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Potential assessment of an innovative hybrid ventilator for building ventilation †

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Abstract

In this study, an innovative rooftop turbine ventilator powered by a hybrid of wind and photovoltaic energy, "Hybrid Ventilator" for short, was developed. The performance differences between Hybrid Ventilators and conventional ventilators were assessed through a series of experiments. Then, CFD (Computational Fluid Dynamics) simulations were applied to survey the building ventilation efficiency of this Hybrid Ventilator. The results show that, considering the ventilation quantity (rate), a Hybrid Ventilator provides approximately 4 times the exhaust capacity of a conventional ventilator. All of the investigated space configurations that were examined via CFD simulations exhibited similar indoor airflow patterns and air velocity distributions (ventilation quality).

Keywords: Ventilator; Ventilation; Renewable energy; CFD (Computational Fluid Dynamics)

1. Introduction

Indoor air quality in Taiwan is poor due to congested living spaces, highly airtight buildings, poor air circulation and lack of ventilation. This problem has been receiving increasing attention recently. Properly inducing natural ventilation can significantly improve indoor air quality and decrease reliance on air-conditioning, thus cutting energy consumption. This field of environmental design requires further research.

Turbine ventilators use natural wind to rotate the turbine, creating negative pressure at the down-stream end of the pipeline to exhaust airflow. The form and concept are quite simple, yet ideal in practicality. Turbine ventilators are widely installed in Taiwan to enhance building ventilation (especially with spaces like bathrooms and kitchens where negative pressure is highly demanded) and the ventilation of factories. Theoretically, the proper combination of turbine ventilators and natural ventilation will tremendously help indoor air quality and decrease reliance on air-conditioning, reducing energy consumption.

Previous works, [1, 2], examined the potential of installing a new common roof turbine ventilator onto an existing bathroom ventilation system serving fourteen bathrooms and assessed its overall ventilation performance. The experimental results demonstrate that the combination of the roof turbine ventilator and existing bathroom ventilation successfully achieved an adequate air change rate in the bathrooms. Therefore, this alternative ventilation design is a promising means of improving the indoor air environment in bathrooms.

A following study [3] was aimed at increasing the operation and energy efficiency of the rooftop turbine ventilator and then developing a prototype of the rooftop turbine ventilator powered by a hybrid of renewable energy (wind and photovoltaic (PV) energy). Building ventilation issues may be ramified by the successful utilization of wind and solar energy in Taiwan: high outdoor wind speeds and minimal sunlight will result in fast wind-powered ventilator rotation, which can generate the partial negative pressure in the turbine ventilator at the down-stream end of the ventilation shaft necessary to induce airflow in the ventilation duct. Conversely, with low outdoor wind speed and full sunlight, airflow at the down-stream end can be attained using the inner fan powered by the PV system.

A conventional rooftop ventilator is an obviously helpful part of a building's ventilation system. In this study, an innovative rooftop turbine ventilator powered by a hybrid of wind and photovoltaic energy, or simply "Hybrid Ventilator" for short, was developed. The performance differences between Hybrid Ventilators and conventional ventilators were assessed through a series of experiments. Then, CFD (Computational Fluid Dynamics) simulations were applied to survey the building ventilation efficiency of this Hybrid Ventilator.

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2. Experimental investigations of the hybrid ventilator

2.1 Design development

The aforementioned investigations, [1, 2], confirmed that the installation of roof turbine ventilators successfully achieved the required ventilation level. Considering this finding, this study aimed to enhance the ventilation efficiency using renewable energy without consuming additional electricity. Therefore, without altering the ventilator's main structure, a 16-inch diameter inner fan was installed in the neck of a 20-inch diameter ventilator, replacing the existing inner vane (the previous works have shown that a turbine ventilator exhausts better with inner vanes than without them; however, the difference between the two is not significant). The DC inner fan's electricity demand was met by PV panels. Fig. 1 illustrates this turbine ventilator powered by hybrid wind and PV.

During the design process, the rotation end and the PV end were considered separately: (1) The rotation end incorporates the rooftop turbine ventilator and the inner fan; (2) The PV end (energy supply end) incorporates the 50 W PV panels, wirings, batteries and control panel to provide the power to operate the inner fan. These electrical elements were designed to meet the inner fan's power requirement, operating at the optimum rotational speed proposed by the test results of the low-speed wind tunnel.

2.2 Experimental method

The research team conducted field studies on the top floor of the building block of National Cheng-Kung University. In those experiments, the major measuring device was the TESTO 445 Multi-functional ventilation/air-conditioning detector equipped with two sensing connectors that could be used to detect a variety of environmental factors such as wind speed, temperature, humidity, etc. Data analysis was conducted using an RS 232 transmitting line and professional analyzing software ComSoft 3 (Testo 0554 0830) on the Windows platform.

2.3 Experiment results and discussion

As the outdoor wind velocity was between 0.3 to 1.2 m/s, the ventilation rate induced by the conventional ventilator was 86 - 259 CMH (Cubic Meter per Hour), while that of the Hybrid Ventilator was 2159 - 2633 CMH. When the outdoor wind velocity was between 3.1 and 5.3 m/s, the ventilation rate of the conventional ventilator was 130 - 518 CMH, while that of the Hybrid Ventilator was 2029 - 2849 CMH. The Hybrid Ventilator can induce much more ventilation because it has an additional driving force: photovoltaic power. These measurements were taken with sunlight exposure between 419 and 851 W/m^2.

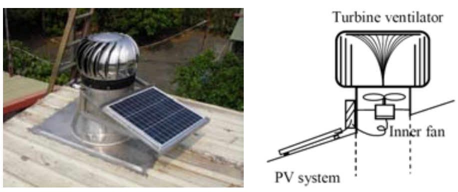


Fig. 1. The Hybrid Ventilator developed and investigated in this study.

Outdoor wind velocity is the main factor controlling the turning of conventional ventilators (the mechanism that induces indoor ventilation). Fig. 2 shows that the faster the outdoor wind velocity is, the higher the ventilation rate of conventional ventilators. The slope of the regression curve in Fig. 2 (y = 98.4x) indicates that as the outdoor wind velocity increases by 1 m/s, the indoor ventilation increases by 98.4 CMH. Instead of outdoor air, Hybrid Ventilators are primarily driven by photovoltaic power. Therefore, the slope of its regression curve (y = 24.5x + 2382.2) is only 24.5, as shown in Fig. 2.

Fig. 3 shows a ventilation rate measurement that was induced by the Hybrid Ventilators under the same sunlight exposure but different outdoor wind velocities. The average slope of the curves is 146 (CMH/m/s). In other words, when the outdoor wind velocity increases, the Hybrid Ventilator's ventilation rate rises only slightly more than 146 CMH. This study reconfirms that Hybrid Ventilators are driven primarily by photovoltaic power. The intercepts of the curves in Fig. 3 indicate that even at a low wind velocity, ventilation rates induced by the Hybrid Ventilator still maintain up to 1298.4 - 2402.3 CMH. The higher the amount of sunlight exposure, the more ventilation the Hybrid Ventilator provides. This makes

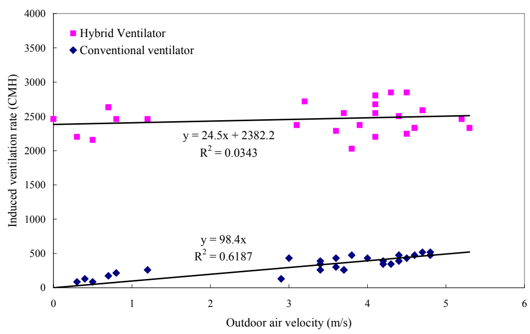


Fig. 2. Ventilation rate variations between a conventional ventilator and a Hybrid Ventilator affected by outdoor wind velocity [4].

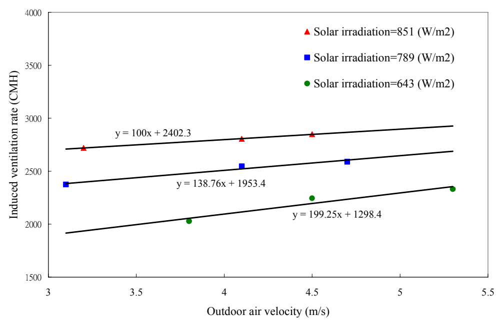


Fig. 3. Ventilation rate variations of Hybrid Ventilators under different outdoor wind velocities (in the same sunlight exposure).

Hybrid Ventilators very suitable to Taiwan's summers.

3. Application in building ventilation

The interior geometry, partition, position of equipment, machinery temperatures and pressure, as well as layout of inlet and outlet openings are all factors that influence indoor air circulation. In this section, CFD simulations were applied to examine the indoor air patterns of a building when using Hybrid Ventilators as compared to conventional ventilators.

3.1 Physical model

There are a variety of factory space shapes and sizes as well as machine sizes and positioning. As production proceeds, the aforementioned factors will be manipulated. We designed a target space based upon factory sizes, opening sizes and types of factories commonly seen in Taiwan. Due to the symmetry of the physical problem, the geometric figure under investigation has dimensions of 7.5m×7.8m×9m with a slanted roof. Main length scales and relevant parameters for the model space used for the investigation are depicted in Table 1 and illustrated in Fig. 4.

3.2 Configurations for numerical simulations

In Taiwan, it takes 4 conventional ventilators (with a rated ventilation of 450 CMH, as mentioned in Section 2.3) to sufficiently ventilate an outdoor air velocity of 3-5m/s, while it takes only 1 Hybrid Ventilator (with a rated ventilation of 2000 CMH as previously mentioned) to achieve the same ventilation. Therefore, we applied the CFD simulations to observe the differences between the "4 conventional ventilators on the rooftop" and "1 Hybrid Ventilator on the rooftop." The locations of the ventilators installed were also taken into account, as shown in Table 2. All the boundary conditions of the 5 modes were the same, except for the described parameters in Table 2. The forced airflow drawn by the ventilator (s) is assumed to be three-dimensional and turbulent. Possible inlets and outlets at the computational boundary were set according to the Neumann boundary condition. The environmental pressure was 1 atm; both the initial and outdoor wind temperatures were 25°C. The walls and the roof were made of concrete and metal.

3.3 Numerical method

Numerical simulations of the physical problem under consideration have been performed via a finite volume method for solving the governing equations and boundary conditions mentioned above. A commercial CFD code, PHOENICS, was used to simulate the airflow and temperature distributions. The governing equations solved by PHOENICS include the three-dimensional time-dependent incompressible Navier-Stokes equation, time dependent convection diffusion equation and k-ε turbulence equations. These formulated equations can be found in the PHOENICS user's manual [5] as well as any CFD textbook and will not be provided here. For the k-ε turbulence equation, the empirical turbulence coefficients were assigned as: σ_k=1.0, σ_ε=1.22, $\sigma_{\varepsilon1}$=1.44, $\sigma_{\varepsilon2}$=1.92, and Cμ=0.09, respectively. These values were widely accepted in the CFD k-ε model. To bridge the steep dependent variable gradients closely to the solid surface, the "general wall function" was employed. The iteration calculation was continued until a

Table 1. Geometric data of the model space.

Geometric elements	Size
Computational domain	7.5m × 7.8m × 9m
Indoor air volume	7.2m × 7.5m × 4m (the measurement of 4m is taken from the top of wall to the ground)
Slanted roof	7.5m × 4.48m × 6.24m (the measurement of 6.24m is taken from the roof ridge to the ground)
Slanted angle	30 degree
Interior partition boards	0.3m × 7.5m × 4m (at X=0 and 7.2)
Induced airflow area of a Hybrid Ventilator or a conventional ventilator	0.2027m^2
Lateral opening area	7.5m × 0.45 m

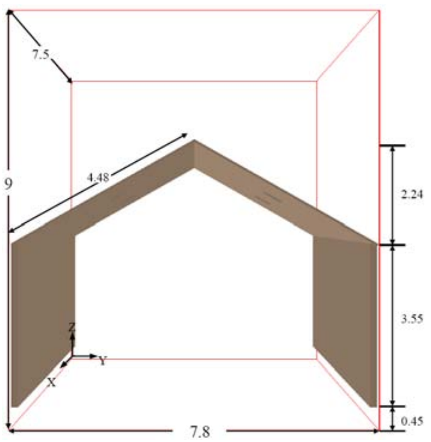
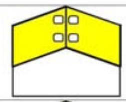
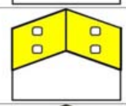
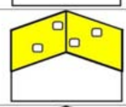
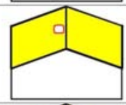
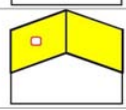


Fig. 4. Schematic diagram of the investigated space (unit: m).

Table 2. Configurations for numerical simulations.

Mode	Type of ventilator	Amoun t	Installation Position	Diagram
1	Conventional ventilator (its symbol as ▢)	4	Near roof ridge	
2	Conventional ventilator (its symbol as ▢)	4	Near the center of the slanted roofs	
3	Conventional ventilator (its symbol as ▢)	4	2 near the ridge, 2 on the slanted roof center	
4	Hybrid Ventilator (its symbol as ▢)	1	Near roof ridge	
5	Hybrid Ventilator (its symbol as ▢)	1	Near the center of the slanted roofs	

prescribed relative convergence of 10^{-3} was satisfied for all field variables of this problem. Numerical simulation accuracy depends on the resolution of the computational mesh. A finer grid leads to solutions that are more accurate. In this study, a grid system with approximately 76×88×102 cells was used for numerical simulation. The increase in cell number will provide information that is more favorable; however, it will be accompanied by a significant increase of computation resources.

3.4 CFD Simulation results and discussion

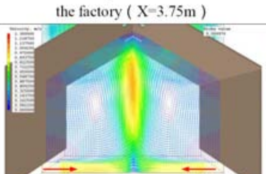
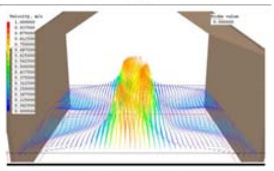
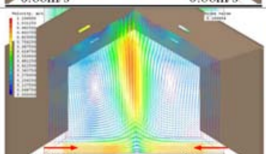
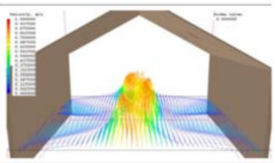
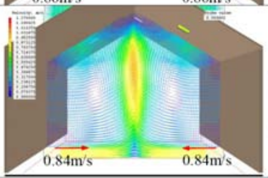
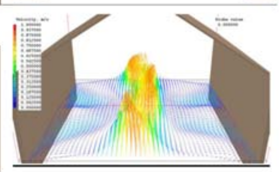
The simulation results of Modes 1 to 3 are compared in Table 3. The results show that no matter where the conventional ventilators are installed, flow patterns are very similar. The air velocity of inlet ventilation is approximately 0.8m/s and that of the flow below the ridge line is approximately 0.7m/s. No apparent velocity differences were found among the 3 Modes.

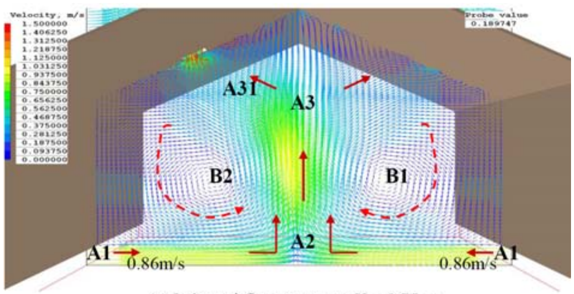
Next, the simulation results of Modes 4 and 5, which had the Hybrid Ventilator installed differently on the slanted rooftops, were investigated. Fig. 5 shows the flow patterns at X = 3.75 m (Fig. 5(a)), X = 5 m (Fig. 5(b)) and an interior height of 1.5 m (Fig. 5(c)) for Mode 5, in which the Hybrid Ventilator is installed at the center of the rooftop. In Fig. 5(a) we can see that outdoor air was flowing at a velocity of about 0.86 m/s into the factory through the lateral openings, A1, at the bottom of both walls, and met in the middle, A2, to form an upward airflow. The Hybrid Ventilator causes the air to move upward in addition to this outdoor airflow. Thus, as seen in the diagram, the air flows to the left. The airflow reaching A3 was directed along the slanted ceiling and drawn by the airflow from below, A1, which created a clockwise air circulation, B1, and a counterclockwise air circulation, B2, on both sides of the interior. Fig. 5(b) shows a flow pattern similar to Fig. 5(a), except that a higher air velocity, which is induced directly by the Hybrid Ventilator, can be found near the ridge (A3) in Fig. 5(a). In Fig. 5(c), similar to Mode 1, an upward airflow is generated in the middle of the interior space, A4. The air circulation flows at a higher velocity than that on the two sides. On the sides, A5, the air flows feebly at a velocity less than 0.3 m/s.

Though a minor variation in the air velocity may seem to exist between Modes 4 and 5, their indoor flow patterns are primarily the same. After comparing and analyzing the results of the simulation, we determined that the flow patterns were very similar among the five Modes using either Hybrid Ventilators or conventional ventilators installed at possible locations on the slanted rooftop.

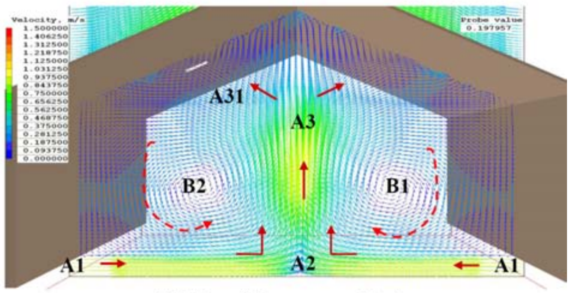
Fig. 6 shows the variations in air velocities of the Modes at different distances from the wall (at an average height of between 0.45 m and 4 m above the ground). It is indicated that no matter the Mode, air velocity is stronger closer to the middle of the space. This results from the upward flow that forms in the middle and is joined by the air from the openings on both walls. The middle space, which has a higher air velocity, is often used for aisles, but is more suitable for machinery or

Table 3. Simulation results for four conventional ventilators installed on the slanted rooftops in three Modes.

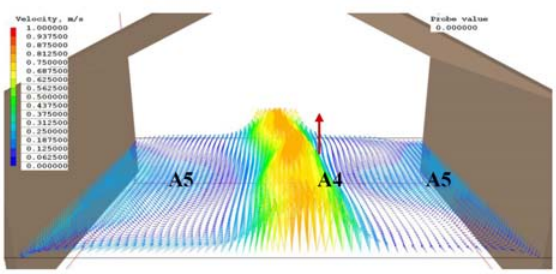
mode	Indoor airflow pattern in the middle of the factory (X=3.75m)	Indoor airflow pattern at the height of 1.5m
Mode 1	 0.88m/s 0.88m/s	
Mode 2	 0.86m/s 0.86m/s	
Mode 3	 0.84m/s 0.84m/s	



(a) Indoor airflow pattern at X = 3.75 m



(b) Indoor airflow pattern at X = 5 m



(c) Indoor airflow pattern at Z = 1.5 m

Fig 5. Flow patterns of the interior of Mode 5 at X = 3.75 m, X = 5 m and Z = 1.5 m, respectively.

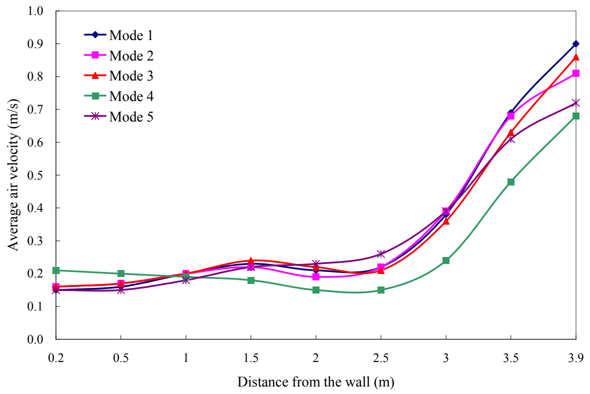


Fig. 6. Average indoor air velocity of the 5 Modes between Y=0.2 m and Y=3.9 m.

operations requiring high ventilation rates. The average air velocity at both sides remains at 0.1-0.3m/s. In any Mode at heights below 1 m, the air velocity decreases almost linearly as the height increases, while above 1m, the velocity remains between 0.2m/s and 0.4m/s.

4. Conclusions

This study proposed an innovative Hybrid Ventilator, developed from an improved conventional rooftop turbine ventilator and powered by a hybrid of wind and photovoltaic panels. The ventilation performance differences between Hybrid Ventilators and conventional ventilators were first assessed through a series of experiments. A Hybrid Ventilator provides approximately 4-times the exhaust capacity of a conventional ventilator. It is indicated that no matter the Mode, air velocity is stronger closer to the middle of the space because of the upward flow that forms in the middle and is joined by the air from the openings on both walls. All of the space configurations that were examined via CFD simulations exhibited similar indoor airflow patterns and air velocity distributions (ventilation "quality").

Acknowledgment

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