Using a New Modification on Wind Turbine Ventilator for Improving Indoor Air Quality

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ABSTRACT

This paper describes a newly modified wind turbine ventilator that can achieve highly efficient ventilation. The new modification on the conventional wind turbine ventilator system may be achieved by adding a Savonius wind turbine above the conventional turbine to make it work more efficiently and help spinning faster. Three models of the Savonius wind turbine with 2, 3, and 4 blades' semicircular arcs are proposed to be placed above the conventional turbine of wind ventilator to build a hybrid ventilation turbine. A prototype of room model has been constructed and the hybrid turbine is placed on the head of the room roof. Performance's tests for the hybrid turbine with a different number of blades and different values of wind speeds have been conducted. The experimental test results show that the performance of the improved ventilation turbine with three blades is the best. It is found that the maximum rotation speed of the improved turbine is 107rpm, while the air flow rate is $0.0103 m^3/s$ and the air change rate per hour is $32.67 hr^{-1}$, at a wind speed of 3m/s. The proposed design has been achieved an increase in the turbine rotational speed, increase of the extraction rate of the indoor air and the air-changes per hour, provided the requisite ventilation and improved the quality of the indoor air.
Keywords: hybrid turbine ventilator, Savonius wind turbine, airflow ventilation, air change rate per hour.

استخدام تعديل جديد على توربينِ رياح التهوية لتحسين نوعية الهواء الداخلي

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الخلاصة

يوضح هذا البحث تعديل جديد على توربين التهوية الذي يعمل بواسطة حركة الرياح والذي لديه القدرة على تحقيق التهوية بكفاءة عالية. التعديل الجديد لنظام التهوية بواسطة توربين رياح التهوية التقليدي يمكن تحقيقه بإضافة توربين الرياح نوع سافونيس فوق التوربين التقليدي لجعله يعمل بكفاءة أعلى ومساعدته في تحقيق دوران أسرع. تم اقتراح ثلاثة نماذج من توربين الرياح نوع سافونيس ذو زعنفتين وثلاثة زعانف وأربعة زعانف من أقواس نصف دائرية لوضعها فوق توربين التهوية التقليدي لكي ينتج توربين التهوية الهجين. وقد تم عمل نموذج مصغر لغرفة اختبار حيث تم تثبيت توربين التهوية الهجين في أعلى سقف الغرفة، وأجريت اختبارات الأداء على توربين التهوية الهجين لكافة النماذج التي تحتوي على عدد من الزعانف المختلفة وبسرعات رياح مختلفة. وظهرت النتائج التجريبية أن الأداء لتوربين الرياح ذو الثلاثة زعانف هو الأفضل. وجد أن أقصى سرعة دوران للتوربين تم الحصول عليها هي 107 دورة/دقيقة في حين كان معدل التدفق ألحجمي للهواء 0,0103 م^3/ثا ومعدل تبديل الهواء بالساعة 32,67 1/ساعة، عند سرعة رياح مقدارها 3 م/ثا. إن هذا التصميم المقترح قد تم تحقيق زيادة

في عدد الدورات للتوربين وبالتالي زيادة معدل استخراج الهواء من الأماكن المغلقة وأيضا زيادة في عدد مرات تبديل الهواء خلال الساعة الواحدة، وكذلك وفرت التهوية المطلوبة وحسنت من نوعية الهواء الداخلي.

1. INTRODUCTION

Wind turbine ventilators are those ventilators powered by a wind to create effective ventilation for different attic places. These turbines operate on wind assisted ventilation. The turbine ventilators are round metal vents with blades in them. Even just a little bit of wind can be just enough for the turbo ventilator to rotate. The faster the wind, the faster the turbine will rotate and exhaust the heat, smoke, fumes, humidity, etc. The wind turbine ventilators have been vastly used for many years in residential, agricultural crops drying, industrial buildings, sports halls, and warehouses. The development of ventilation systems by using wind ventilation turbine must take into account the airflow cross-sectional area which is pre-designed in the building roof to increase the speed of the air extraction rate and improve the internal environment.

Up to now, a few studies have been done on the application of hybrid design in ventilation systems, especially the turbine ventilation. Because ventilation turbines are the most commonly used systems in the renewable energies sector, any attempt for improving the rate of energy harvest seems very attractive.

No external conventional energy is required for the ventilation turbine since it works by natural wind. This turbine had been originally patented by, **Meadows, 1932,** as one type of rooftop turbo ventilator**. Dale,** and **Ackerman, 1993,** observed that speed and direction of wind had some effects on the mass flow rate of the turbo ventilator. **West, 2001,** studied the effect of blade height on the turbine ventilator performance. Long Volume Turbines (LVTs) were considered for an experimental study. The experimental studies also had been carried out by adding an extractor air fan placed on the bottom of the turbine ventilator shaft. This method produced a good mass air flow rate. It can conclude that this addition sized 360 mm and 500 mm does not give percipient variations in the mass air flow rate produced. For designing and developing any new model for the turbo ventilator, constructive factors were studied by, **Lai, 2003.** Measurements of air extraction characteristics of 4 wind influenced ventilators had been presented by**, Revel,** and **Huynh, 2004.** They compared the extraction performances of roof-mounted ventilators with data obtained from tests based on an Australian/New Zealand Standard. The results show that a single performance curve (embodying air extraction rates, wind speeds, throat size and pressure differentials across the devices) characterizes each ventilator. **Kuo,** and **Lai, 2005**, had enhanced the ventilation in bathrooms by providing a large turbo ventilator. The results indicated that the turbo ventilator did significant improvements in the ventilation rate and the induced negative pressure helped to reduce odors and moisture in the room. **Lai, 2006,** proposed adding a small DC fan placed in the base air duct supplied with PV solar cells to the conventional turbine air ventilator to effectively enhance the rate of ventilation at lower wind speeds. The performance of a hybrid turbine ventilator had been investigated by**, Ismail, and Rahman, 2010,** for Malaysian climate conditions. The turbo ventilators were provided with an opening on the top (80mm) and solar powered extracted fan at the bottom levels. The inner duct of diameter 200mm was fitted inside the turbo ventilator. It was observed that indoor air temperature had been dropdown by 0.70°C and humidity by 1.7%. Three different kinds of the turbine ventilator were proposed by**, Nguyen, et al., 2012.** The first kind, fans had mounted at the bottom of the turbine shaft. The second kind used the gear system to increase the rotational speed of the shaft. While the third kind, the existing turbine ventilator was modified by providing extracted fan at the bottom of the turbine as well as putting a set of propeller on the top. The last one had been marked to be the best design which gave an additional rotational speed and extraction of hot air which caused a better thermal comfort.

1.1 Comparison with the literature

Several studies were carried out for enhancing the performance of the conventional wind turbine ventilator via changing its configurations, like the turbine diameter, turbine height, forming the blade shape (curved or straight vane), and air duct diameter. On the other side, other studies had been implemented to improve the wind turbine ventilator which depends in its work on the wind motion by making some modifications on various hybrid turbine ventilators to improve their performance. There were three samples for these ventilators in the literature which depended on the wind energy or any source of the renewable energy. **Table 1** demonstrates the comparison of three samples in the literature with the present study.

The addition of the Savonius wind turbine is proposed in this paper for some reasons: it's being one of the vertical axis wind turbines; its pivot is superposing with the wind turbine ventilator axis, it is simple to be assembled with the ventilator, it occupies very small place as compared with the other vertical axis wind turbines, and it has a lightweight, which does not cause any valuable vertical force may apply on the turbine rotation axis as brake force which may cause stopping the rotation of the wind turbine ventilator.

The acceptability degree of the proposed addition of the Savonius wind turbine in achieving an increase in the air extraction rate was accompanied by some advantages and disadvantages:

- The advantages are:

1- Utilizes a renewable energy.
2- Operates at low wind speed rates.
3- Has high flow rate.
4- Utilizes one high-quality air duct for high air flow rate, equivalent to two ducts.
5- Simple installation.
6- Can deal with the wind with any direction, so there is no need to redirect the turbine to the wind.

- The disadvantages:

1- The turbine air flow rate specifically depends on the wind strength.
2- Has elevated initial cost.

The aim of this work is proposing a hybrid turbine design as a new ventilation turbine to enhance the performance of the wind ventilation by using more swept area. This is done by adding a Savonius wind turbine, which has two, three, or four blades. The new modification on the conventional wind turbine ventilator is employed to produce the hybrid turbine ventilator with higher air quality and comfort and minimum negative impact on the environment. This configuration opens new horizons towards the renewable energy.

2. EXPERIMENTAL SETUP

A practical test is conducted on the improved wind ventilation turbine which is constructed from steel with the following dimensions (width = 25cm, height = 18 cm, throat = 13 cm). The conventional turbine has 13 blades curved as demonstrated in **Fig. 1**.

The turbine is installed at the top of the roof of the modeled testing room. The room is shown in **Fig. 2** and has been built with dimensions (1.5 x 0.87 x 0.87) m^3. It is consisted of base and frame structure, makeup of different materials; iron sheets and thermal insulation, having slots for air entry at the lower side and air exit slot at the top of the attic of test room at which the hybrid ventilation turbine is installed.

Fig. 3 shows the several shapes for the proposed models of the Savonius wind turbine used in this work with two, three and four blades. Each blade has a semi-circular shape of a plastic tube with a diameter of 10cm and height 14cm. These blades have been installed on a steel circular plate with a diameter of 22 cm. The swept area of the Savonius wind turbine is (14×20) cm^2.

3. EXPERIMENTAL PROCEDURE

A series of experimental tests have been carried out using variable speed air fan, with five different speeds (1.6, 1.9, 2.3, 2.7, and 3) m/s, projected on the hybrid ventilation turbine which have been installed inside an enclosed space, so that it is not affected by the external winds as shown in **Fig. 4**.

Four test cases for the ventilation turbine models are proposed to be experimentally carried out, the first one is the conventional model of the turbine wind ventilator and the rest three models are for the modified hybrid turbine with two blades, three blades, and four blades as shown in **Fig. 5**.

The procedures in this paper are achieved according to the following steps:

1- Running the electric fan and directing it toward ventilation turbine blades approximately at a one-meter distance far from the turbine in the first model.
2- Measuring the first airspeed at a point very close to the turbine is measured by using an Anemometer. It is found (1.6 m/s).
3- Measuring and recording the rotational speed of the turbine in rpm by using a Digital Tachometer.
4- After that, the airspeed passing through the circular mouth exit located below the turbine is measured by using an Anemometer.
5- Repeat the steps (1-4) with other different speeds (1.9, 2.3, 2.7, and 3) m/s.
6- Installation the first additional Savonius wind turbine with two blades on its circular plate above the traditional ventilation turbine on the same axis of rotation via using screws and nut in order to produce the hybrid turbine.
7- Repeating same previous steps (1-5) on the hybrid turbine with two blades.
8- Repeating the same above scenario on the hybrid turbine with three and then four blades, respectively.

4. DATA REDUCTION

Fig. 6 shows the method of measuring the pressure difference between two points inside the model room based on the principle of Bernoulli's equation. The first point "1" is located below the throat slot with 50cm distance and the second point "2" is located directly under the throat of the turbine (circular mouth exit of air). The differential pressure can be calculated as follows, **Wylie, et al., 1993.**

$$\Delta p = \frac{1}{2}\rho(v_2^2 - v_1^2) + g\rho(Z_2 - Z_1) \qquad (1)$$

Where: $v_1 = 0$ is assumed as the static air speed inside the room, v_2 is the air speed outside the room measured at the throat, $g = 9.81\ m/s^2$ is the ground acceleration, $\rho = 1.2 Kg/m^3$ is the air density, Z_1 = 0m, Z_2 = 0.5m, where (Z_2-Z_1) is the elevation difference in (m), $P_2 = P_1 - \Delta p$ kN/m^2. P_1 = 101.25 kN/m^2 is the atmospheric pressure. Volume flow rate Q (drainage) can be calculated as: $Q = A_t * v_2$, where: $A_t = \frac{\pi}{4} d^2$ is the cross sectional area of the throat, d is the diameter of throat, and v_2 is the air speed outside the room.

The power transmitted to the fluid by the ventilator can be calculated according to the following equation**, Edwards, 2005.**

$$P_h = Q * P_2 \quad (2)$$

The value of the wind flow coefficient can be obtained as follows**, Revel, and Huynh, 2004.**

$$C_f = \frac{v_2}{u_w} \quad (3)$$

Where u_w is the wind speed acting on the hybrid turbine ventilator.
The air change rate per hour can be expressed by**, Bearg, 1993.**

$$ACR = \frac{Q*3600}{V_R} \quad (4)$$

Where: $V_R = 1.135 m^3$ is the volume of the room model with dimensions of (1.5×0.87×0.87) m^3.
The turbine torque is defined as an influential force tangent to the rotary blade, which may be given as follows:

$$T = I.\alpha \quad (5)$$

Where I is the rotor moment of inertia and α is the rotor angular acceleration. α is calculated as follows:

$$\alpha = \frac{\omega_2 - \omega_1}{\tau} \quad (6)$$

Where ω_1 and ω_2 are initial and final angular velocities, respectively, and $\omega_1 = 0$, and τ is the time period.
The moment of inertia could be considered as the (stored energy estimator in the rotating shaft or the amount of energy that will speed up the shaft to a certain speed, and this is called the second moment of area or moment of inertia) and might be expressed as**, Jha, 2010.**

$$dI = r^2 \times dm \quad (7)$$

Where: r = the radius of blades arc in m (the distance of the infinitesimal element of mass from the origin) = $d \times cos\emptyset$, and dm = $\rho \times H \times t \times d \times cos\emptyset \times d\emptyset$ is the infinitesimal element of mass in kg, where, t is the blade thickness in m.
The moment of inertia for the semi-circular shape of the blade shown in **Fig. 7** might be obtained using the following equation:

$$I_b = \int r^2 \, dm \quad (8)$$

Therefore, the moment of inertia of the blade (I_{b1}) becomes as follows:

$$I_{b1} = \int_0^{\pi/2} \rho H t d^3 cos^3\Phi d\Phi = \rho H t d^3 \int_0^{\pi/2} cos^3\Phi d\Phi \quad (9)$$

$I_{b1}=\frac{2}{\pi}m.d^2 \int_0^{\pi/2} cos^3\Phi d\Phi = \frac{4}{3\pi}m.d^2$

Where: $m = \frac{\pi}{2}\rho.H.t.d$ (kg)

Thus, the moment of inertia of the Savonius wind turbine with two, three and four blades cases, respectively, becomes:

$I_{2b} = \frac{8}{3\pi}\ m.d^2, I_{3b} = \frac{4}{\pi}\ m.d^2$ and $I_{4b} = \frac{16}{3\pi}\ m.d^2$

So, the total moment of inertia for the hybrid turbine ventilator is being equal to:

$$I = I_b + I_p + I_{Tr} \qquad (10)$$

Where, I_b is the two, three, or four blades moment of inertia, I_p is the end plates moment of inertia and I_{Tr} is the hybrid turbine ventilation moment of inertia.

5. RESULTS AND DISCUSSION

5.1 Rotational speed

The rotational speed of the turbine ventilator is increased with the wind speed increase, also increased by adding the blades as compared with the traditional turbine ventilator (without adding blades) at certain wind speed conditions as shown in **Fig. 8**. From the curves, it can be seen that the rotational speed of the hybrid ventilation turbine with three blades is the highest up to 107 rpm at wind speed condition 3m/s. Adding additional blades to drive the wind turbine ventilator gives higher rotation speed.

5.2 Air extraction speed

Fig. 9 shows the air extracted speeds versus the wind speed for different model types of the turbine. The figure shows that the extracted airspeed is increased with the wind speed increase for the turbine ventilator without and with the addition of the blades. Also, it can be noticed that the maximum air extracted speed has been obtained when using three blades with the ventilator turbine as compared with other cases.

5.3 Air flow rate

It can be shown from **Fig. 10** that the air flow rate (Q) passing through the circular mouth entry at the top of the room model increases with the increase of the wind speed. Also, the addition of blades to the conventional turbine model causes an increase in the air flow rate. Using three blades produces a greater air flow rate than other turbine cases.

5.4 Power transmitted to the air

Fig. 11 shows the increase in the power transmitted to the air resulting from the turbine ventilator with the wind speed increase. Also, it can be concluded that the power transmitted of the extracted air increases with the increase of the number of blades added to the conventional turbine at certain values of wind speed. The highest power transmitted to the air is 0.987 kW at 3 m/s wind speed in the case of three blades.

5.5 Air flow coefficient

Fig. 12 shows the increase in the air flow coefficient (C_f) with the increase of the wind speed. The figure shows that the airflow coefficient for the hybrid model with three blades has the highest value as compared with the conventional turbine and the modified hybrid turbine with another number of blades.

5.6 Air change rate per hour (ACR)

The air change rate per hour (ACR) increases with the increase of the wind speed as shown in **Fig. 13**. Also, the ACR for the modified hybrid turbine with three blades increases with the highest value compared with other cases. It is observed that the biggest ACR reaches to 32 times for the hybrid turbine containing three blades as compared with other types. The maximum ACR is 32.67 1/hr at 3 m/s wind speed.

5.7 Pressure differences

Fig. 14 shows the relationship between the pressure differences inside the room with the wind speed. Increasing the air wind speed will increase the air movement inside the room, resulting disturbance in the pressure and thus the pressure difference increases. On the other side, the pressure difference increases too with adding the blades as compared with the conventional turbine ventilator at certain wind speed conditions. It is found that the hybrid model with three blades is the best one.

6. CONCLUSIONS

1- The measured and calculated results have proved that the improved hybrid ventilation turbine which consisting of the turbine ventilator combined with the Savonius wind turbine with three blades as compared with the conventional turbine and the modified hybrid turbine with two or four blades. This is because that the values of the angles between the three blades with 120° will decrease the drag surfaces against the wind air flow of convex blade when the wind direction is perpendicular to the surface of the concave blade. This will cause a decrease in the reverse torque and increase in the net torque.

2- The Savonius wind turbine with two or four blades has the lowest performance than with three blades because, the position of the concave blades is opposite to that of the convex blades which produce two opposing forces, increases the reverse torque and drops the net turning moment (torque).

3- In this paper, only one pre-designed duct in the room model is used with the increase in the air flow rate exit from that duct instead of utilizing several ducts and another wind turbine ventilator, therefore this contribution acts as a relatively low-cost design.

4- Because of the location of the wind turbine ventilator at the top of the roof, it is possible to put additional turbine blades on it to acquire an increase in the swept area of the wind without any obstruction.

5- The proposed hybrid wind turbine needs less wind speed to spin than the conventional wind turbine ventilator because of the addition of the Savonius wind turbine which operates at low wind speed conditions.

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NOMENCLATURE

ω_1= initial angular velocity, 1/s.
ω_2 = final angular velocity, 1/s.
A= swept area, m^2.
ACR= air change rate per hour, 1/hr.
A_t= cross-sectional area of throat, m^2.
C_f= flow coefficient for a particular wind speed, dimensionless.
d_{vent}= diameter of turbine wind ventilator, m.
h_{vent}= height of turbine wind ventilator, m.
I= rotor moment of inertia, kg.m^2.
I_b= two, three, or four blades moment of inertia, kg. m^2.
I_p= end plates moment of inertia, kg. m^2.
I_{Tr}= hybrid ventilation turbine moment of inertia, kg. m^2.
P= air pressure inside the room, kN/m^2.
P_{fl}= power transmitted to the fluid by the ventilator, Watt.
Q= air flow rate through ventilator, m^3/s.
t_{vent}= throat of turbine wind ventilator, m.

t= blade thickness, m.
U_W= wind speed acting on hybrid turbine ventilator, m/s.
V_R= volume of the model room, m^3.
w_{vent}= width of turbine wind ventilator, m.
Z= elevation, m.
ΔP= drop of pressure inside the room, kN/m^2.
τ= time, sec.
υ_1= speed of the air inside the room, m/s.
υ_2= speed of the air outside the room, m/s.
g= ground acceleration, m/s^2.
α= rotor angular acceleration, $1/s^2$.
ρ= air density, kg/m^3.

Table 1. Configurations description of the Hybrid turbine ventilators in the literature.

Configuration	Description	References
Using an inner vane	The existence of internal vane does not give importantly variances in the ventilating rate produced. This method causes an obstruction to the air exiting from the duct.	Lai (2003)
Using extractor fan	The combination with the extractor air fan might guarantee its harmony and produces much more ventilation rate. However, This method of ventilation is perfect only in the condition of weak wind with speed not exceeds 5m/s. This ventilator configuration depended upon the fan's work only, as well as on the solar energy which is just obtainable from sunlight through the daytime.	Lai (2006), Ismail & Abdul Rahman (2010)
Other additions	Integration with other extensions (using a fan at the bottom of the turbine shaft, the gear system and set of the propeller on the top) might give an additional rotational speed and good extraction of the air. All these additions were complex in the installation process and high cost.	Nguyen et al, (2012)

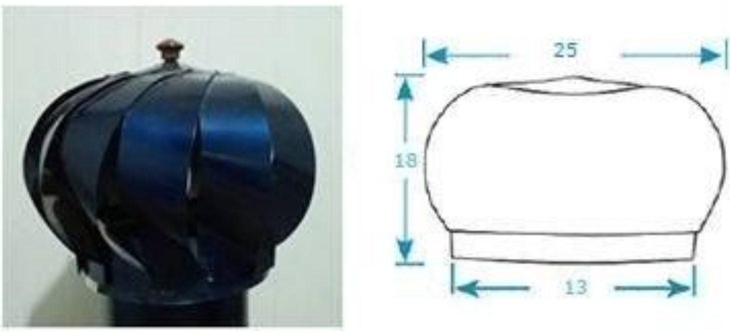

Figure 1. Conventional wind turbine ventilator.

Figure 2. Structure of the room model.

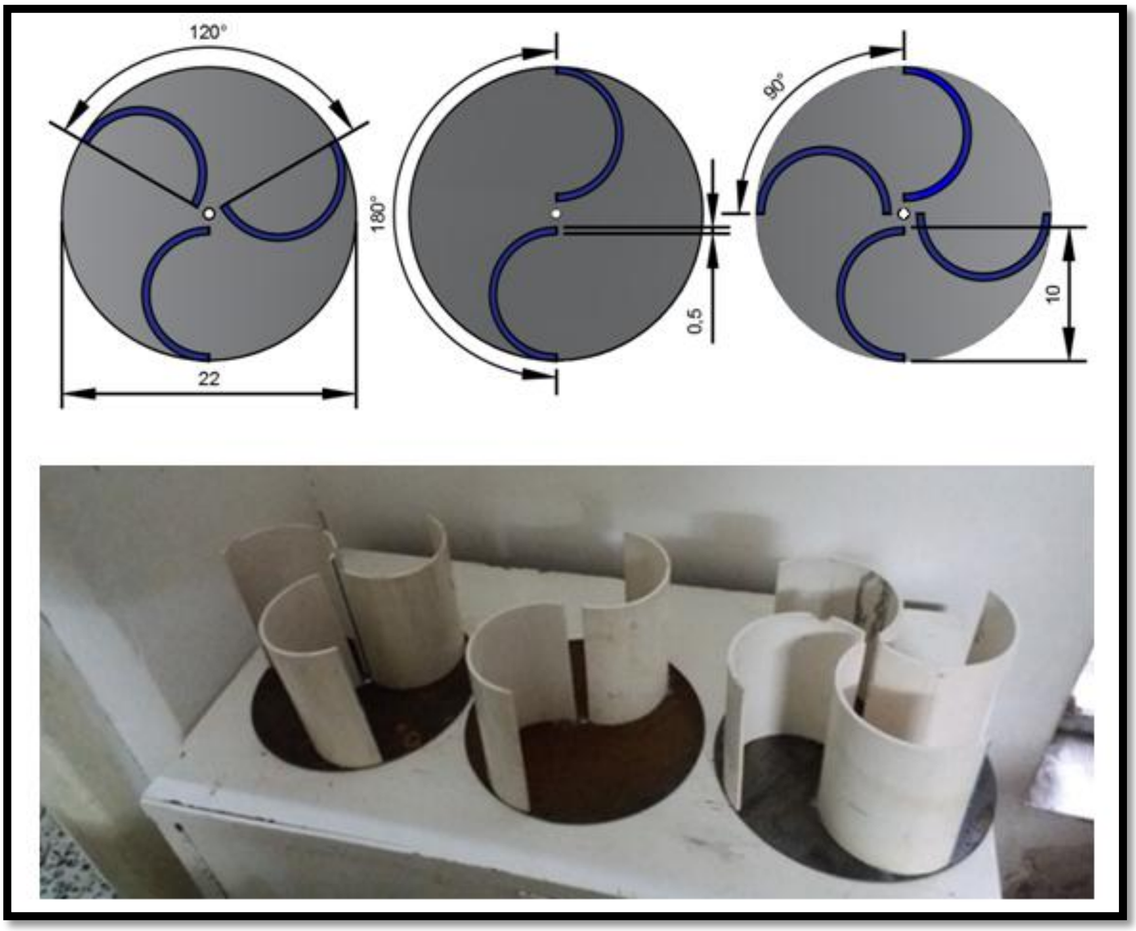

Figure 3. The proposed three schematic and photo models for the Savonius wind turbine.

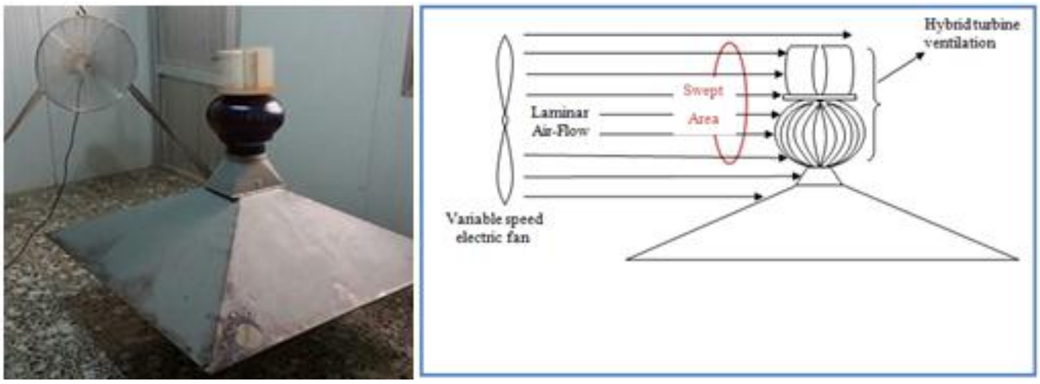

Figure 4. Schematic drawing & experimental rig for the hybrid turbine ventilator.

Figure 5. The three proposed models of the hybrid turbine ventilator.

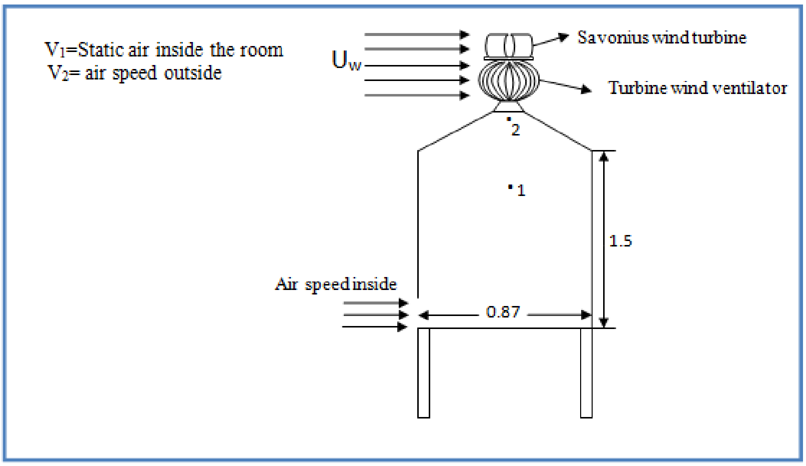

Figure 6. Schematic diagram of the experimental test rig.

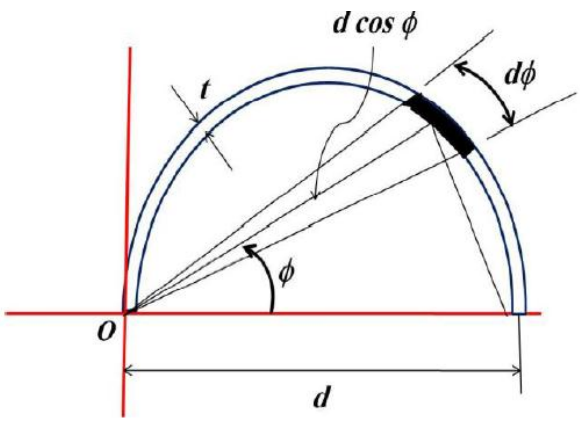

Figure 7. Semi-circular shape schematic for a moment of inertia calculation.

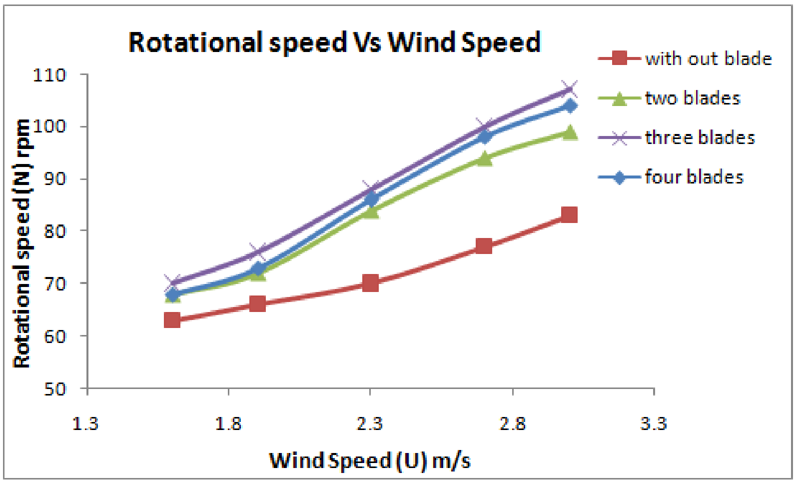

Figure 8. Turbine rotational speed versus wind speed.

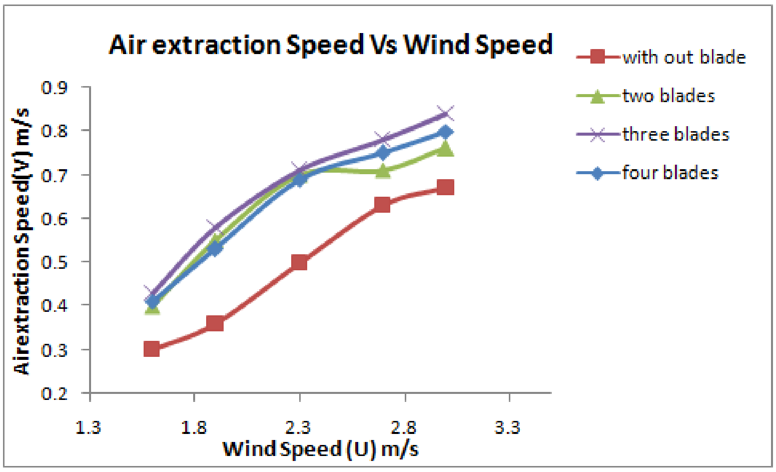

Figure 9. Air extraction speed versus wind speed.

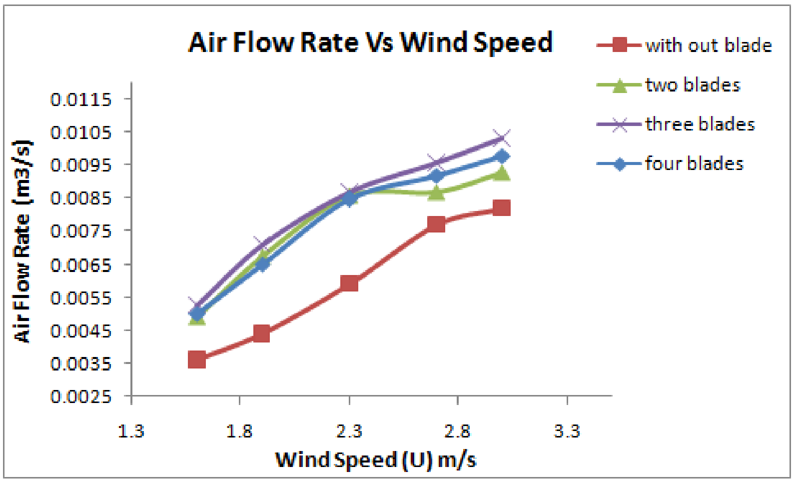

Figure 10. Airflow rate versus wind speed.

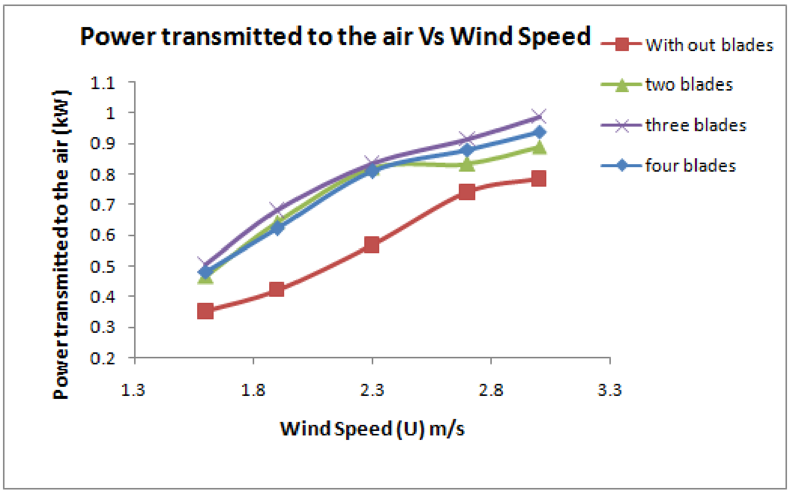

Figure 11. Power transmitted to the air versus wind speed.

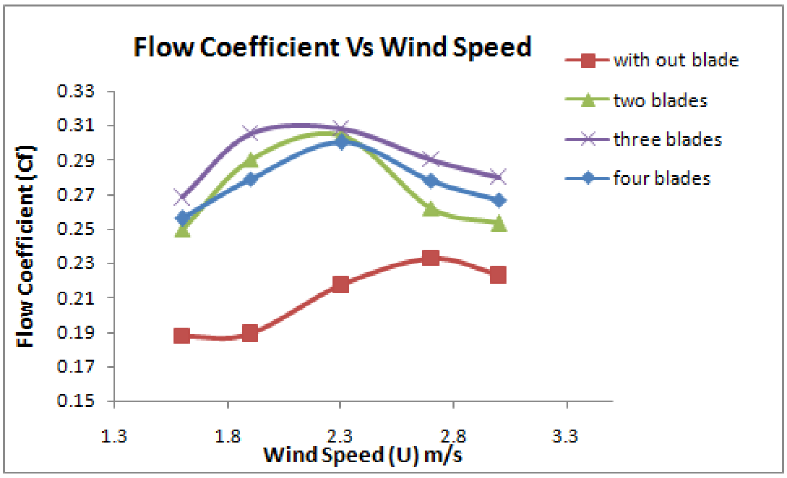

Figure 12. Airflow coefficient versus wind speed.

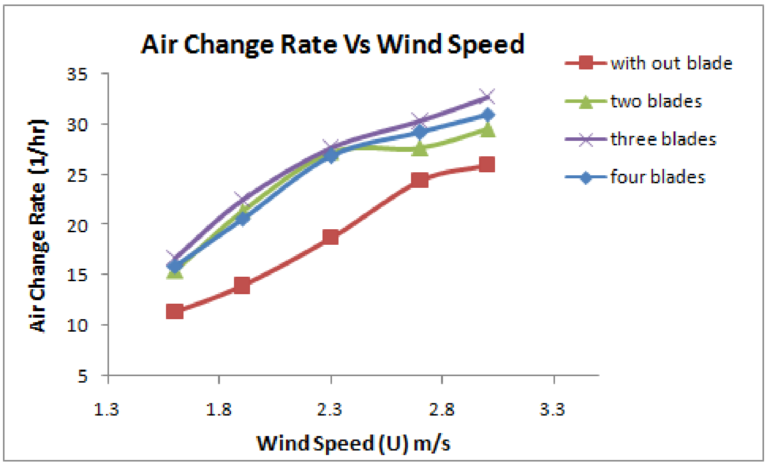

Figure 13. Air change rate per hour versus wind speed.

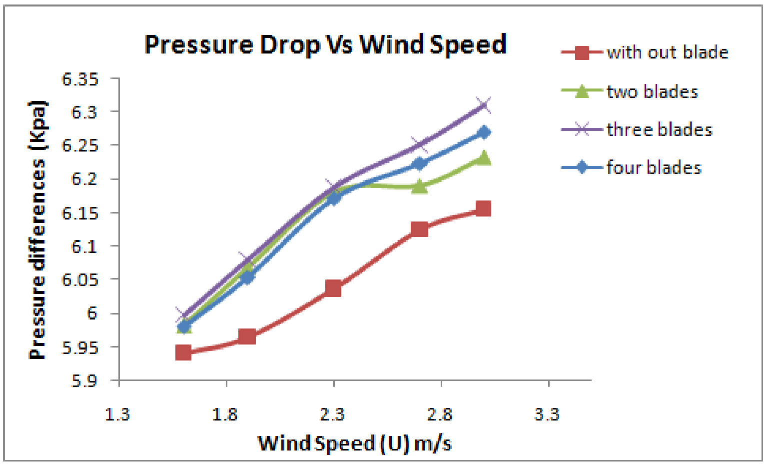

Figure 14. Pressure differences versus wind speed.