple ducts. It was determined that the rotary thermal wheel did not impede the flow of air through the wind tower into the building, sufficiently delivering fresh air to meet guideline air supply rates.

The work conducted in this study uses CFD analysis to determine the effect the rotation speed of the rotary thermal wheel has on the air supply rate into the building and the heat recovered from the exhaust air.

2. CFD Setup

The CFD code ANSYS FLUENT 14.5 was employed for the prediction of characteristics deemed essential for analysis of the rotation rate of the rotary thermal wheel, particularly the air velocity below the rotary thermal wheel and the heat transfer across the wheel. The CFD code, FLUENT, solves a number of conservation equations relating to the flow for mass and momentum. Furthermore, when thermal conditions are set within the model, the energy conservation equation is solved. The theoretical backgrounds, which will not be detailed here, are taken from ANSYS FLUENT Theory Guide Release 14.5 [8]. The fluid flow within the model was assumed to be three dimensional, fully turbulent and incompressible. The low-Reynolds, turbulent nature of the flow was modelled in the CFD software by using the k-ε viscous model with standard wall functions.

2.1. Design Geometry and Mesh Generation

A computational model was created to accurately analyse the effect of rotation speed of a rotary thermal wheel on the ventilation rate through a wind tower into a building and the heat transfer capability of a rotary thermal wheel. The geometry reflected the dimensions of an experimental setup described in [7]. The geometry was created in three separate parts and connected for the flow to move through. Seven individual louvers, each angled at 45°, were attached on the wind tower to channel air flow through the wind tower, rotary thermal wheel and into the building. Dimensions for the geometry can be seen in Figure 1.

The rotary thermal wheel was connected below the wind tower as a separate part. Due to technical limitations, the rotary thermal wheel was modelled as a cylinder and porous media setting were applied to the volume to replicate the characteristics of a rotary thermal wheel. Finally, a building was created as a separate part, connected to the rotary thermal wheel. The louvers and rotary thermal wheel were deemed to be areas of significance and meshed appropriately. The mesh arrangement consisted of 1,039,329 mesh elements. Grid sensitivity analysis method was used to verify the mesh [7].

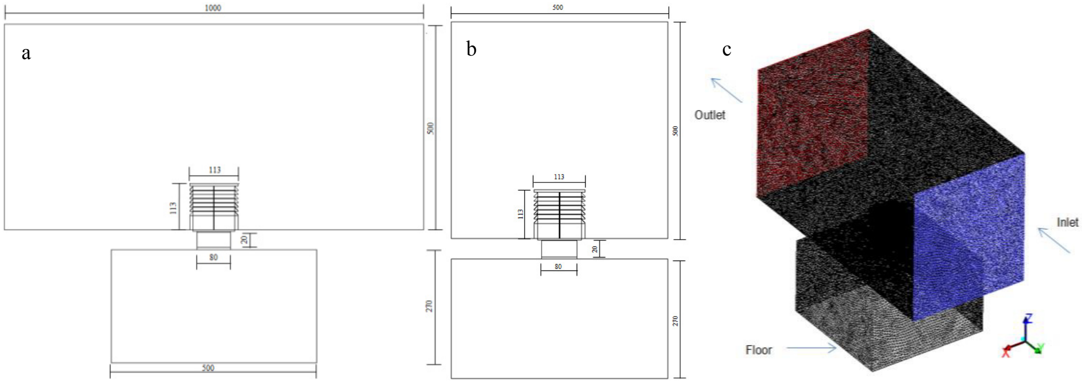

Figure 1. (a) Side view of geometry with dimensions; (b) end view of geometry with dimensions (dimensions in mm), (c) mesh generation of CFD domain

The rotation speed and porosity of the rotary thermal wheel were modelled using mesh motion and porous media conditions in ANSYS FLUENT [7]. The mesh motion of the rotary thermal 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. Porous media setting were applied to the surfaces of the volume. Inertial resistance values were assigned to each direction axis. Values of inertial resistance in the X and Y axis direction were several orders of magnitude greater than the values in the Z axis direction. This was to prevent any fluid flow through the rotary thermal wheel in a radial direction. The porosity of rotary thermal wheels is commonly 90%, this value was assigned to the porous media settings, along with a inertial resistance C_2 value of 89.6 [7].

2.2. Boundary Conditions

The k-ε (2 equation) viscous flow model is the most appropriate flow model for use in simulating passive ventilation analysis [9, 10]. Standard wall functions were applied for the model. A velocity inlet and pressure outlet (atmospheric pressure) were configured on opposing walls of the macroclimate in order to create uniform air flow parallel to the length of the enclosure. The remaining surfaces of the macroclimate were set as symmetry planes. The building (microclimate) bottom surface was set to "floor" to enable thermal settings to be applied. A full summary of the boundary conditions can be seen in Table 1.

Table 1. Summary of CFD model boundary conditions

Boundary Condition	Type/Value
Velocity Inlet (m/s)	3
Inlet Temperature (K)	283 (10°C)
Gravity (m/s^2)	-9.81 (Z-Axis)
Wheel Porosity	90%
Wheel Rotation (rpm)	0 – 500
Rotary Thermal Wheel Material	Aluminium
Thermal Conductivity (W/m K)	202.4
Floor Heat Flux (W/m^2)	45

A temperature of 283K (10°C) was assigned to the inlet air volume at the velocity inlet; this was to represent a cold outdoor temperature. A constant heat flux was set to the floor boundary to simulate the presence of occupants with sedentary activity levels and electrical equipment commonly found in a classroom, the value of 45W/m^2 was applied to the floor boundary [11].

The rotary thermal wheel was able to freely rotate due to the mesh interface design enabling mesh motion. As the model was separated into three individual parts, four surfaces were created at the point of interaction between the wind tower, the rotary thermal wheel and the building. By using mesh interface design, a volume was created around the rotary thermal wheel which allowed the rotary thermal wheel to be rotated.

3. Results and Discussion

3.1. Air Supply Rates

The air supply rates were calculated using the air velocity measured 150mm below the rotary thermal wheel at the mid-height of the building. This was because of a problem when measuring the air velocity directly below the rotary thermal wheel due to the influence of the wheel rotating at high speeds causing the movement of air to interfere with the velocity measurements. The measured air velocity was extrapolated to determine the air velocity directly below the wind tower to calculate the air supply rates [7].

The data shown in Figure 2 displays the trend of air velocity, as the rotation speed increases the air velocity rate decreases, this leads to air supply rate reduction. Ventilation systems should be capable of supplying 8l/s/p of fresh air at any given time as recommended by CIBSE [12]. The rotation speed of the rotary thermal wheel does not impede the flow of air significantly until the rotation speed reaches 50rpm. Above this value, the air supply rate decreases significantly and is not high enough to meet the recommended air supply rate.

The high rotation speed prevents air moving through the rotary thermal wheel, reducing the air supply rate. The porosity and free area of the rotary thermal wheel has a significant impact on the air supply rate. The higher the porosity and free area, the more air that is capable of flowing through the rotary thermal wheel [7].

Though the decreasing trend in air supply rate as rotation speed increases is clear between 0rpm and 200rpm, there is a minor increase in air supply rate between 200rpm and 500rpm. It is likely that this increase in air supply rate is due to the influence of the rotation speed of the rotary thermal wheel. The high rotation speed at 500rpm will cause the movement of air around the building, affecting the air velocity measurements taken.

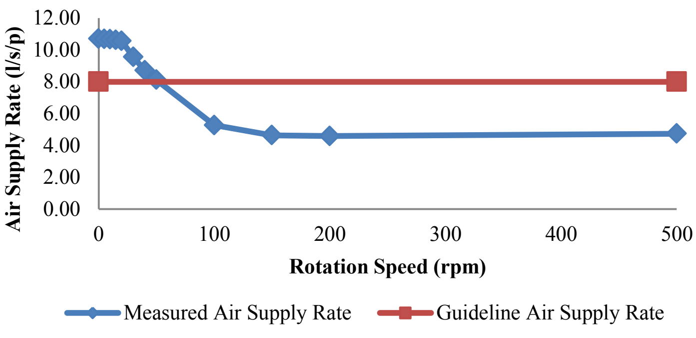

Figure 2. Measured air supply rates at increasing rotation speed of a rotary thermal wheel.

3.2. Heat Recovery

The internal temperature of the building was measured as 15°C (289K), approximately 5°C greater than the external air temperature. As the external air temperature was assumed to be constant, the air supply temperature was measured directly below the rotary thermal wheel to find the exact temperature after transfer by the rotary thermal wheel. Furthermore, this was done to prevent the internal air temperature mixing with the inlet air, creating error in the data.
Figure 3 shows the measured temperature change across the rotary thermal wheel compared to an idealised temperature change. As expected the lowest temperature change is seen at 0rpm, when the rotary thermal wheel is not rotating. Heat transfer across the wheel will be low at 0rpm as the matrix will not be warmed and rotated to the inlet quadrant to transfer heat. The temperature change seen at 0rpm is likely due to conduction through the rotary thermal wheel as the exhaust air exits the building. A clear increase in temperature change is observed from 0rpm to 20rpm. A maximum temperature change of 1.77°C is observed before the trend begins to reverse as the rotation speed increases.
The reduced temperature change as rotation speed increases is due to the reduced contact time. As the rotation speed increases, the contact time between the metallic matrix and the air is shortened, reducing the amount of thermal energy that can be transferred by the rotary thermal wheel.

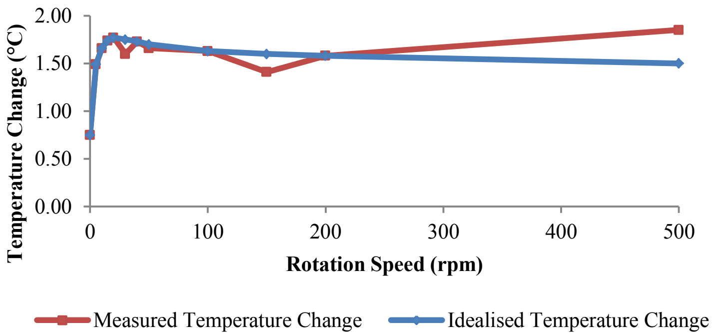

Figure 3. Temperature change of inlet macroclimate air passing through rotary thermal wheel as rotation speed increases

The measured temperature change in the inlet microclimate air shows considerable variability as the rotation speed increases, without the consistent pattern identified between 0rpm and 20rpm. An idealised trend for the temperature change has been constructed across the measured rotation speed range. It would be expected that as the rotation speed increases, the temperature change would decrease at a linear rate due to the reduced contact time and reduced volume of air passing through the rotary thermal wheel. The temperature measurement at 500rpm is the greatest temperature change. The cause of this has been determined as a result of the inability of microclimate air to escape through the rotary thermal wheel due to the high rotation speed. This causes the air temperature to rise as a result of the constant heat flux.

4. Conclusion

CFD analysis was used to measure the air velocity within a building ventilated by a wind tower with a rotary thermal wheel and measure the temperature change of the inlet macroclimate air. Between a range of 0rpm and 50rpm, the wind tower is capable of supplying adequate ventilation. Above 50rpm, the air supply rates are too low to adequately ventilate an occupied building.
The temperature change across the rotary thermal wheel increased as the rotation speed increased up to 20rpm where a temperature change of 1.77°C was measured. Beyond this rotation speed, the temperature

change did not exceed this value due to the reduced contact time between the rotary thermal wheel and the air exhausting and incoming. Based on the data collected in this study, the rotary thermal wheel operates optimally within a range between 5rpm and 20rpm.

5. Future Work

Further analysis of the integrated rotary thermal wheel wind tower system will be investigated through the use of CFD simulations and experimental testing. Increasing the air temperature of the microclimate to more common levels will increase the temperature change across the wheel. Also, using smaller increments of rotation speed will give greater insight to the technology.

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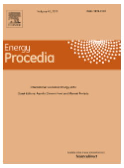

Biography

Dominic O'Connor is a PhD student under the supervision of Dr. Ben Hughes and Dr. John Calautit in the School of Civil Engineering at the University of Leeds. His PhD focus is on integrating heat recovery device into passive ventilation system to reduce energy consumption in buildings.