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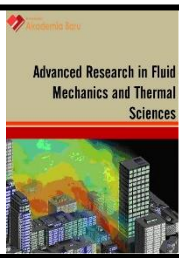

Experimental Study of Savonius Wind Turbine Performance with Blade Layer Addition

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ABSTRACT

Savonius, a type of vertical axis wind turbine (VAWT), is applicable for harvesting wind energy in Indonesia, having an average wind speed of 4 - 5 m/s. Owning the advantages as suitable for placing in the urban areas as well as reducing the huge electricity load, the Savonius received considerable attention from researchers in making the performance improvement. Therefore, the current research provides an investigation on the effect of adding extra layers on concave blades on the performance of the Savonius wind turbine model. As the novelty, the modification of conventional Savonius turbine has been developed by adding single and multiple layer blades on the tip blade with an overlap ratio (OR) of 10 and 15%. It was tested under wind speeds of 6.46, 6.99, and 7.27 m/s, which generated by the fans blower with a 2x2 configuration. The results show that the addition of multiple layers increased the Savonius power coefficient by 22.4% and 11.2% at OR of 10 and 15%, respectively. The highest power coefficient (Cp) is found at 0.12, which obtained by the Savonius turbine with multiple layers of 90^{o} and OR of 10% configuration. It is concluded that adding the multiple layer blades enhanced the performance of Savonius wind turbines.

Keywords:
Wind energy; savonius wind turbine; single layer; multiple layers

1. Introduction

The energy is the main factor that would have an impact on the economic growth of a country [1]. Since energy issues increase these days, many countries are looking for alternative energy sources as a solution to the reduction of fossil energy. In one of the cases, recently, more than 4.5 million people in Indonesia do not have access yet to electricity networks. Therefore, to solve the electricity crisis in remote areas, independent power plants are needed [2]. However, most of the existing power plants are driven by employing fossil fuels which potentially harm the environment [3-5], so that it needs to be reduced. Nowadays, renewable energy is widely used as a substitution of energy from fossil [6]. Among them, wind energy is one of the renewable energy that grows very fast,

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and it is economical in the world comparing to other energy sources [7,8]. It supported by their characteristics, which are clean and environmentally friendly, as well as naturally free. Over the advantages, the development of wind energy as a primary alternative energy source becomes very important, and it well recognized by many countries in the world [9]. That is why wind power plants in small-scale are desirable in many countries [10].

Wind turbines, commonly, are divided into two categories, horizontal axis wind turbine (HAWT) and vertical axis wind turbine (VAWT). HAWT is popular with higher efficiency when compared to VAWT; but, HAWT solely operates in areas with high wind speeds (> 5 m/s). Whereas, VAWT is less commercialized since only a few companies have made investments and evaluated VAWT objectively [11]. Interestingly, the developments show that many researchers were interested in making improvements to VAWT as VAWT could be applied in urban areas to reduce the huge electricity load [12]. Besides, Savonius type VAWT is suitable to be placed in the countries located near to the equator line with a relatively low average wind speed (4 – 5 m/s).

The basic design of a conventional Savonius wind turbine consists of an arrangement of two half-cylinders on a shaft. Savonius operates by a pure drag force that attacks concave blades. The concave blade behaves as a barrier object of wind flow to extract the kinetic energy of the wind into mechanical energy, then transmitted into electrical energy by generator devices. The advantages of the Savonius wind turbine are; (1) operated at relatively low speeds, (2) omnidirectional, and (3) produced less noise [13]. Savonius can be installed on the roof of high-rise buildings such as hotels, hospitals, and offices in urban environments. The current development of research on Savonius turbines focuses on the improvement of the performance of Savonius, which has a power coefficient of less than 0.25 [14]. The performance of the Savonius turbines is influenced by several design parameters, including blade profiles such as blade shape, number of blades, geometry design, and wind inlet speed [15].

One of the important parameters that affected the increment of Savonius turbine performance is end-plate addition. Jeon *et al.,* added end-plates to the upper and lower sides of the blade to improve the performance of the Savonius turbine [16]. It was found that adding end-plates increased efficiency by up to 36% compared to Savonius without end-plates. End-plates provide a blocking effect on airflow at both ends of the blade so that it increased the transfer of fluid flow momentum. As a result, it raises the positive torque. Their findings also show that the addition of end-plates enhanced the Savonius power coefficient as the end-plates prevented fluid from the concave side exit the blade and maintained the different pressure between the concave side and convex blade during the turbine spinning [17].

The aerodynamic performance of Savonius wind turbines depends on the turbine aspect ratio (AR) [18]. The aspect ratio is an important factor for designing appropriate wind turbines on a small scale [19]. Kamoji *et al.,* conducted a study on the effect of AR variations of 0.88, 0.93, and 1.17 on Savonius performance [20]. They used a Savonius turbine with a twisted angle of 90^{o}. It was found that Savonius wind turbines with an AR of 0.88 reached the highest power coefficient value of 0.165 at TSR 0.7. However, some research of the Savonius turbines, with new blade profiles, used aspect ratio near to 1 [18].

Many works also considered parameters related to turbine geometry, such as overlap ratio (OR). The OR was employed to increase the pressure on the concave side of the returning blade of the turbine so that it makes rotate easily [21]. The experimental study on OR and the number of blades in Savonius wind turbines had been carried out by Sheldahl *et al.,* [22]. The variations were the number of blades (2 and 3) and ORs of 0, 10, 15, and 20% at wind speeds of 7 and 14 m/s. They proved that the maximum Savonius performance was obtained in OR between 10 and 15% [23].

It had been developed various profiles of new types of blades or often known as Savonius Style Wind Turbines (SSWT) so far; it aimed to increase the performance of Savonius wind turbines [24]. One of them by inserting an extra multiple quarter blade [25]. Their study focused on estimating and comparing power coefficient values between Savonius with the new design configuration and conventional Savonius. The Savonius with a new design configuration was Savonius 180^o with the addition of multiple quarter blades that installed parallel to the Savonius concave blade. Ansys CFX software was used for the simulation. The design affected the incoming fluid flow on the concave side of the advancing blade to be directed to the concave side of the returning blade through the overlap ratio gap, therefore, increasing the positive torque. The results showed the power coefficient in the new configuration increased by 8.89% at a speed of 8.23 m/s and 13.69% at a speed of 9.21 m/s compared to the conventional configuration.

Further research also conducted on Savonius wind turbines by re-proposing a new design [26]. The new design was done by adding a miniature multiple-layer blade in a concave blade. Multiple blade layers increased the surface area of a concave blade, where the kinetic energy possessed by the fluid was utilized inefficiently. A small and simple multiple layers blades could improve Savonius performance without the need for complex designs and weights. The maximum power coefficient achieved at 0.226 at a wind speed of 8.23 m/s.

Based on the literature review, it is found that the performance of the Savonius turbine was affected by the design of the turbine geometry and blade profile. Therefore, as the novelty of this experimental study, a conventional Savonius turbine is designed by a new geometry of aspect ratio (H/D) of 1 and end-plate of 1.1 D with an overlap ratio of 10 and 15% combined with the addition of single and multiple layers blades on tip blade. The purpose of this research is to determine the effect of the addition of single and multiple layers blades installed on each concave blade tip on the Savonius turbine performance. The addition of single and multiple layers is expected to increase the efficiency (coefficient of power) of the Savonius turbine.

2. Important Parameters

The important parameters which represent the performance of a wind turbine are power coefficient (C_P) and torque coefficient (C_T) to tip speed ratio (TSR). C_P represents the percentage of wind kinetic energy which converted into mechanical energy. Power coefficient (C_P) and torque coefficient (C_T) can be determined using Eq. (1) and (2).

$$C_P = \frac{P}{P_A} = \frac{P}{\frac{1}{2}\rho A v^3} \quad (1)$$

$$C_T = \frac{T}{T_A} = \frac{T}{\frac{1}{2}\rho A v^2 R} \quad (2)$$

Tip speed ratio (TSR) is the ratio between tangential speed from the rotor tip and the free-flow speed of the wind (Eq. (3)).

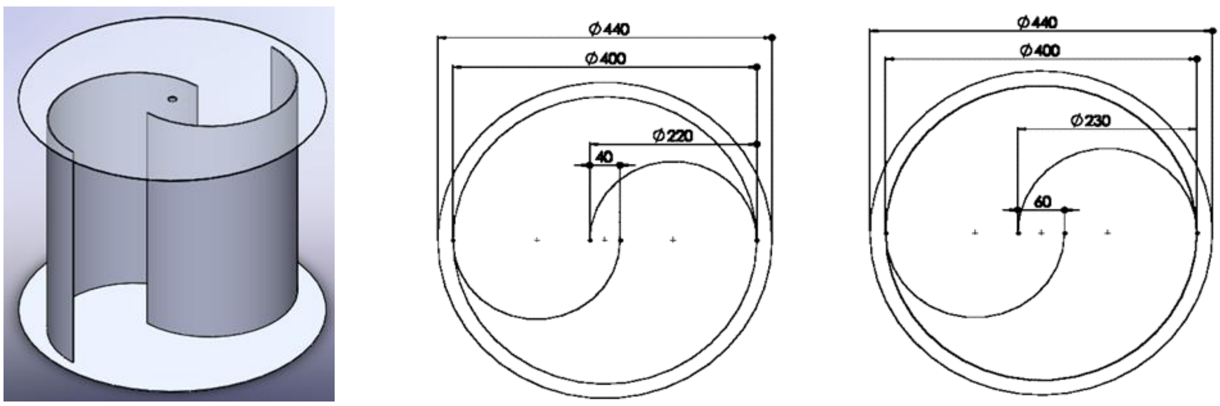
$$TSR = \lambda = \frac{V_{rotor}}{60\, V_{wind}} = \frac{\omega\, .R}{60\, V_{wind}} \quad (3)$$

The static torque coefficient (C_{TS}) is the ratio between actual static torque (T_S) and theoretical torque available in the wind (T_A) as defined in Eq. (4).

$$C_{TS} = \frac{T_S}{T_A} = \frac{T_S}{\frac{1}{2}\rho A V^2 R} \quad (4)$$

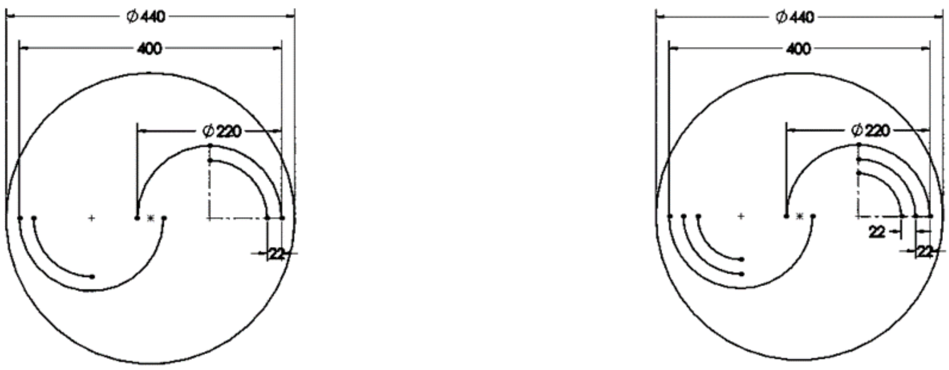
3. Methodology

Savonius vertical axis wind turbine (VAWT) was designed with a height of 400 mm (H), a diameter of 400 mm (D), an aspect ratio of 1 (H/D), and an overlap ratio of 10 and 15%. The turbine consists of two blades made of aluminum material with a thickness of 1.3 mm. Figure 1. provides the Savonius turbines with overlap ratio variations of 10 and 15%, while Figure 2(a) and 2(b) depict the addition of a single and multiple layers of 90^o, respectively.



(a) (b) (c)

Fig. 1. (a) Conventional Savonius wind turbine; (b) Geometry of Savonius with overlap ratio of 10%; (c) Geometry Savonius with overlap ratio of 15%

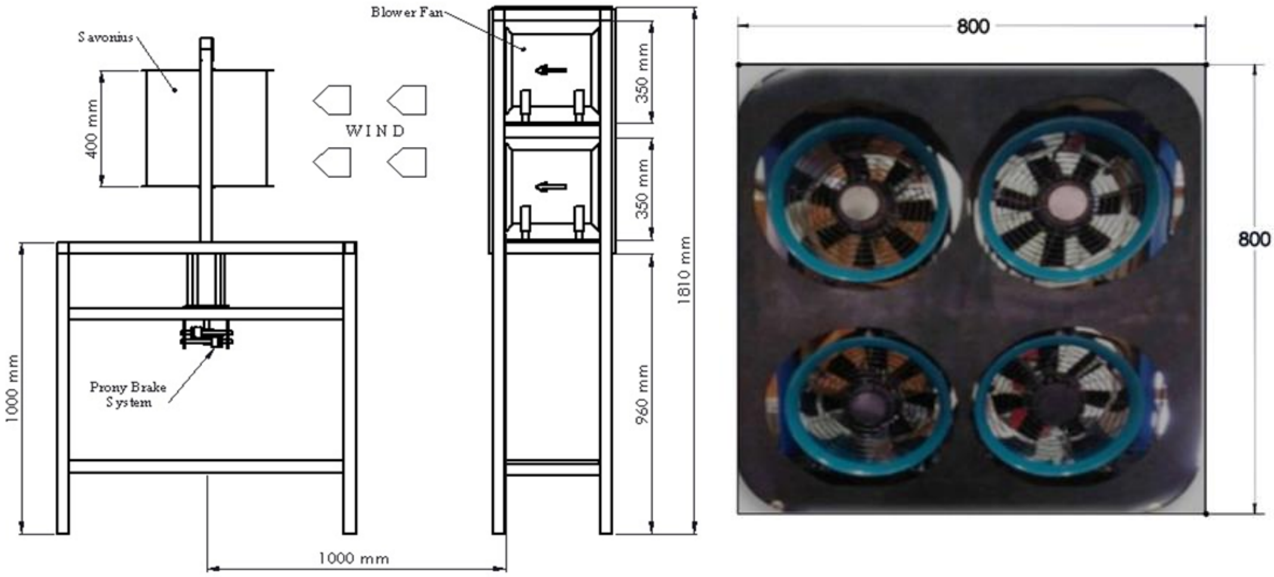


(a) (b)

Fig. 2. (a) Geometry of Savonius wind turbine with single layer 90^o; (b) Geometry of Savonius wind turbine with multiple layers 90^o

The experimental set up comprises of Savonius wind turbines, fan blowers, and measurement devices. The schematic diagram of the experimental apparatus is shown in Figure 3(a). The wind source was generated by four fan blowers arranged in a 2 x 2 configuration with a size of 800 x 800 mm, as shown in Figure 3(b). The distance between the fan blower and the turbine shaft was 1000 mm to obtain stability and uniformity of the wind speed [27]. The balance of airflow causes the turbine rotation to be more constant and produced more stable power.

The experimental apparatus was equipped with a prony brake system where placed at the shaft under the turbine. The wind from the fan blowers was directed towards the turbine to make the Savonius turbine spin. The turbine rotation speed was measured by using a tachometer. The wind speeds were adjusted at 6.46, 6.99, and 7.27 m/s. The turbine performance was displayed in actual power, C_P, and C_T charts.



(a) (b)

Fig. 3. (a) Experimental apparatus; (b) Fan Blowers with 2 x 2 configurations

4. Results and Discussion

4.1 The Effect of Variation Extra layers 90^o with Overlap Ratio of 10 and 15% on Dynamic Test

Wind speed has a profound effect on the power produced by wind turbines. Ideally, the graph of wind speed variations to power has a cubic shape. But in practice, it forms as linear, quadratic, cubic, and others [28]. The turbine rotation produces the output power due to the interaction of the wind and the blade. Figure 4 shows the relationship between wind speed variations and the actual power obtained by the turbine**.** The actual power generated by the turbine increases with increasing wind speed; it occurs in all turbine variations [29]. The turbine obtained the highest actual power when it designed with the addition of multiple layers 90^o with OR of 10% at a wind speed of 7.27 m/s. It was 4.15 Watt. The multiple layers 90^o with OR of 10% improves Savonius wind turbines performance due to fluid flow, which entered the multiple layers gap was directed towards the concave side of returning blade through the overlap ratio gap [25]. The incoming wind towards the concave side of the returning blade will reduce the drag resistance of the returning blade [30].

The turbine cannot fully convert the energy carried by the fluid. Some of the energy loses from the fluid when the fluid passes through the turbine. The efficiency, or the performance of the turbine, is represented by the power coefficient (C_P) at certain TSR, which is the ratio between the actual power of the turbine shaft and the available fluid power [31,32].

The relationship between the power coefficient (Cp) and tip speed ratio (TSR) of the rotor configurations under *V* of 6.46 m/s forms a parabolic curve, as shown in Figure 5(a). The value of the power coefficient raised with increasing TSR. Moreover, the value of Cp tends to decrease after reaching the maximum Cp and TSR [33]. The maximum Cps were 0.098 at TSR 0.463 and 0.089 at TSR 0.425 for conventional Savonius turbines with OR of 10 and 15%, respectively. In the case of the Savonius turbines with the addition of multiple layers of 90^o with OR of 10 and 15%, the highest Cp values were 0.12 at TSR of 0.428 and 0.099 at TSR of 0.394, correspondingly. The addition of multiple layers 90^o variations increased Cp by 22.4% at OR of 10% and 11.2% at OR of 15%.

Figure 5(b) shows the relationship between the torque coefficient (C_T) and tip speed ratio (TSR). The graph describes the value of the torque coefficient. It can be seen that the graph was inversely proportional to the tip speed ratio. Hence, the C_T value tends to decrease with increasing TSR [34]. The Savonius turbine with multiple layers of 90^o with OR of 10% has the highest C_T in all TSR variations.

Figure 6(a) shows the relationship between Cp and TSR at *V* of 6.99 m/s. The graph shows a similar trend to the Cp at V of 6.46 m/s. The highest Cp, which also produced by multiple layers of 90^o with OR of 10%, was 0.11. The Cp increases by 13% comparing to the conventional rotor at OR of 10%. Whereas in the OR of 15%, the single and the multiple layers revealed the same maximum Cp value of 0.097. Both can increase the Cp to 2% as compared to conventional rotors. The C_T and TSR values at *V* of 6.99 m/s are provided in Figure 6(b). In OR of 10%, rotor with single and multiple layers obtained the highest C_T of 0.34. The addition of single and multiple layers at OR 15% also gained the highest C_T of 0.343.

At the wind velocity of 7.27 m/s, as depicted in Figure 7(a), the multiple layers turbine of 90^o with OR of 10% having the highest Cp of 0.108, while at OR of 15% giving about 0.086. The multiple layers turbine of 90^o at OR of 10% also producing higher C_T than the other configurations. The highest C_T obtained is 0.315.

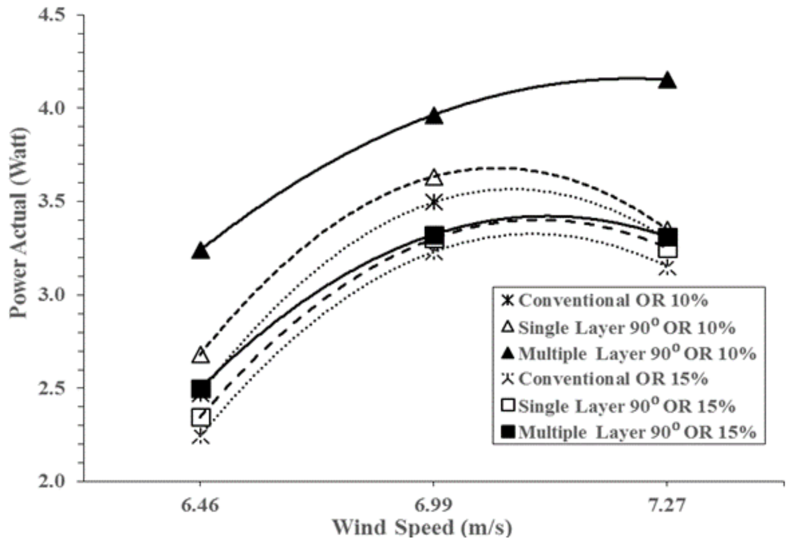
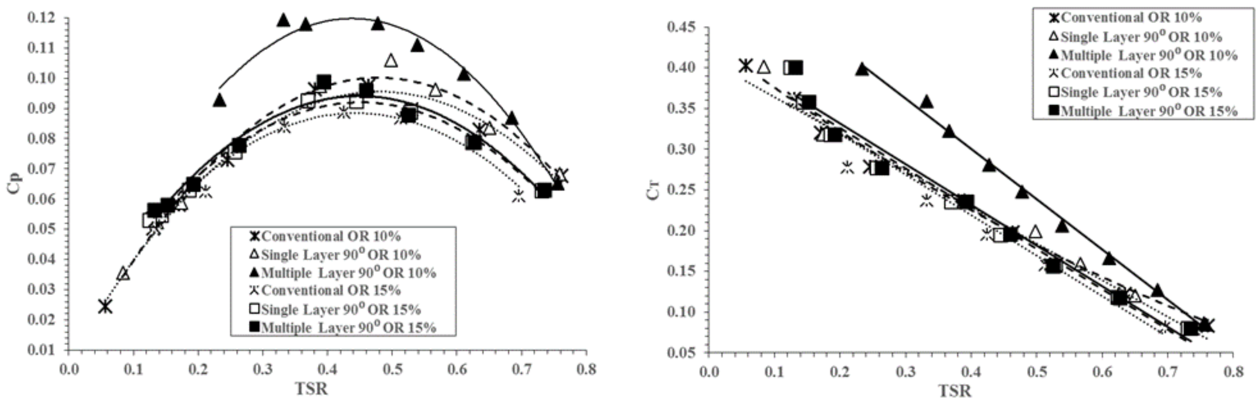
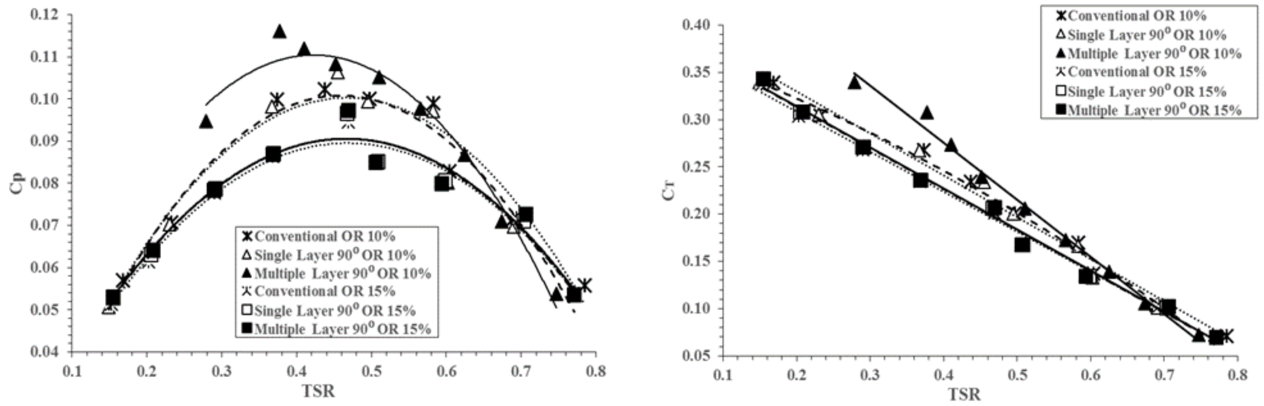


Fig. 4. Turbine actual power on various wind speed for basic and modified Savonius turbine configuration



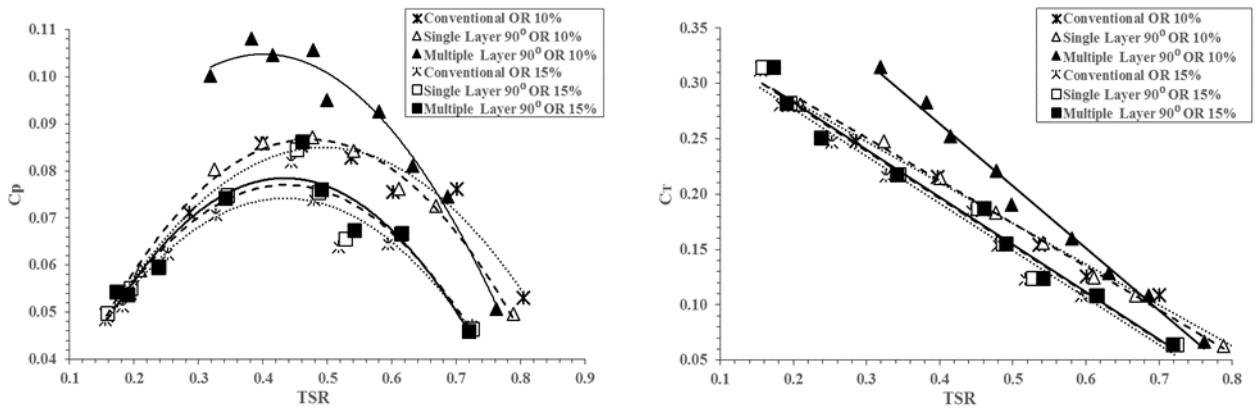
(a) (b)

Fig. 5. (a) Cp of all rotor configuration with TSR variation on *V* = 6.46 m/s; (b) C_T of all rotor configuration with TSR variation on *V* = 6.46 m/s



(a) (b)

Fig. 6. (a) Cp of all rotor configuration with TSR variation on *V* = 6.99 m/s; (b) C_T of all rotor configuration with TSR variation on *V* = 6.99 m/s



(a) (b)

Fig. 7. (a) Cp of all rotor configuration with TSR variation on *V* = 7.27 m/s; (b) C_T of all rotor configuration with TSR variation on *V* = 7.27 m/s

The experimental results show a good agreement with the literatures, which also added multiple quarter blades and multiple-layer blades on the concave blade [25,26]. The modifications elevate the turbine performance value due to the increase of surface area on the concave side of the blade. Therefore, the turbine captures more kinetic energy. The concave blade, with the addition of a layer, also serves the fluid flow as a guide to accelerate the fluid flow towards the concave side of the returning blade. As a result, it improves the positive torque on the turbine.

The drag coefficient of the blade increased by the addition of flow resistance, which was caused by the presence of multiple layers. Correspondingly, it raises the drag force. Adding the mass of material to each concave blade tip could also boost the moment of inertia. So, the power coefficient would be improved. The increasing moment of inertia in the turbine will raise the stability of the turbine while rotating.

The turbine with multiple layers variation of 90^o at OR of 10 and 15% has a high torque coefficient (C_T) because the fluid flows faster in the concave side of advancing blade toward the concave side of the returning blade, so that, it increased the positive torque. It can also be supported by variations in the overlap ratio, which gives a gap for the fluid to flow into the concave side of the blade [17,22,35]. The overlap ratio variation has a direct influence on the value of the power coefficient. Besides, each design of the Savonius wind turbine behaves with different characteristics. The improper overlap ratio will reduce the performance of the turbine [1]. Therefore, it is very important to understand the appropriate value of the overlap ratio to design a particular Savonius turbine. Within the study, we found that the combination of multiple layers addition and the overlap ratio of 15% is unsuitable. It can be explained by the surface area of the concave blade with OR of 15% is smaller than the 10%, so the kinetic energy captured is reduced. The gap between the two blades with a 15% overlap ratio is also too large, which caused the occurrence of a vortex or secondary flow around the turbine root. It is certainly will reduce positive torque [35].

4.2 The Effect of Multiple Layer 90 ° with Overlap Ratio of 10 and 15% O]on Static Test

The second analysis was carried out to understand more deeply the effects of starting performance on the turbine, i.e., the static analysis of the turbine configurations. The turbine configurations, namely, Savonius conventional turbines, Savonius turbines with a single layer, and Savonius with multiple layers of 90^o, at an overlap ratio of 10 and 15%, were tested in the current study. The static tests were carried out at wind speeds of 6.46 m/s. It was conducted to get the value of the static torque coefficient (C_{TS}) from variations of turbine position toward the azimuth angle (0^o to 180^o). The Zero position from the azimuth angle was defined as the Savonius turbine chord in a perpendicular position to the wind speed.

The result, as depicted in Figure 8, shows that the C_{TS} of all turbines tends to decrease in the rotor position of 0^o - 90^o. Then, it increased in the rotor position of 90^o - 180^o. The results have relatively similar trends with the previous study by Raupke and Probert [36] and Kamoji *et al.,* [34]. The C_{TS} of the rotors with an overlap ratio of 10% enhanced the starting torque as compared to the overlap ratio of 15%. In the rotor position of 105^o - 165^o, the multiple layers of 90^o at OR of 10% increased C_{TS} by 17%, while the single layer with OR of 10% improved C_{TS} by 8.5% as compared to the conventional Savonius OR 10%.

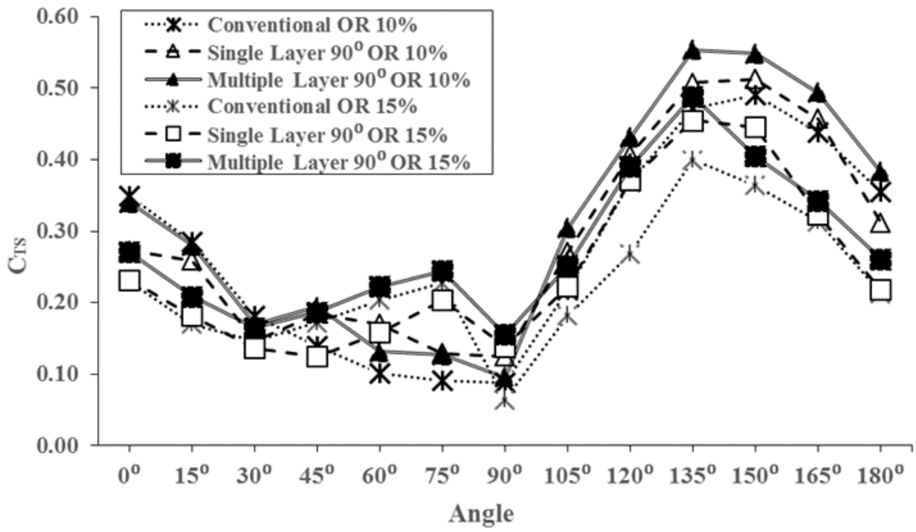


Fig. 8. Static Torque Coefficient (C_{TS}) by experienced the different rotors for *V* = 6.46 m/s

The presence of fluid flow through the single and multiple layers, which directly forwarded to the concave side of the returning blade, causes the increase in C_{TS}, leading to an increased of positive torque. Table 1. confirms that the single and multiple layers configurations enhanced the starting torque in various OR as compared to the conventional Savonius turbines. It also suggested that the best Savonius turbine configuration should have a rotor with multiple layers of 90^o at OR of 10%.

Table 1
Average C_T static value over half a cycle of the rotor

Configuration	C_{TS}	Configuration	C_{TS}
Conventional OR 10%	0.275	Conventional OR 15%	0.227
Single Layer OR 10%	0.289	Single Layer OR 15%	0.247
Multiple layers OR 10%	0.312	Multiple layers OR 15%	0.276

5. Conclusions

The experimental research had been carried out on Savonius turbines with variations of single and multiple layers of 90^o at Overlap Ratio of 10 and 15% to improve the Savonius wind turbines performance. It was tested in the experimental apparatus with four fan blowers arranged in a 2 x 2 configuration. The wind speeds were adjusted at 6.46, 6.99, and 7.27 m/s. The main conclusions are summarized below

i. Based on dynamic analysis, it shows that the rotor with single and multiple layers could improve Savonius wind turbine performance. The highest improvement was resulted by the addition of multiple layers 90^o at OR of 10%, which increased Cp by 22.4%.
ii. Under the static analysis, the starting torque of single and multiple layers rotors was better than the conventional rotors. The results revealed that Savonius turbines with multiple layers of 90^o at Overlap Ratio of 10% had the best results compared to other rotor configurations.

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