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An experimental study on improvement of Savonius rotor performance

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Abstract For solving the world energy problem and the bad effect of conventional sources of energy on environment, great attention allover the world is paid towards the use of renewable energy sources. Special interest is paid towards wind energy because of its competitively.

Savonius rotor is a vertical axis wind turbine which is characterized as cheaper, simpler in construction and low speed turbine. This makes it suitable for generating mechanical energy in many countries especially in Egypt.

In this work different geometries of Savonius wind turbine are experimentally studied in order to determine the most effective operation parameters. It was found that, the two blades rotor is more efficient than three and four ones. The rotor with end plates gives higher efficiency than those of without end plates. Double stage rotors have higher performance compared to single stage rotors. The rotors without overlap ratio (β) are better in operation than those with overlap. The results show also that the power coefficient increases with rising the aspect ratio (α). The conclusions from the measurements of the static torque for each rotor at different wind speeds verify the above summarized results of this work.

1. Introduction

Wind energy is very important as one of clean energy resources. Wind rotors are the most important tool of the wind energy. Savonius wind rotor is one of the vertical axis wind turbines. It is simple in structure, has good starting characteristics, relatively low operating speeds, and an ability to capture wind from any direction. But it has a low aerodynamic efficiency. Savonius wind rotor is constructed simply of two vertical half cylinders, as shown in Fig. 1. The ratio between rotor height (H) and rotor diameter (D) is called the aspect ratio (α). Another parameter that affects the performance of Savonius rotor is the overlap ratio (β) which is expressed as: $\beta = (e - a)/d$, where e is the overlap, a is the shaft diameter and d is the blade diameter.

The performance of Savonius rotor has been studied by many researchers from 1977 until 2010 in order to determine

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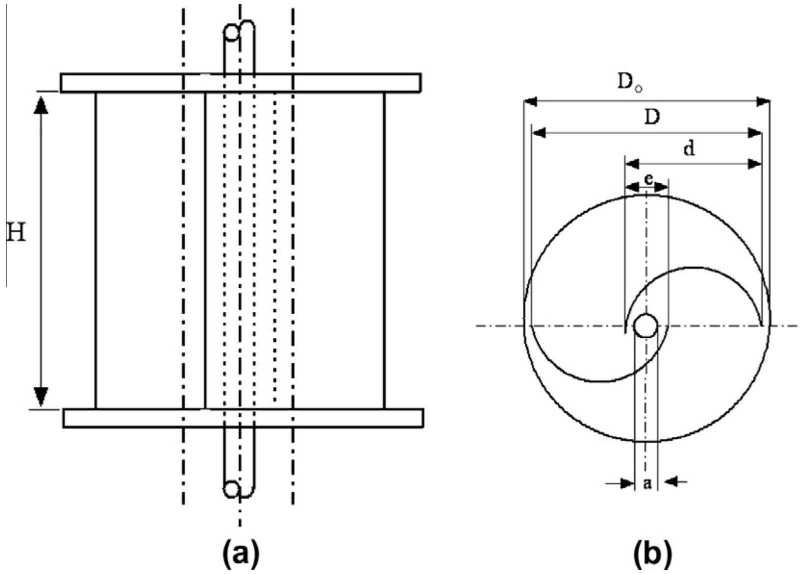

Figure 1 Scheme of a single-stage Savonius rotor: (a) elevation view; (b) plan view.

the optimum design parameters of this rotor. In the following, the main trends in these studies are summarized and discussed.

The effect of blade aspect ratio, blade overlap and gap besides the effect of adding end extensions, end plates and shielding were tested by Alexander and Holownia [1]. The test was carried out in a wind tunnel on a number of Savonius rotor geometries with wind speeds ranging from 6 to 9 m/s. They concluded that, there is an improvement in rotor performance with increasing the aspect ratio. The tests for three and four bladed geometries gave appreciably lower values of efficiency than two blades rotor. They used four values of the extensions and found that the efficiency increases with the increase of the extension. They concluded also that the efficiency for the rotor with end plate and shielding is greater than that with end plate and without shielding. Furthermore, the efficiency obtained for a rotor with end plate and without shielding is greater than that of rotor without end plate. They found also that, increasing the rotor overlap ratio increases the rotor efficiency. Modi et al. [2] reported that the optimum values of the aspect and overlap ratios are 0.77 and 0.25 respectively. Mojola [3] examined the performance of Savonius wind rotor under seven values of the rotor overlap ratio namely 1/8, 1/5, 1/4, 1/3, 1/2, 3/4 and 7/8. He concluded that the effect of overlap ratio on rotor performance depends on its tip speed ratio ($\lambda = \omega R/V$) where ω is the angular speed, R is the rotor radius = $D/2$ and V is the wind speed. The aerodynamic performance and the flow fields of Savonius rotors at various overlap ratios have been investigated by Nobuyuki [4]. The static torque performance of the rotor, specially of the returning blade, is improved by the presence of the overlap and the best value of the overlap is 0.15. Menet [5] aimed to construct a prototype of Savonius turbine to charge a battery. He used blades from plastic tube (PVC) and steel shaft. He utilized a rotor with aspect ratio of 4 and overlap of 0.25. He found that starting velocity was 3 m/s, velocity for maximum production is 13 m/s and the mean efficiency between 5 and 10 m/s was found to be 29%. The range of speed rotation was 200–800 rpm. Kamoji et al. [6] examined helical Savonius rotors in an open jet wind tunnel. From their results, the helical rotors with shaft have lower power coefficient than the helical rotors without shaft. Saha et al. [7] carried out a comparison between Savonius rotor with different geometries. They reported that, the optimum number of blades is two for the Savonius rotor whether it is single-, two- or three-stages. Twisted geometry of the blade profile has a good performance as compared to the semicircular blade geometry. Two-stages Savonius rotor has better power coefficient as compared to the single- and three-stage rotors. Altan et al. [8] studied the curtain arrangement using two plates, one in the upper end of rotor and the second at the rotor lower end. This arrangement is used to prevent the air leakage from the concave side. They concluded that the arrangement increases the rotor performance. They used three curtaining arrangements by changing the two plate lengths and its angle on the horizontal axis. The results showed that the curtaining which has longest plates is better and the optimum angel is 15° on the horizontal axis for the upper plate and 45° for the lower one. Altan et al. [9] examined the parameters in Ref. [10] and compared the measurements with the numerical results. Gupta et al. [10] made a combination between Savonius wind rotor and Darrieus wind rotor. They compared the results obtained with those of conventional Savonius rotor. They observed that there is a retable improvement in the power coefficient for the combined Savonius–Darrieus rotor. Kamoji et al. [11] studied the effect of the overlap ratio, blade arc angle, aspect ratio and Reynolds number on the performance of Savonius rotor. They found that, the modified Savonius rotor without overlap ratio, with blade arc angle of 124° and with an aspect ratio of 0.7 has a maximum power coefficient of 0.21 at Reynolds number of 150,000. The obtained value of the power coefficient is higher than that of conventional Savonius rotor. Roth [12] tested the effect of both aspect ratio and overlap ratio. He reported that the best values are 0.77 and 0.22 respectively. Blackwell et al. [13] reported that the two-stages geometry has better aerodynamic performance than the three-stage one, with the exception of starting torque. They decided also that, the increase in the aspect ratio improve the rotor performance. Shankar [14] tested both two-blades and three-blades geometries. He found that, two-bladed Savonius rotors have almost 50% higher peak power output than the three-bladed ones. Mahamarakkalage [15] examined experimentally and analytically blade geometry, overlap ratio, aspect ratio and Reynolds number on the performance of Savonius rotor. The results showed that optimum geometries of Savonius rotor corresponding to the blade geometry are as follows: gap size of 0, overlap ratio of 0, aspect ratio of 0.77, blade shape parameter of 0.2 and blade arc angle equals 135°. The rotor with the previous configuration will have a peak power coefficient of about 0.32 at tip-speed ratio of 0.79.

The above results on Savonius rotors give different optimum geometries. In the present paper; various geometry parameters of Savonious rotors including number of blades, number of stages, overlap ratio, aspect ratio and existence of end plates are studied experimentally. The aim of this work is to determine the optimum configuration of Savonius rotor which gives the higher performance. Various geometries of Savonius rotors are designed and examined at the rear exit of a wind tunnel in Advanced Fluid Mechanics Laboratory at Mechanical Power Engineering Department, Faculty of Engineering, Shebin El-Kom, Menoufiya University.

2. Experimental arrangement

Fig. 2 shows the schematic diagram of the test rig which is used in the present work. It consists mainly of the following components: a subsonic wind tunnel (1), ball bearing (2), steel housing (3), steel shaft (4), Savonius blades (5) and end plates (6).

The tested rotors are supported vertically in steel housing as shown in Fig. 2b. System of tested rotors and steel housing has been installed 125 cm downstream the exit section of a suction type wind tunnel such that the vertical axis of rotating rotor is in line with the centre line of the wind tunnel exit area. The wind tunnel is 49 cm in diameter with wind speed range of 0–13 m/s at tunnel exit.

The present experimental investigations are concerned with various geometries of Savonious rotors. These geometries have different values of the following parameters: number of blades of two blades (2b), three blades (3b) and four blades (4b); single stage (1st.) and double stages (2st.); overlap ratios (β) of 0, 0.2, 0.25, 0.3 and 0.35 and aspect ratios of 0.5, 1, 2, 4 and 5 besides the existence and absence of end plates. The Savonius rotor is placed at its proper position using a structure housing fabricated from mild steel plates. Two ball bearings (SKF) are mounted to the mild steel plates in order to support the Savonius rotor. The usage of studs, nuts and bolts in housing construction facilitates the replacement of various tested geometries of Savonious rotor and helps also in determining the proper position of rotor axis at the centre line of the wind tunnel. The blades of rotors are made from light plastic (PVC) tubes with different diameters (0.3, 0.2, 0.1 and 0.08 m). The end plate is fabricated from light wood plates with 2.5 mm thickness. The diameter of the end plate (D_o) is greater than the rotor diameter by 10% in order to have a good performance as recommended previously [4,5,13]. The steel shaft which is used here has 14 mm in diameter and 62 cm in length for all models.

2.1. Measurements and instrumentation

The mechanical power for the tested Savonius rotor is determined by measuring the mechanical torque on the rotating

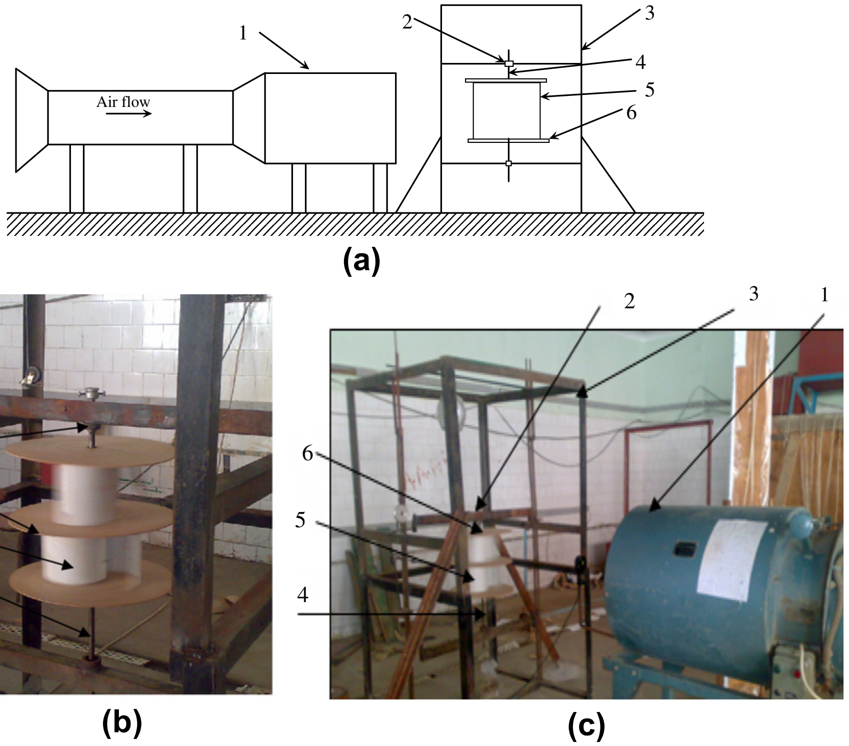

Figure 2 (a) Schematic of the test rig, (b) photograph of double stage Savonius rotor, (c) photograph of the test rig, considered in this work it consists of 1 – wind tunnel, 2 – bearing, 3 – steel housing, 4 – steel shaft, 5 – blades and 6 – end plate.

shaft and rotational speed at different values of wind speed. The arrangement used to do that is shown in Fig. 3. It contains pulley system, nylon string, weighing pan and spring balance. The weighing pan, pulley and spring balance are connected by a nylon string of 1 mm diameter as shown in Fig. 3. The wind speed is measured by a propeller type digital anemometer. While the shaft rotational speed is measured using a digital dc tachometer.

From the measured values of mechanical torque and rotational speed, the mechanical power can be estimated at each wind speed as:

$$P_m = T\omega \quad (W) \tag{1}$$

where T is the mechanical torque and ω is the angular speed

The angular speed is defined in rad/s as:

$$\omega = \frac{2\pi n}{60} \tag{2}$$

where n is the shaft rotational speed in rpm.

The mechanical torque is obtained in (N m) by

$$T = Fr \tag{3}$$

where r is the pulley radius.

The force acting on the rotor shaft obtained in (N) by:

$$F = (m - s)g \tag{4}$$

where m is the mass loaded on the pan in kg, s is the spring balance reading in kg and g is the gravitational acceleration.

The power coefficient C_p and static torque coefficient C_{ts} can be determined from the following equations:

$$C_P = \frac{P_m}{P_w} \tag{5}$$

where P_w is calculated from the following equation:

$$P_w = \frac{1}{2}\rho A V^3 \tag{6}$$

where ρ is air density, kg/m^3, A is the projected area for the rotor (HD), m^2 and V is the wind speed, m/s

Finally, the power coefficient can be formulated as:

$$C_p = \frac{gr\pi n(m - s)}{15\rho A V^3} \tag{7}$$

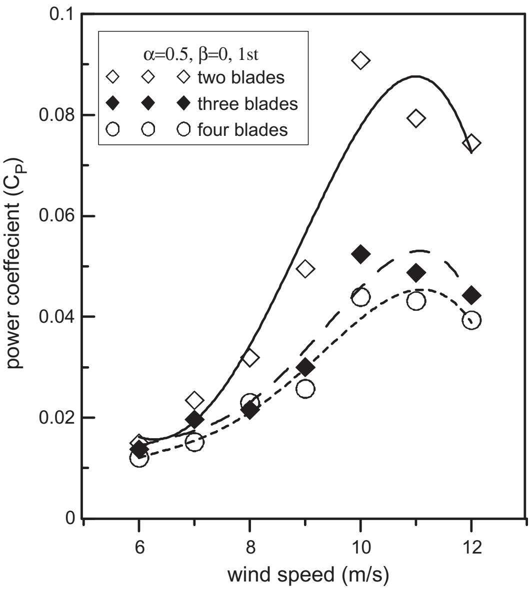

Figure 4 Relation between power coefficient and wind speed for rotors with two, three and four blades.

The static torque coefficient is calculated from

$$C_{ts} = \frac{4T}{\rho D^2 V^2 H} \tag{8}$$

3. Results and discussion

3.1. Effect of number of blades

Fig. 4 shows the relation between power coefficient and wind speed for two, three and four blades arrangement with aspect ratio of 0.5, overlap ratio equals 0 and for single stage rotor. The power coefficients for two blades rotor is higher than power coefficients obtained for both three and four blades rotors. This may be due to the net drag force affected on rotor in two blades case is higher than those for three and four blades cases.

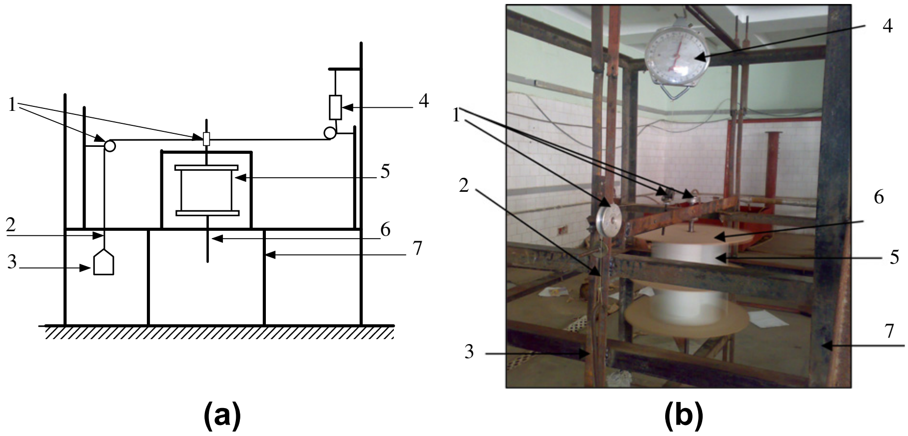

Figure 3 (a) Schematic diagram of Savonius rotor connected with mechanical torque measurement arrangement (b) photograph, (1: pulley; 2: nylon string; 3: weighing pan; 4: spring balance; 5: Savonius rotor; 6: rotating shaft and 7: structure.

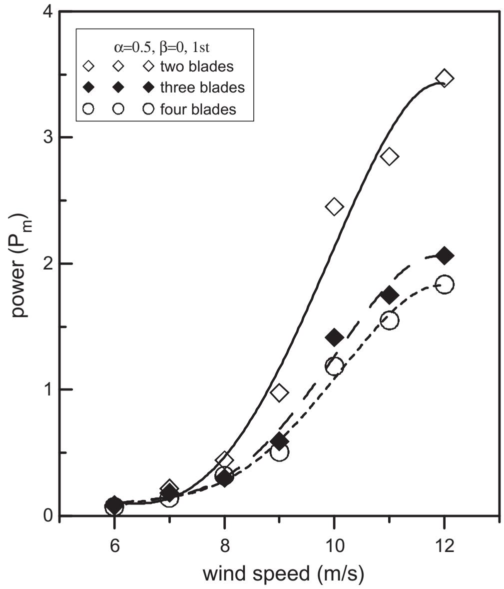

Figure 5 Variation in mechanical power with wind speed for rotors with two, three and four blades.

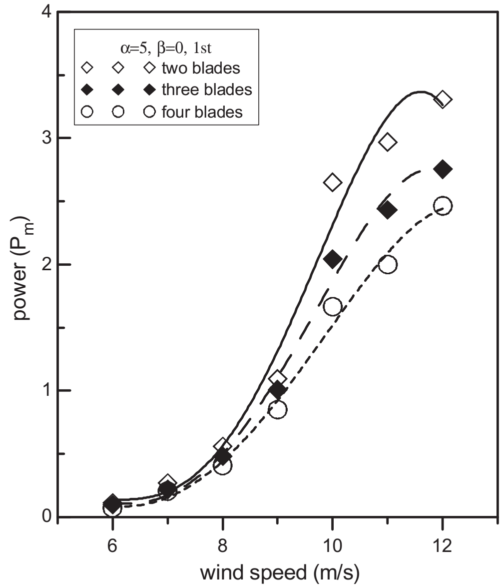

Figure 6 Variation in mechanical power with wind speed at aspect ratio 5.

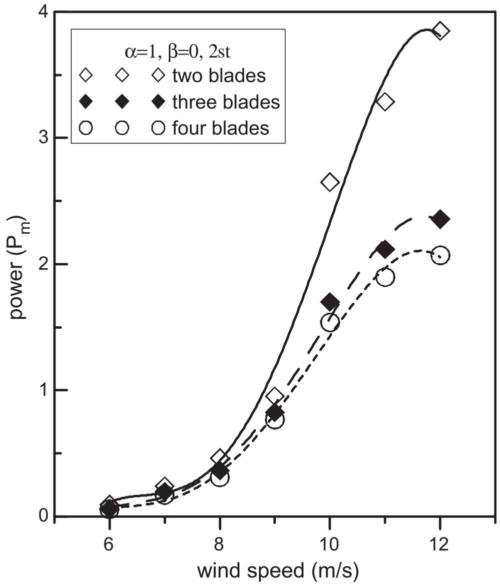

Figure 7 Variation in mechanical power with wind speed for double stage rotor.

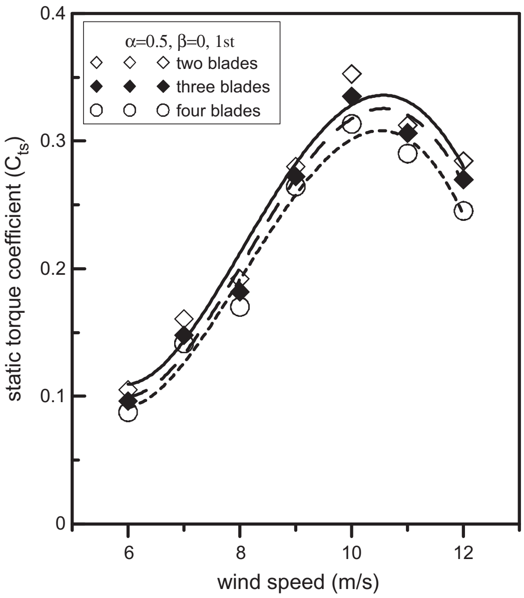

Figure 8 Relation between static torque coefficient and wind speed for α = 0.5.

Fig. 5 illustrates the variation in mechanical power with wind speed for the investigated rotors. The two blades rotor gives higher mechanical power compared to three and four blades rotors. The two blades rotor is more efficient also for other aspect ratios and for double stages rotor as shown in Figs. 6 and 7. From the above figures, it is seen that the two blades rotor gives higher performance than three and four blades rotors for all aspect ratios as well as for single or double stages too.

To verify this result, the static torque is measured for each rotor at different wind speeds. The static torque in the present work is defined as the torque affected on rotor to stop its rotation. The static torque coefficient can then be calculated from Eq. (8). Figs. 8 and 9 illustrate the relation between static torque coefficient and wind speed for two, three and four blades rotors at two aspect ratios of 0.5 and 5 respectively. It is seen from Figs. 8 and 9 that, the static torque on two blades rotor exceeds static torque on both three and four blades rotor. This result is confirmed with that the two blades rotor gives more power as depicted in Figs. 6 and 7.

3.2. Effect of number of stages

Effect of number of stages is studied here for rotors of single and double stages at constant values of other studied parameters. The two stages rotor gives higher specific power than single stage rotor as shown in Fig. 10. The specific power is defined as the

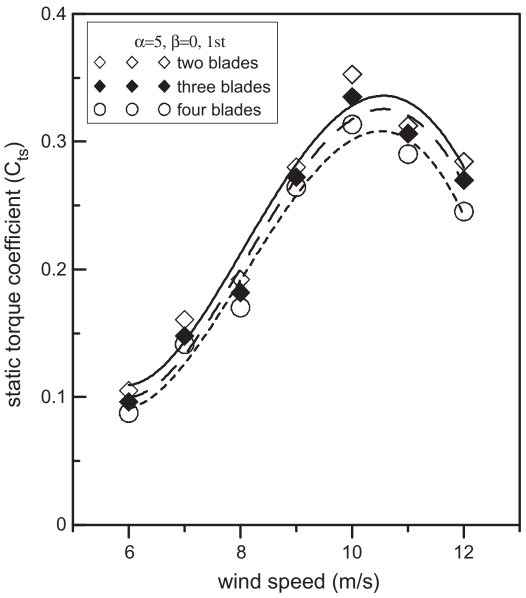

Figure 9 Relation between static torque coefficient and wind speed for $\alpha = 5$.

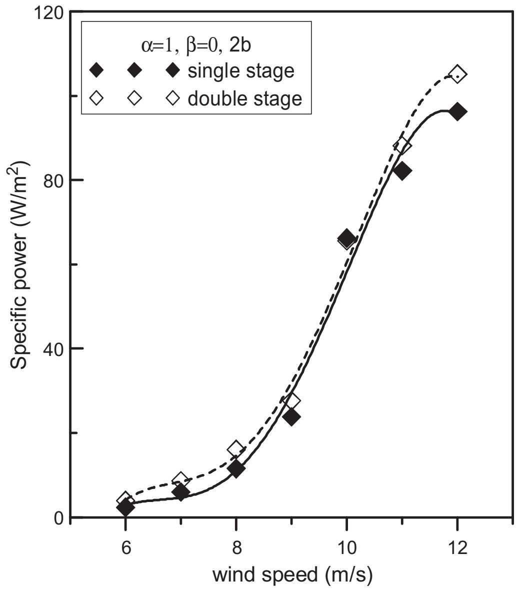

Figure 10 Variation of specific power with wind speed for single and double stage rotors.

power obtained from unit projected area of the rotor. In order to verify this result, the static torque affected on rotor blades for both single and double stages rotors is measured at the same angle of rotation and at different wind speeds. Fig. 11 indicates that double stages rotor has higher static torque and consequently higher static torque coefficient compared to the single stage rotor.

3.3. *Effect of overlap ratio*

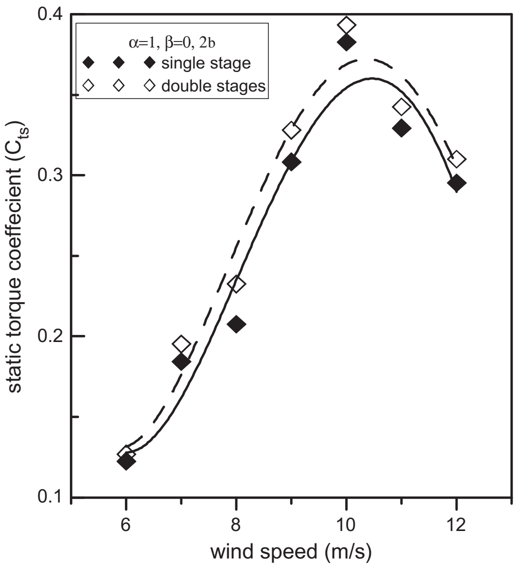

Figure 11 Variation of static torque coefficient with wind speed for single and double stage rotors.

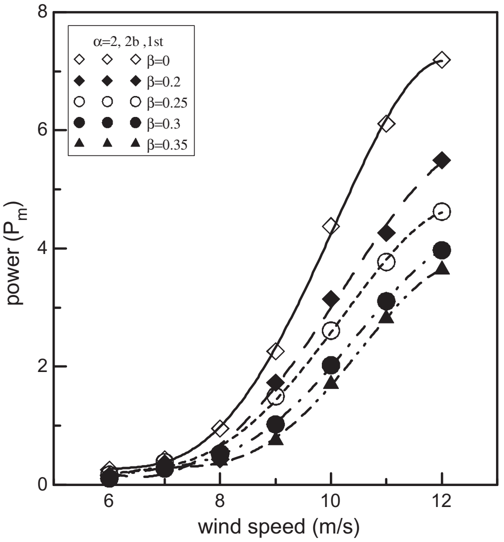

Figure 12 Variation of mechanical power with wind speed for different overlap ratios.

Various overlap ratios from 0 to 0.35 are studied experimentally at constant values of the other studied parameters. Fig. 12 illustrates the relation between mechanical power and wind speed for the tested overlap ratios. It can be noticed here that the rotor without overlap gives higher mechanical power than rotors with overlap.

3.4. *Effect of aspect ratio*

Different rotors with aspect ratios from 0.5 to 5 are studied experimentally at constant values of the other studied parameters. Fig. 13 presents the variation of power coefficient with wind

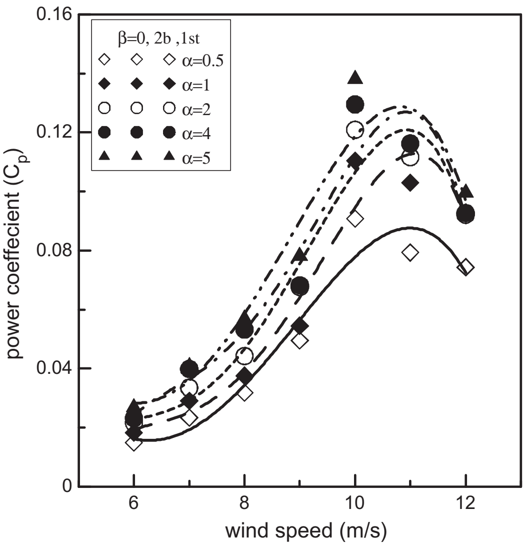

Figure 13 Variation of power coefficient with wind speed for different aspect ratios.

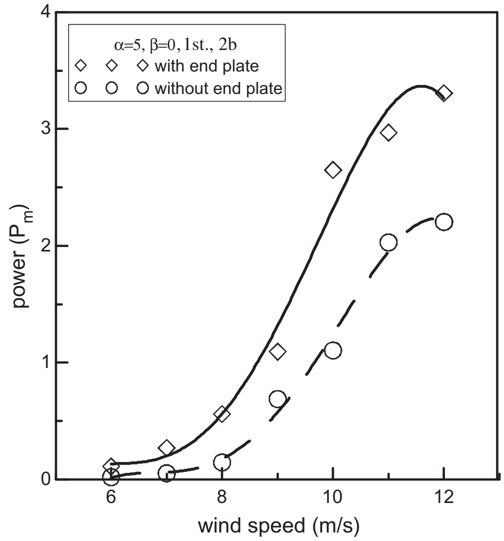

Figure 14 Variation of mechanical power with wind speed for rotors with and without end plates.

speed for the different tested aspect ratios. It is clear here that there is an increase in power coefficient with the rise in aspect ratio. This tendency has been confirmed with the results obtained from [1].

3.5. Effect of end plates

To study the effect of end plates, rotors with and without end plates are tested at constant values of other considered parameters. Variation in mechanical power with wind speed for rotors with and without end plates is given in Fig. 14. Rotors with end plates give higher mechanical power than rotors without end plates. This is because the existence of end plates increases the amount of air which strikes the blades of Savonius rotor.

4. Conclusions

In this work various rotors with two, three and four blades; with single and double stages; with end plates and without end plates; with aspect ratios of 0.5, 1, 2, 4 and 5 and with different overlap ratios from 0 to 0.35 are investigated experimentally to determine the optimum geometries of Savonius turbine. It was found here that, the two blades rotor is more efficient than three and four blades rotors. The rotor with end plates gives higher efficiency than those without end plates. Double stages rotor have higher performance than single stage rotor. The rotors without overlap ratios are better in operation than those with overlap. The results show also that the power coefficient increases with the rise in aspect ratio (α).

The conclusions of the measurements from the static torque for each rotor at different wind speeds make verification of the above concluded results of this work.

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