Experimental investigation of modified Savonius wind turbines

J Priyadumkol 1, * K Khaothong 2 and W Chaiworapuek 3

1 Department of Mechanical Engineering, Mahidol University, Nakhon Pathom, 73170, Thailand
2 Department of Mechanical Engineering, Faculty of Engineering at Kamphaeng saen, Kasetsart University, Nakorn Pathom, 73140, Thailand
3 Department of Mechanical Engineering, Kasetsart University, Bangkok, 10900, Thailand

* Corresponding Author: jetsadaporn.pri@mahidol.ac.th

Abstract. This aim of this study was to experimentally characterize the performance of Savonius wind turbine. The turbine rotors were modified by varying the distances, measured from blade tip to the most concave point of rotor. To achieve this objective, the investigated parameters were shape factor, including 0.5, 0.4, 0.3, and 0.2 while the Reynolds numbers were set as 136,640 and 156,160. The results showed that the Savonius rotor performed better performance at the higher Reynolds number. Also, the tip speed ratio and shape factor were found to have a strong influence on the characteristic of power coefficient. The maximum power coefficient was obtained during the tip speed ratio of 0.4-0.6 while the shape factor of 0.4 provided a better performance than other rotors. This corresponds with the modified rotor 1, having the higher power coefficient compared to conventional rotor by 6.67% and 18.75% for a Reynolds number of 136,640 and 156,160, respectively.

1. Introduction
It is a well-known fact in scientific circles that wind energy is one of the largest renewable energy resources. Wind turbines are used to generate electricity from the wind energy. They can be classified into two types, which are horizontal axis wind turbine (HAWT) and vertical axis wind turbine (VAWT) based on their axis of rotation. The VAWTs have some advantages over HAWTs in that its constructions are simple with low cost, they are independent of the direction of the wind, as well as they have low noise emission and a high starting torque. Thus, these advantages make them suitable for small-scale power generation [1-2]. The Savonius wind turbine is a simple type of VAWT. The main driving force of the Savonius rotor is the difference of the drag force between the convex and the concave sides of the rotor blades [1].

Up to now, Savonius wind turbine has been continuously developed by many researchers. They have focus on studying various design parameters both experimentally and numerically [1-6]. The modified rotor shapes are one of the popular method to increase the performance of Savonius wind turbine. The changes in rotor shapes result in the changes in power coefficient. The results showed that power coefficient was in the range of 0.14 to 0.32 [7].
In this research, the experiment are carried out to study the effect of several parameters, including shape factor, tip speed ratio, and Reynolds number on the performance of modified Savonius rotors in term of power coefficient. The obtained results can be an important information, leading to the better understanding of the Savonius rotor design.

2. Experimental details

2.1 Design of the Savonius wind rotor

The designed Savonius rotors were developed on CAD software. 3D printing (Wanhao duplicator 9) had been used to create Savonius wind rotor models with Fused Deposition Modeling (FDM). The nozzle was maintained a temperature of 230 °C for the extrusion of the ABS material and the bed platform was maintained at 90 °C. The layer thickness had been taken as 0.2 mm. After finalizing forming up all layers, Savonius rotor was manufactured as depicted in figure 1.

The designed Savonius rotor and its geometrical parameters are presented as shown in figure 2 and table 1, respectively. In the table, D is the rotor diameter, d is the blade chord length, e is the gap distance, H is rotor height, Do is end plate diameter, and a is the distance from the tip of the blade. The thickness of blades and end plates is 3 mm and 5 mm, respectively. In the previous studied [8-13], they suggested that the conventional Savonius rotor with the following parameters had a good performance. Accordingly; the end plate parameter (Do/D) = 1.1 [8]; Overlap ratio (e/d) = 0.10 - 0.15 [9-10]; Aspect ratio (H/D) = 1.0 - 2.0. [11-13]

Figure 1. (a) CAD model (b) Savonius rotor.

Figure 2. Schematic diagram of Savonius wind rotor.
The objective of this research was to study the influence of shape factor (a/d) and Reynold number (Re) on the performance of modified Savonius rotor. The ratios between the distance from the tip of the blade (a) and the blade chord length (d) have been considered in the experiments. In this paper, four different blades are given as conventional rotor, modified rotor 1, 2 and 3 for Reynolds number of 136,640 and 156,160. The conventional Savonius rotor has been made from a half ellipse with the ratio of 0.5. The modified blades have been studied by varying the ratio (a/d). The factors of blade shape have been adjusted to find the optimum factors which generate maximum power coefficient. This study focused on the shape factors less than 0.5 as in the numerical study [14]. The shape factor (a/d) of the modified rotors 1, 2, 3 were 0.4, 0.3 and 0.2, respectively. The schematic models for all blades are illustrated as shown in figure 3.

Table 1. Geometrical parameters of the Savonius rotors.

| Type            | D (mm) | d (mm) | e (mm) | Do (mm) | H (mm) | r (mm) | a (mm) |
|-----------------|--------|--------|--------|---------|--------|--------|--------|
| Classical rotor | 148    | 80     | 12     | 165     | 180    | 40     | 40     |
| Modified rotor  | 148    | 80     | 12     | 165     | 180    | 40     | 32, 24, 16 |

The experimental set-up, used in the present work is shown in figure 4. It consisted mainly of a wind tunnel, the manufactured Savonius wind rotors, velocity measuring devices, and torque measuring system. In experiment, an open-circuit type wind tunnel has been used (AEROLAB Educational Wind Tunnel) and its length is 61 cm while a size of cross-section area is 30.5 cm x 30.5 cm. The Savonius wind rotor has been placed vertically inside the test section. Pitot tube Anemometer (Extech HD-350) has been used to measure wind velocity. Test velocities have been conducted at two wind speeds that are v=7 and 8 m/s as in the experiments [9]. A tachometer (DIGICON DT-245P) was used to measure the rotational speed of shaft.

Figure 3. Schematic models of (a) conventional rotor, (b) modified rotor 1, (c) modified rotor 2 and (d) modified rotor 3.

2.2 Experimental setup

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Figure 4 shows mechanical torque measuring system. It was used to measure the mechanical torque of the rotating rotor. As shown in Fig 4b, it consists of rotor, steel shaft, bearing housing, pulley, nylon string, spring balance, weighting pan and aluminum profile housing. Two shafts were made of steel with a diameter of 15 mm. The shafts were used to mount in bearing housings. A belt pulley was installed on the upper shaft. The pulley was assumed to be smooth. Flat leather cord and string were assumed to be massless and to move without slipping over the pulley. The string was pulled at both ends by spring balance and weighting pan. In the experiment, the weighting pan of 50 grams was loaded on the string. The tension in the string can be calculated by spring balance. If the rotor is still rotated, the mass of 10 grams is placed on the weighting pan until the rotor had stopped rotating. The experiments were conducted by repeating 3 times and averaging the results.
3. Energy in the wind
When the mechanical torque and rotational speed are measured, the mechanical power \( P_m \) can be calculated at each wind speed as:

\[
P_m = T\omega = T \left(\frac{2\pi n}{60}\right)
\]  

where \( \omega \) is the angular speed, \( n \) is the shaft rotational speed and \( T \) is the mechanical torque.

The mechanical torque, determined from the measured load and spring balance load is given by:

\[
T = Fr = (m-s) g r
\]  

where \( F \) is the force acting on the rotor shaft, \( r \) is the pulley radius, \( m \) is the mass placed on the pan, \( s \) is the spring balance and \( g \) is the gravitational acceleration.

The wind power \( P_w \) can be obtained as follow:

\[
P_w = 0.5\rho AV^3
\]  

where \( \rho \) is the density of air, \( A \) = the projected area for the rotor (HD), \( V \) is the wind speed.

The power coefficient \( (C_p) \) can be calculated from the following equation:

\[
C_p = \frac{P_m}{P_w}
\]  

Tip speed ratio \( (TSR) \) means the ratio between rotor blade tip speed and freestream velocity and is defined as follows:

\[
TSR = \frac{\omega d}{v}
\]  

The Reynold number is calculated from

\[
Re = \frac{\rho V d}{\mu}
\]

4. results and discussion
Conventional and modified Savonius rotors performance have been investigated experimentally to determine the optimum geometries of Savonius rotor. Experiments were conducted in a wind tunnel for two Reynolds number of 136,640 and 156,160. The rotors were fabricated to study the effect of shape factor (a/d) that are 0.5, 0.4, 0.3 and 0.2.

Table 2 gives the maximum value of power coefficient with respect to the tip speed ratio at a Reynolds number of 136,640 and 156,160. The highest power coefficients of conventional rotor were 0.15 and 0.16 for a Reynolds number of 136,640 and 156,160, respectively. These have shown good agreement with the results of Kamoji et al. [6]. It was clear that the power coefficients increased according to increase in Reynolds number. The performances of the modified Savonius rotors are compared with the performances of the conventional rotor as shown in table 2. It was found that the rotor with shape factor of 0.4 was having the higher power coefficient compared to conventional rotor by 6.67% and 18.75% for a Reynolds number of 136,640 and 156,160, respectively. While, the maximum power coefficients of modified rotor 3 were decreased by about 60% and 18% from the conventional rotor for two Reynolds number. The results show that the modified rotor 2 resulted in the highest power coefficient of 0.2 at a Reynolds number of 156,160, which was higher than that of modified rotor 1 (0.19). However, at a Reynolds number of 136,640, the performance of modified rotor 2 was decreased by 6.65% from the conventional rotor.

Table 2. Comparison of main performance parameters.

| Type of rotor          | Re    | Cp, max  | TSR at Cp, max | Change of Cp, max [%] |
|-----------------------|-------|----------|----------------|-----------------------|
| Conventional rotor    | 136,640 | 0.15     | 0.51           | -                     |
| (a/d=0.5)             | 156,160 | 0.16     | 0.44           | -                     |
| Modified rotor 1      | 136,640 | 0.16     | 0.61           | 6.67                  |
| (a/d=0.4)             | 156,160 | 0.19     | 0.58           | 18.75                 |
| Modified rotor 2      | 136,640 | 0.14     | 0.59           | -6.65                 |
| (a/d=0.3)             | 156,160 | 0.2      | 0.59           | 25                    |
| Modified rotor 3      | 136,640 | 0.06     | 0.42           | -60                   |
| (a/d=0.2)             | 156,160 | 0.13     | 0.57           | -18.75                |

The effect of blade shape factor on coefficient of power is shown in figure 5 and figure 6 for Reynolds number of 136,640 and 156,160, respectively. Change of power coefficient according to tip speed ratio has been showed both for conventional and modified rotors. It was clear that the power coefficient had a different behavior with varying shape factors.

In figure 5, the power coefficient of modified rotor 1 is increased over the whole tip speed ratio range, compare to the conventional rotor for a Reynolds number of 136,640. It has appeared that the power coefficient value obtained when TSR is 0.61 is the highest of 0.16. The power coefficients of conventional and modified 2 rotors were similar for tip speed ratio between 0.5 and 0.7. In contrast, it is obvious that the performance of modified rotor 3 was decreased compared to other rotors.

The variation of the power coefficients of the rotating rotor with the tip speed ratio for a Reynolds number of 156,160 is shown in figure 6. For tip speed ratio up to 0.5, the difference between the power coefficient of rotors was small. While, the performance of modified rotor 1 and modified rotor 2 were higher than the performance of conventional rotor for tip speed ratio more than 0.5. The results showed that the two peak power coefficient values obtained from modified rotor 1 and modified rotor 2 were close which are 0.19 and 0.2 at tip speed ratio of 0.58 and 0.59, respectively.
Figure 5. The effects of shape factor on the power coefficient with respect to the tip speed ratio at a Reynold number of 136,640.

Figure 6. The effects of shape factor on the power coefficient with respect to the tip speed ratio at a Reynold number of 156,160.

5. Conclusions

In this study the performance of various rotors with shape factors of 0.5, 0.4, 0.3 and 0.2 were determined by experimental investigation. The optimum shape factor has been found as 0.4. The use of modified rotor with shape factor of 0.4 significantly increased the power coefficient by 6.64% and 18.75% compared with conventional rotor for a Reynolds number of 136,640 and 156,160, respectively. It also provides good agreement with the numerical study [14]. At a higher Reynolds number, all of the rotors exhibit better power coefficient. The obtained results can be an important information, leading to the better understanding of the developed Savonius rotors.

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