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Effect of Blade Materials on the Performance of Savonius Wind Turbine for Operation in Taif City-Saudi Arabia

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Abstract: Renewable energy technologies are considered as the key driver of the country's economic growth and development. One of the important targets of Saudi Arabia's vision 2030 is to generate 9.5 Gigawatts of renewable energy (solar and wind power) in the near future. The application of wind energy in industrial and household sectors is becoming increasingly attractive and widely extended to substitute the traditional oil-produced energy. This can also minimize the environmental pollution. Different types of wind turbine have been used for low as well as high power applications. Recently, an increased attention has been given to vertical axis wind turbine due to its simplicity and advantages over horizontal axis wind turbine. Savonius wind turbine is considered as one of the most popular types of vertical axis wind turbine due to its simplicity in design and operation for low power applications especially in low wind speed regions. Different design parameters of Savonius wind turbine have been previously investigated towards the best performance. However, the blade materials have not been considered previously in order to show its impact on Savonius wind turbine performance. In the present paper, the design and operation of Savonius wind turbine are investigated according to the local climate conditions in Taif-city, Saudi Arabia. Two different materials have been used for blade manufacturing, namely Aluminum sheets (3003) and PVC (ASTM D2665 -14) materials. The effects of such materials on the performance of Savonius rotor related to its output power are experimentally investigated. It is found that, the blades made from Aluminum sheets showed better performance than those made from PVC material. In general, it is concluded that Savonius wind turbine can be used efficiently for household applications in Taif region, Saudi Arabia.

Keywords: Blade material; Renewable energy; Saudi Arabia; Savonius wind turbine; Taif city; Wind energy.

1. INTRODUCTION

Renewable energy developments and technologies are of great importance to the Kingdom of Saudi Arabia (KSA) as it can be considered the most important standard of the economic growth and the country's developments. It is well known that, the electricity sector in KSA has great challenges in supplying the increased demand for electricity consumption in industrial and household applications. In order to meet such demand, renewable energy (solar and wind) should have a large share of electrical energy production in the future. The application of wind energy still faces some technical problems, such as high cost and production difficulties, that still have to be worked out in order to simplify the widespread use of such renewable energy. Moreover, the estimation of the wind power potential and resources in different locations in KSA is the first step of establishment of wind farms in KSA. Therefore, many previous investigations have been carried out to assess the wind resources in different locations in KSA, such as Eastern Coastal Region, Gassim, Tabouk, Yanbou, Dhahran, Douhlom, Riyadh and Qaisumah, see for more details [1-7].

Taif is a city in Mecca province of Saudi Arabia, shown in Figure 1, located at an elevation of about 1800 m. Taif has latitude and longitude coordinates of 21.43 and 40.35, respectively. Based on population, the area is ranked #7 in Saudi Arabia. Taif has a population of 1,200,000 people and the 5th largest city in Saudi Arabia. Moreover, the nice weather in all parts of Taif led to a huge rush at tourist spots. Visitors from other Gulf countries and from across Kingdom came to enjoy their time in Taif. In recent years, the number of tourists and visitors to Taif increased rapidly up to 3.5 million. Consequently, the Arab Tourism Organization (ATO) has named Taif as the Arab Summer Capital for 2014 and later years. Accordingly, the energy consumption of Taif region will increase rapidly in next years. Therefore, the application of renewable energy, such as solar and wind energy, in electricity production is becoming necessary.

Figure 1. Taif city indicated in map of Saudi Arabia

Table 1. Wind Speed Data Analysis from Taif monitoring station [9].

Location	Possible records	Valid records	Mean (m/s)	Median (m/s)	Max. (m/s)
Taif	13514	10677	3.73	3.6	10.29

The main characteristic of wind energy potential for a certain location is the wind speed characteristics. The wind speed measurements should be measured at different heights; namely, 20 m, 30 m, and 40 m above ground level [8]. Other important parameters should also be collected in the place where the wind farm is considered, such as: wind direction, air temperature, relative humidity, surface station pressure and global solar radiation. Such parameters are known as the meteorological data of a region. Other factors can be also determined such as wind statistics, local values of wind shear exponent, Weibull distribution parameters, turbulence intensity, and wind energy. Consequently, for the establishment of a wind farm in a certain place, the known wind characteristics should be firstly available.

In order to collect data about renewable energy on Taif, a Monitoring Station, among of 30 stations distributed across the Saudi Arabia is located on Taif University with elevation of nearly about 1518 m. Sample data of such station is shown in Table 1. The main purpose of such station is one-minute measurements of Global Horizontal Irradiance (GHI), Diffuse Horizontal Irradiance (DHI), Direct Normal Irradiance (DNI), and related meteorological parameters [9].

Recently, assessment of wind power cost at twenty locations in Saudi Arabia has been presented [10]. It is found that at Taif city, the required wind speed was available for 45±5% of the times per year. Moreover, the cost of each kilowatt-hour of electricity produced using wind was calculated for all twenty locations using the capital cost, investment cost, operation and maintenance cost, depreciation, inflation rate, and interest rate. According to the generating machines used, the minimum cost of electricity was found to be 0.0234, 0.0295, and 0.0438 US$/kWh at Yanbo, while the corresponding maximum was 0.0706, 0.0829, and 0.121 US$/kWh at Nejran when using 2500, 1300, and 600 kW machines.

More recently, the economic feasibility of development of 15 MW (50 m hub-height) wind power plant at Taif, Saudi Arabia has been investigated by analyzing long-term wind speed data [11]. The cumulative frequency distribution indicates that the wind speeds are less than 3 m/s for 46% of the time during the year at Taif. This implies that wind electric conversion systems (WECS) or wind farms (if installed at Taif) will not produce energy for about 46% of the time during the year [11]. Moreover, it is found that by the development of 15 MW wind farm, nearly about 453 tons/year of carbon emissions can be avoided entering into the local atmosphere.

Recently, an increased attention has been given to investigation of small wind turbines due to its wide applications and economic installation [12]. Small wind turbines are generally those operated until 10 kW. Mid-sized wind turbines are ranging up to several hundred kilowatts. The vertical axis wind turbines are simple in construction, having low cost and self-starting at low wind speed. No wind turbine yaw mechanism is required in order to turn the wind turbine rotor against the wind. It always orients towards the wind direction, making it suitable for generating electrical energy for house hold application at rural and urban areas in many countries especially in Saudi Arabia. The Savonius wind turbine is a vertical axis wind turbine with lower performance compared with other conventional wind rotors. However, it has many advantages such as simplicity in design, low cost, low operating wind speed, independent of the wind direction, and good self-starting ability.

Previously, many investigations have been carried out, either experimentally or numerically, in order to study how to improve the performance of Savonius wind turbine. Such performance is strongly influenced by the geometric design parameters; such as swept area of blades, number of blades, overlap ratio, rotor height and radius, aspect ratio, tip speed ratio and many others parameters, as seen in [13] and the included references.

More recently, a numerical investigation with the commercial CFD package FLUENT software for modified Savonius rotor with two deflector plates in the upstream of the turbine has been conducted. Such investigation was performed to find the optimum position of the two deflector plates in order to increase the power coefficient using water as a working medium [14]. The obtained results showed that the model with the best orientation of the two deflector plates in the upstream increases the power coefficient by 80%.

Although the blade material plays a significant role on the performance of Savonius wind turbine, no previous investigations can be found in literature regarding such effect. Therefore, in the present study the effect of blade material on the Savonius wind turbine performance is experimentally investigated. The geometric parameters of the designed Savonius wind turbine are selected to produce low out power operated with a range of the local wind speed in Taif city, Saudi Arabia.

2. DESIGN PARAMETERS

Figure 2 shows the essential geometric and designed parameters required for the proposed model of the SWT. A mini-electrical generator (HSM8316-100W) is coupled directly to the main axis of the Savonius rotor.

3. DESIGN MODEL

In order to experimentally investigate the effects of blade material on the Savonius wind turbine performance, two designed models were made. Blade materials are selected from Aluminum sheets (Model_1) and from PVC (Model_2). Both models have the same geometric design parameters and electrical generator, shown in Table 2. The performance of the tested models against the blade material is evaluated through the measured output power of the selected model using a suitable multimeter.

The starting point of the designed parameter of the model is the required output power. The output power of the present model is selected in the low range of about 5 Watt. The value of small output power is suitable for small Savonius wind turbine which can be applied for household applications. The other designed parameters are calculated accordingly as it will be explained in the following section. Figure 3 shows the final designed model of the proposed Savonius wind turbine with its miscellaneous parts.

The parameters shown in Figure 2 can be defined as follows:

d - diameter of the curved blade (m)
D - wing spread of the rotor (m)
e - blade spacing (m)
F - diameter of end plates (m)
h - height of blades (m)

Two different materials have been used for blade manufacturing of SWT, namely Aluminum sheets (3003) and PVC (ASTM D2665 -14) materials. The rotor axis is made from stainless steel 301 with Dshaft = 1.27 cm.

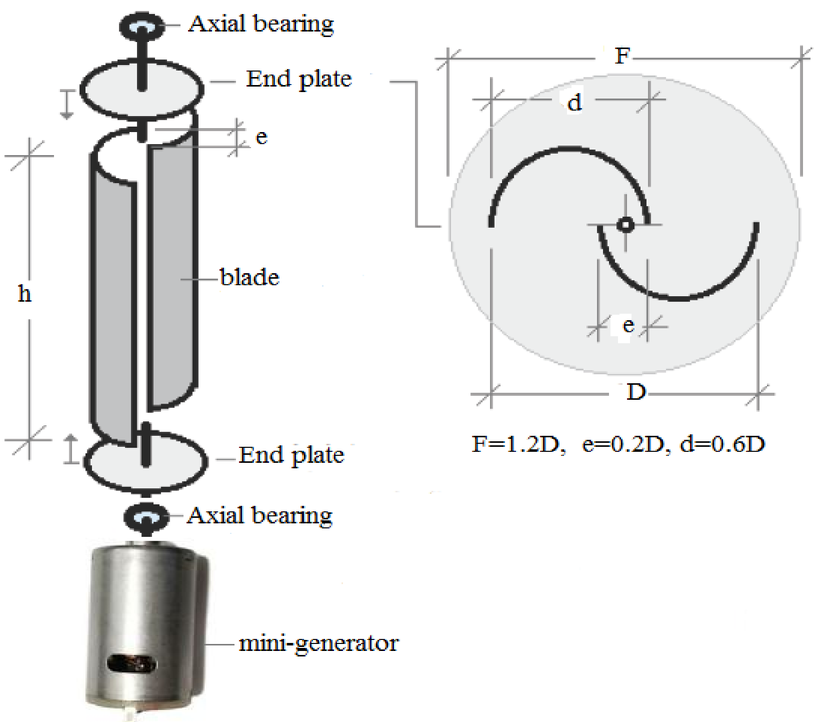


Figure 2. Sketch of the Savonius wind turbine and its geometric dimensions

Table 2. Geometric and operating parameters of design models

Designed Output power	*h*	*D*	Wind speed	*d*	*e*	*F*
4.94 W	0.5 m	0.245 m	6 m/s	0.1524 m	0.058 m	0.305 m

Figure 3. The design model of Savonius wind turbine with its accessories; (1) Turbine blades, (2) End plate, (3) Sleeves, (4) Base, (5) Bearing, (6) Frame, (7) Shaft, (8) Generator, (9) Wheels

3. THEORETICAL ANALYSIS

In this section, the basic equations of Savonius wind turbine are explained and some numerical results are presented in order to show the effects of the designed parameters and the operating conditions on its performance.

The maximum theoretical output power of the Savonius rotor is estimated according to the following equation:

$$P_{out} = \eta_o * 0.5 * C_p * \rho * A * v^2 \quad (1)$$

where ρ is the air density (kg/m^3), $A = h * D$ (m^2) is the area of the rotor, v is the wind speed (m/s) and P_{out} is the output power. The overall efficiency due to aerodynamic and mechanical losses can be considered as $\eta_o = 50\%$ and the Betz coefficient $C_p = 0.593$ [15].

The angular velocity can be given by:

$$\omega = 2\lambda . \frac{v}{D} \quad (2)$$

where λ is the tip-speed ratio and it is assumed that $\lambda = 1$ for the presented theoretical analysis. The tip-speed ratio (TSR) for wind turbines is defined as the ratio between the tangential speed of the tip of a blade and the actual wind speed.

Consequently, the rotational speed is given by:

$$N = \frac{60\omega}{2\pi} \quad (3)$$

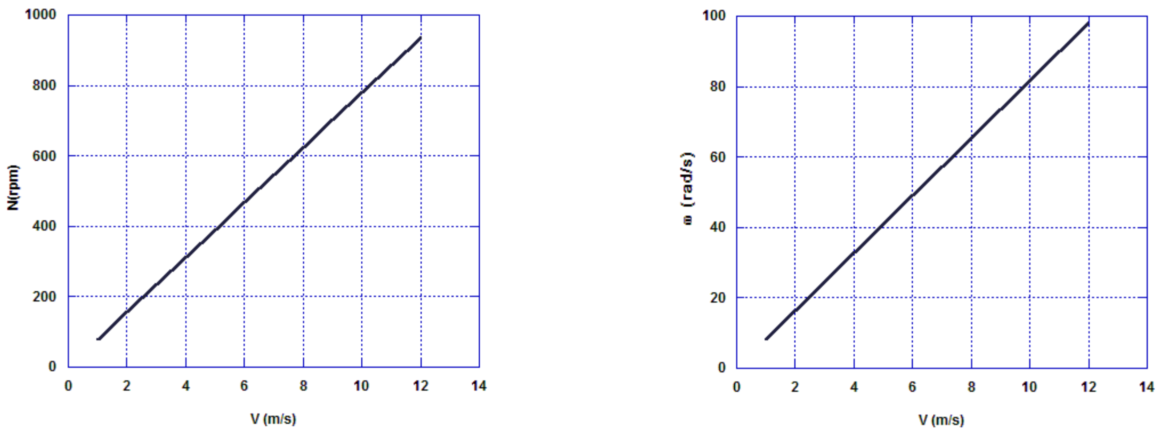
Furthermore, the torque at the rotor shaft can be given as:

$$\tau_{out} = \frac{P_{out}}{\omega} \quad (4)$$

By using the above equations, it is now possible to calculate the key parameters for the performance of the Savonius wind turbine. Figures 4 and 5 show the theoretical variations of the angular velocity, rotational speed, output power and the output torque against the wind speed calculated from the above system of equations (Equations 1-4). It is important to notice the linear variation of the angular velocity and the rotational speed with the wind speed. However, parabolic relations are obtained for the output power and the output torque against the wind speed. The range of the wind speed is considered as the local average wind speed in Taif city, Saudi Arabia [16].

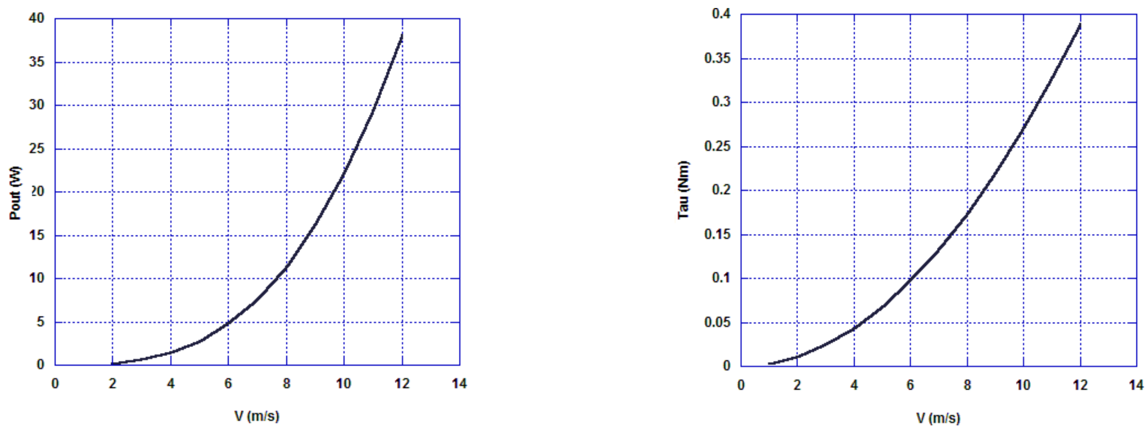
5. EXPERIMENTAL MEASUREMENTS

In this section of the experimental measurements of the Savonius wind turbine performance parameters are presented. The wind speed is measured using Extech HD300: CFM/CMM Thermo-Anemometer with built-in Infra-Red Thermometer, shown in Figure 6(a). For measuring the output voltage, current and electrical output power, a Multimeter - BTMETER BT-39K is used, shown in Figure 6(b). Moreover, a Photo-contact Tachometer (Model ST-6236B) is used for measuring the angular velocity of the rotor, shown in Figure 6(c). The two designed models (Model_1 and Model_2) are used to predict the output power and the angular velocity according to the available wind speed range 4-9 m/s [16]. The air flow rate can be obtained in the laboratory through a vertical fane with the type of KSM-2460. The designed models are located at the points where the maximum wind speed is obtained from the fan as illustrated in the next section.



(a) (b)

Figure 4. The variation of the rotational speed and the angular velocity with wind speed



(a) (b)

Figure 5. The variation of the output power and the output torque with wind speed

(a) (b) (c)

Figure 6. The measuring devices used in the experiments

6. RESULTS AND DISCUSSION

In the present section, samples of the obtained experimental measurements are illustrated and the results are discussed. The first group of results was carried out in the laboratory using a vertical fane with the type of KSM-2460 in order to produce air flow similar to the wind energy obtained in free places. However, the velocity profile obtained from the vertical fan is different from that obtained freely. Figure 7 shows the vertical distribution of the three axial velocities that can be obtained from the vertical fan according to the built-in motor speed controller. It should be pointed out that, he adopted experimental measurements procedure was based on a number of repeated experiments with the same conditions. An average value of the experimental measurements has been taken and presented.

It can be seen that, from Figure 7, that the velocity profile is similar to the fully developed turbulent jet flow velocity profile with maximum velocity obtained at a vertical distance *Y* of about 7 cm from the hub of the fan. This is similar to the obtained results of [18]. Therefore, by using such fan in our measurements, the center of the Savonius designed model is located directly at that distance (Y = 7 cm) in order to apply directly the maximum velocity obtained from the fan.

Figure 8 shows experimental measurements of the output power obtained in our lab using the vertical fan for both models (Model_1, and Model_2). The results show that the power obtained from the Model_1, made from Aluminum sheets is much higher than that obtained from Model_2, made from PVC material. That can be referred to the large weight of the blades on Model_2, which required high wind speed to produce a similar output power of Model_1. However, due to the small weight of Aluminum blades, high power was obtained. The maximum improvement of the obtained power from the two models can reach to about 90% in the range of wind speed considered. It can be concluded that, by increasing the weight of the blades a small output power can be obtained. In such cases, most of the incoming air stream power is consumed on overcoming the high resistance of the blades weight.

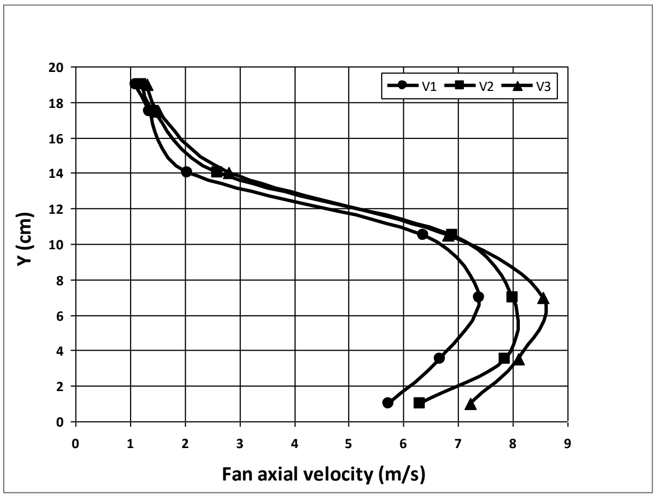


Figure 7. The vertical distribution of the three axial velocities obtained from the vertical fan according to the built –in motor speed controller, v_1, v^2 and v_3

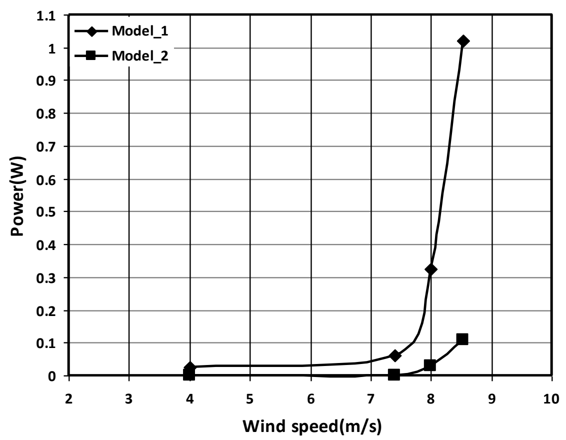


Figure 8. The measured output power obtained using a fan for both designed model

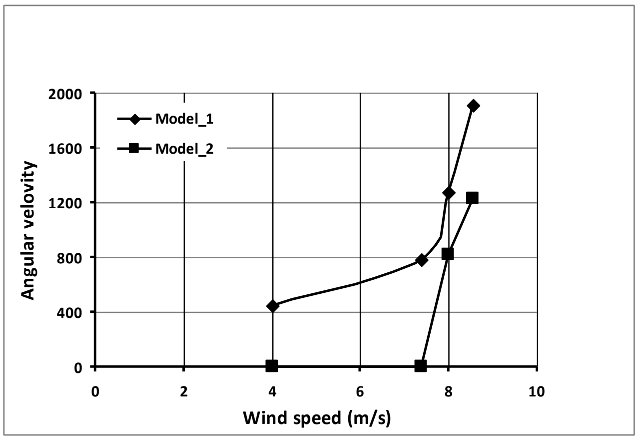


Figure 9. The measured output angular velocity (rad/s) obtained using a fan for both designed models

Figure 8 shows experimental measurements of the output power obtained in the lab using the vertical fan for both models (Model_1, and Model_2). The results show that the power obtained from the Model_1, made from Aluminum sheets is much higher than that obtained from Model_2, made from PVC material. That can be referred to the large weight of the blades on Model_2, which required high wind speed to produce a similar output power of Model_1. However, due to the small weight of Aluminum blades, high power was obtained. The maximum improvement of the obtained power from the two models can reach to about 90% in the range of wind speed considered. It can be concluded that, by increasing the weight of the blades a small output power can be obtained. In such cases, most of the incoming air stream power is consumed on overcoming the high resistance of the blades weight. These results can be also approved in Figure 9, where the angular velocity was measured for both designed models using the air stream issued from the vertical fan. High values of angular velocity were obtained from Model_1 in comparison with these values measured for Model_2 for the same wind speed applied.

In order to test the model in free places, additional experimental measurements were carried out in ALHADA region in Taif city, Saudi Arabia. ALHADA region is located in the west of Taif city, with a high of about 2000 m over sea level, shown in Figure 10. In this region, high wind speed can be obtained naturally. Therefore, an important test for the designed Model_1 is tested according to such normal conditions. Figure 11 shows the measured values of the output power obtained from Model_1 at ALHADA region, Taif city, Saudi Arabia. It can be shown that the wind speed reaches a value of about 13 m/s and the output power of about 5.0 Watt.

It can be noticed that, the output power obtained from the lab-based experiment is different from that obtained from the outdoor experimental test with a nearly percentage of 50%. This might be referred to the velocity distribution obtained in both regions. In the outdoor experiment a really uniform velocity distribution with constant maximum speed can be easily obtained. However, in the lab experiment a velocity distribution was obtained similar to that described in Figure 7 with different maximum velocity. Consequently, the effect of incident velocity distribution is clearly indicated.

In order to test the accuracy of the experimental measurements, a comparison with the output power equation (Equation 1) is made. An additional constant has been included in such equation in order to account for the blade material type, it is called here k_{blade}. The value of such coefficient is found to be about 0.11 that gave the best comparison between the theoretical results of (Equation 1) and the experimental measurements. That can be shown in Figure 12. It is recommended that by changing the blade material, the blade coefficient should also be changed. Therefore, wide range experimental measurements for different materials should be performed in order to find out the associated values of such blade coefficient. This can be considered in our future work.

Figure 10. ALHADA region, Taif city, Saudi Arabia

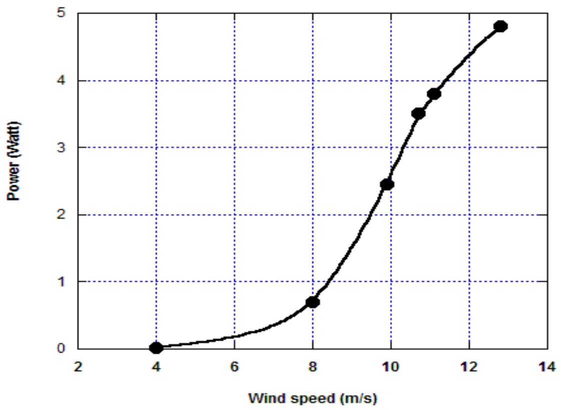


Figure 11. The measured output power of Model_1 obtained at ALHADA region, Taif city, Saudi Arabia

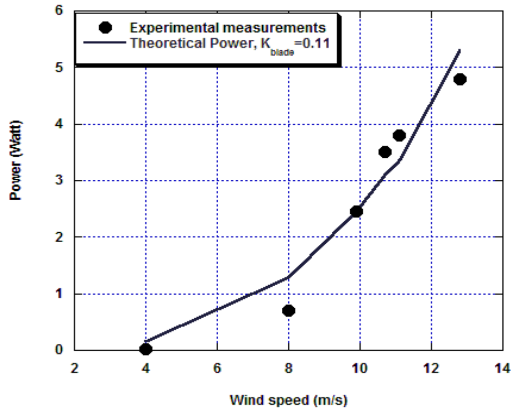


Figure 12. A comparison between the experimental measurements and the theoretical prediction of output power for Model_1

7. CONCLUSION

In the present paper, two different material models for Savonius wind turbine rotor were designed with the same dimensions in order to check the effect of material type on the performance of the turbine. The blades were made form Aluminum sheets (3003) and PVC (ASTM D2665 -14) materials for Model_1, and Model_2 respectively. Model_1 has showed better performance in comparison with the output power obtained from Model_2, when the experiments were performed in our lab and by using an axial fan. Experimental measurements have been also carried out in ALHADA region, Taif city, Saudi Arabia with maximum wind speed of about 13 m/s, which can give an output power of about 5.0 Watt. As the theoretical results presented in the present paper were not able to describe the experimental measurements properly, numerical investigations are required to evaluate the experimental measurements. This will be done in the next future research. In general, the results obtained indicate that the Savonius wind turbine can be used efficiently for household applications in Taif region, Saudi Arabia.

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