Performance Analysis of a Combined Blade Savonius Wind Turbines

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Abstract

The Savonius wind turbine has a lower performance than other types of wind turbines which may attract more study focus on this turbine. This study aimed to improve wind turbine performance by combining a conventional blade with an elliptical blade into a combined blade rotor. The analysis was performed on three blade models in computational fluid dynamics (CFD) using ANSYS Fluent Release 14.5. Then the results were verified experimentally using an open wind tunnel system. The results of the numerical simulation were similar to the experimental and showed that the combined blade rotor has better dragging flow and overlap flow than the conventional and elliptical blade. Experimental verification showed that the combined blade was to increase the maximum coefficient of power (C_p max.) by 11% of the conventional blade and to 5.5% of the elliptical blade.

Keywords: Savonius turbine, combined blade, performance, CFD, experimental

1. Introduction

The utilization of renewable energy is now emerging due to the limited resources of fossil fuels and increasing concern about environmental pollution caused by the burning of fossil fuels. One source of the promising renewable energy is such as the development of wind energy. Savonius wind turbine is a vertical-type wind turbine (VAWT) as a renewable energy generator that has a simple construction and it is able to operate even at low wind speeds and from all directions. Savonius turbine efficiency is usually low compared to other turbine types [1]. To improve the performance of the turbines, researchers have been conducting research and constructional modifications on the Savonius turbine rotors through different methods either numerically or experimentally. One of the common ways to improve the performance is by increasing the number of blades and rotor stage [2-4]. The research results stated that the most efficient number of the blade is two, while the number of rotor stage performance will be reduced if there are more than two stages as it will be affected by the inertia of the rotor. The performance of the turbine may increase when it is provided with additional equipment such as shielding obstacle in returning blade [5], the use of curtain on the rotor [6], deflector plate [7] and the use grid-box tunnel [8]. The provisions of such equipment, however, may create a more complex Savonius wind turbine.

Some researchers show that the pattern of flow around the rotor blades significantly affects the performances of the turbine. Savonius turbine rotor performances are influenced by the flow parameters and turbines geometry [2]. Fluid flow on Savonius turbine consists of six types of streams, respectively: attached flow, dragging flow, overlap flow, stagnation flow, vortex from advancing blade and the vortex from returning blade [9]. The flow field around the rotor of Savonius turbine is closely linked to the rotor torque and power performance [10]. Based on the specific flow configuration, different geometry may give different results. An optimum axial spacing between turbine components can be obtained for the improved performance of Turbine [11].

Rotor blade turbine with a stream of overlap elliptical have more advanced so that it can produce greater thrust on returning the blade, but the stagnation point structure on the convex side is also greater, resulting in a positive torque reduction [12]. All types of blade showed recirculation at the top end of the advancing blade, which is caused by the flow of the concave and convex side of the blade.

The shape of Savonius wind turbine rotor blade on the inside (concave) and the outside (convex) needs to be the focuses of development in order to increase the torque generated by the rotor [13]. Therefore, there should be research on the concave and convex sides in relation to the combination of two different models to improve the performance of the turbine. Blade shape’s modification is done by combining the conventional models as models of elliptical convex side and a concave side into a...
The performance analysis in this study was initially conducted numerically to analyze the flow patterns of the three blades models, namely conventional blade, elliptical blade, and combined blade. Experimental testing was done to use the numerical results and to obtain better Savonius wind turbine performances, which includes coefficient of power (Cp) and coefficient of torque (Ct) with respect to the tip speed ratio (TSR).

2. Performance of Wind Turbine

The performance of the wind turbine is based on Matthew’s equation [14] with a wide sweep of the rotor $A_T = (2d - e)H$, namely:

Turbine power

$$P_T = \frac{1}{2} \rho v A_T v^3$$  \hspace{1cm} (1)

Turbine torque

$$T_T = \frac{1}{2} \rho v A_T v^2 R$$  \hspace{1cm} (2)

Coefficient of power

$$C_p = \frac{2P_T}{\rho v A_T v^3}$$  \hspace{1cm} (3)

Coefficient of torque

$$C_t = \frac{2T_T}{\rho v A_T v^2 R}$$  \hspace{1cm} (4)

Tip speed ratio

$$TSR = \frac{\omega R}{v}$$  \hspace{1cm} (5)

3. Rotor Design

The dimension and the size of the rotor used in this study were based upon the results of previous studies. Combined blade rotor is the combination of conventional blade and elliptical blade (see Fig. 1(c)). Elliptical blade model as the concave side is the line that connects the coordinates of the X-axis, namely A (-15 mm; 0), B (50 mm, 50 mm), C (-100 mm; 0), where point A - B was spline and point B - C was a quarter circle line with radius of $R_1 = 50$ mm [12]. The conventional model was as the convex side semicircular with radius $R = 57.5$ mm [15]. From that point on there would be blade models with the same dimensions in accordance with Table 1. In addition to the combined blade, the study was also conducted on the conventional blade (Fig. 1(a)) and elliptical blade (Fig. 1(b)) with the same size and model, so the performance comparison of the three rotor blades could be observed. The production of the prototype was done by creating a groove on the end-plate made of acrylic with a thickness of 5 mm using CNC (Computer Numerical Control) machine in accordance with the model and dimensions in Fig. 1. The rotor blade was formed by using the tracks on the end-plate, where the conventional blade and elliptical blade using 2 x 0.6 mm aluminum plate, while the combined blade of each 1 x 0.6 mm for each groove side of the blades (conventional and elliptical) so that all rotors have the same dimensions and weight (Fig. 5).

<table>
<thead>
<tr>
<th>Blade rotor</th>
<th>Diameter $(D)$ mm</th>
<th>Chord $(d)$ mm</th>
<th>Overlap ratio $(e/D)$</th>
<th>Aspect ratio $(H/D)$</th>
<th>End plates $(Do/D)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional</td>
<td>200</td>
<td>115</td>
<td>0.15</td>
<td>1.0</td>
<td>1.1</td>
</tr>
<tr>
<td>Elliptical</td>
<td>200</td>
<td>115</td>
<td>0.15</td>
<td>1.0</td>
<td>1.1</td>
</tr>
<tr>
<td>Combined</td>
<td>200</td>
<td>115</td>
<td>0.15</td>
<td>1.0</td>
<td>1.1</td>
</tr>
</tbody>
</table>

Fig. 1 Configuration and dimension of Savonius wind turbine
4. Numerical Simulation

The numerical study was based on the 2D (two-dimensional) simulation of the rotor turbine by Computational Fluid Dynamics (CFD) using software ANSYS Fluent Release 14.5. Domain rotor rotary was chosen in a symmetrical position, with walls without slip and with regard to the input domain and output of Fig. 2. Input data was provided in the form of wind velocity $v = 5.999$ m/s, by taking all the dimensions of the prototype into account in order to obtain the value of TSR = 0.8 which is the best performance of Savonius wind turbine [12]. The selection of the position of the blade angle was in accordance with studies showing that the maximum static coefficient of torque for all rotor at an angle of $30^\circ$ [15]. As the flow speed was low, the variations of air density were ignored and treated as incompressible, and by using the symmetrical flow means that the vertical flow can be ignored. The Reynolds’ number is based on a rotor diameter (D) using the equation:

$$Re = \frac{\rho_a v D}{\mu}$$

Fig. 2 Simulation domains

The combined blade rotors are selected for simulation with compared experimental study. Simulation combined blade conducted using a sliding mesh by the initial value through the simulation of multiple reference TSR 0.1 to 1.3. Time step refers to a rotation of 1 degree, the simulation was done 2 to 3 rounds of the blade until the solution is considered stable, the value of the moment of the last round averaged to obtain the value of Ct and Cp. Grid Tests carried out on the combined blade mesh with nodes size is approximately 40,000 (mesh1); 80,000 (mesh2) and 130,000 (mesh3) respect to the tip speed ratio (TSR) = 0.8. Based on the convergence moment, then mesh-2 showed no significant difference with mesh-3 (Fig.3), so that mesh-2 (80,000 elements) become a reference in the simulation process to obtain the average torque that is in use for the coefficient of torque (Ct) and the coefficient of power (Cp)

Fig. 3. Grid test of the combined blade for to monitor the convergence moment at TSR = 0.8.
5. Experimental apparatus

Verification of numerical analysis was performed experimentally by using open wind tunnel-type with the cross-sectional area of 300 mm x 300 mm, incorporating other supporting equipment (Fig. 4). The experimental was based on the testing of conventional, elliptical and combined blade prototypes (Fig. 4) which is supported by rotor shaft with a diameter of 15 mm. To measure the torque was using pulley and ropes with a radius of \( R_{\text{pulley}} = 15 \) mm and \( R_{\text{rope}} = 1.5 \) mm. Measurement of the load \( (F_1) \) and the spring balance \( (F_2) \) was carried on through constant reduction of rotor rotation for every 50 rpm using a tachometer, with a wind speed of 4 m/s. For every initial data collection, oil was added for lubrication of the bearings in order to reduce the friction. Torque occurring in each round was determined by the following equation:

\[
T_T = \frac{(F_1-F_2)(R_{\text{pulley}}+R_{\text{rope}})g}{1000}
\]  

(7)

While turbine power was determined through the following formula:

\[
P_T = T_T \left( \frac{2\pi \nu}{60} \right)
\]  

(8)

Blockage Ratio is the comparison between the coverage space of the rotor and cross-section area of wind tunnel [5] as the following:

\[
B = \frac{A_T}{A_W} = \frac{(2d-e)H}{H_w \times W}
\]  

(9)

6. Result and Discussion

6.1 Numerical study

The results of the simulation using ANSYS Fluent Release 14.5 showed the pattern of velocity flow and pressure was different for the three types of blade. Velocity flow pattern in the form of contour presented in Fig. 6 shows the differences in terms of the position and shape of dragging flow, overlap flow and counter-rotating vortices that occurred in the rotor blade. Dragging flow and overlap flow are types of flow that are influential in improving the performance of Savonius turbine, while the vortex gives effect on the decrease of turbine performance [9]. Overlap flow in a conventional blade seems less contributive to the reduction of
the negative torque to the returning blade as it develops at the tip of the blade (Fig. 6(a)), compared with an elliptical and combined blade. Speed contour at the elliptical blade (Fig. 6(b)) shows all types of flow that affect the performance of the blade, but less prominent.

Of the three speed contours showed that the combined blade (Fig. 6(c)) had the largest flow dragging on the advancing convex blade side and overlap flow which flew near the concave side of the returning blade compared with conventional and elliptical blades. Both of these flow patterns contribute huge improvements to the rotor performances, but the counter rotating vortexes formed at the tip of the blade may cause decreasing performance. The formation of the inner blade tip vortex was large enough on the combined blade due to the dragging flow from the convex side and overlap flow from the concave side of the advancing blade which was larger than the other blade.

**Fig. 6** Simulation results of velocity contour of three blades.

(a) Conventional blade                                  (b) Elliptical blade

(a) Conventional blade    (b) Elliptical blade

(c) Combined blade
Figure 7 shows the simulation results of pressure contours of the three types of blades. On the concave side of all blades seems to have high pressure, but the combined blade shows distributed pressures along the concave side of the returning blade model than the other blade. The pressure on the concave side of the blade may cause an increase in positive torque, while the convex side instead may reduce the rotor torque. The increase of pressure on the concave side of the blade returning will contribute to the improvement of the aerodynamics of the turbine torque [16]. The improved static torque by increasing the ratio of overlap is mainly driven by the increased pressure on the concave side of the advancing blade for due to the jet overflow [17].

There were some variations in the shape and position of the low-pressure vortex on the convex side of the advancing blade from each type of blade being simulated. The vortex on the convex side of the advancing blade was rotating clockwise; this rotation can increase the strength of the suction pressure and may cause a torque reduction [1]. There were two vortices on the conventional blade which were in the convex position and the tip of the advancing blade and the other growing and moving away from the rotor as presented in Fig. 7(a). There was smaller vortex on the elliptical blade at the top end of the advancing blade which then evolving into two parts on the convex side as presented in Fig. 7(b), while the combined blade seems to have the vortex centered in the middle of the convex side of the advancing blade and then developing away from the rotor as shown in Fig. 7(c). Considering the contour analysis of the pressure on the concave side of each blade that caused a positive torque and a whirlpool vortex that happened and thrive on the convex side which causes a decrease in torque, the combined blade showed having better performance than conventional and elliptical blades.

6.2 Experimental study

The experiment was conducted to verify the numerical analysis in graphical forms for the coefficient of power (Cp) and coefficient of torque (Ct) with the tip speed ratio (TSR). The experimental results in Fig. 8 to Fig. 10 show that combined blade has the best performance again, followed by the elliptical blade and the conventional blade. The numerical results obtained from the simulations identical and they follow the trend of the experimental results.

Fig. 8 Comparison coefficient of power (Cp) vs. TSR, conventional and combined blades
As shown in Fig. 8 and Fig. 9 that the combined blade produces the highest Cp than the conventional models and elliptical model against TSR. All three blades models achieved a maximum coefficient of power (Cpmax.) on TSR = 0.79. The combined blade model had Cpmax. value = 27% increased 5.5% against the elliptical model and 11% against the conventional model. The increased coefficient of power of up to 0.7 TSR tend to be similar, but after reaching the maximum value the difference was more obvious. Elliptical blade showed gradual downward trend compared to other models. Regarding the Cp value of the conventional and elliptical blades, including the value of maximum coefficient of power achieved against TSR, the experimental values obtained is in accordance with the results of the simulation conducted by Kacprzak et al. [12]

Figure 10 shows the comparison of the coefficient of torque (Ct) of the three blade models based on the experimental results. It can be seen that Ct of the combined blade is higher than the conventional and elliptical blade models. The combined blade and a conventional blade had a tendency to form a similar trend of the chart, but at a low TSR showing the difference up to 9%. Mechanically, certain wind speed may produce a positive torque on the concave side and a negative torque on the convex side of the rotor of Savonius wind turbine [2]. The flow that drives the blade on the concave side of Savonius rotor with a certain speed may produce positive torque (Mr+), while the convex side of the blade may produce negative torque (Mr−). A significant difference of force moment will generate better performance of the turbines. The increasing distance of rotation center of the concave side of the advancing blade may cause the increasing positive moment of the rotor; otherwise, the smaller the distance of rotation center on the convex side of the returning blade will reduce the negative moments. This is consistent with the model combinations made to modify the conventional and elliptical blades shown through the pressure contour from numerical simulations of Fig. 7. The use of the elliptical blade model on the concave side may magnify distant point of force towards the center of rotation, while the convex side that uses the conventional model (half circle) has a smaller distance of force towards of the rotation center than the use of the elliptical model.
7. Conclusion

Based on the results of numerical analysis and experimental verification, the performance of the three rotor blades can be summarized as follows:
- The difference between the model of the concave and convex sides may give influence on the flow pattern around the rotor and thus affect the performance of the turbine rotor.
- Speed and pressure contours that occur on each blade show the combined blade gives particular flow pattern around the rotor that gives better performance, followed by the elliptical blade and conventional blade models.
- Experimental verification shows that the combined blade has the highest coefficient of power (Cp) and coefficient of torque (Ct), compared to the elliptical blade and the conventional blade models. The numerical results of combined blade follow the trend of the experimental results.

Acknowledgments

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Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>$AR$</td>
<td>Aspect Ratio</td>
</tr>
<tr>
<td>$A_{w}$</td>
<td>Cross-section area test of wind tunnel [m$^2$]</td>
</tr>
<tr>
<td>$C_p$</td>
<td>Coefficient of Power</td>
</tr>
<tr>
<td>$C_t$</td>
<td>Coefficient of Torque</td>
</tr>
<tr>
<td>$D$</td>
<td>Diameter of rotor [m]</td>
</tr>
<tr>
<td>$D_o$</td>
<td>Diameter endplate of rotor [m]</td>
</tr>
<tr>
<td>$F_i$</td>
<td>Load [kg]</td>
</tr>
<tr>
<td>$F_s$</td>
<td>Spring balance [kg]</td>
</tr>
<tr>
<td>$g$</td>
<td>Gravity acceleration [kg/s2]</td>
</tr>
<tr>
<td>$\rho$</td>
<td>Fluid density [kg/m$^3$]</td>
</tr>
<tr>
<td>$M_r^+$</td>
<td>Positive torque [N.m]</td>
</tr>
<tr>
<td>$M_r^-$</td>
<td>Negative torque [N.m]</td>
</tr>
<tr>
<td>$n$</td>
<td>Rotational speed [rpm]</td>
</tr>
<tr>
<td>$P_T$</td>
<td>Power Turbine [Watt]</td>
</tr>
<tr>
<td>$R$</td>
<td>Radius of rotor [m]</td>
</tr>
<tr>
<td>$Re$</td>
<td>Reynolds number [= $\rho V D / \mu$]</td>
</tr>
<tr>
<td>$R_{rope}$</td>
<td>Radius of rope [m]</td>
</tr>
<tr>
<td>$R_{pulley}$</td>
<td>Radius of pulley [m]</td>
</tr>
<tr>
<td>$T$</td>
<td>Local mean temperature [K]</td>
</tr>
<tr>
<td>$TSR$</td>
<td>Tip Speed Ratio</td>
</tr>
<tr>
<td>$T_T$</td>
<td>Torque Turbine</td>
</tr>
<tr>
<td>$\mu$</td>
<td>Dynamic viscosity of air [Ns/m$^2$]</td>
</tr>
<tr>
<td>$V$</td>
<td>Velocity [m/s]</td>
</tr>
</tbody>
</table>

References