Простий вертикальний вітрогенератор Савоніуса може генерувати енергію при низькій швидкості вітру в будь-якому напрямку. Однак великий статичний крутний момент має низький коефіцієнт потужності. Тому було зроблено нововведення, що передбачає 16 напрямних лопаток навколо вала зовні лопаті з кутом близько 45° до радіальної лінії. Особливість напрямних лопаток полягає в тому, що вони здатні концентрувати на лопаті турбіни вітровий потік в будь-якому напрямку. Рух рідини навколо лопаті турбіни, який створює крутний момент на валу турбіни, було проаналізовано з використанням моделювання обчислювальної гідродинаміки (ОГД), а потім перевірялося шляхом спостереження за нитками фактичного руху рідини, прикріплених з кожного боку лопаті турбіни. Результат показує, що без напрямних лопаток вітровий потік навколо лопаті турбіни створює вихор на лопаті і вихор Кармана в низхідному потоці. Ці вихори ефективно знижують кінетичну енергію в вітровому потоці, так що механічна енергія на валу турбіни стає невеликою. При певному положенні лопаті вихор стає сильніше, а відділення рідини від поверхні лопаті стає товще. Більш сильний вихор має тенденцію знижувати сильнішу кінетичну енергію рідини, тоді як більш товстий поділ має тенденцію зменшувати підйомну силу на лопаті. Отже, ці два режими потоку мають тенденцію створювати негативний крутний момент. При установці напрямних лопаток навколо лопаті, вітрові потоки концентруються напрямними лопатками на лопаті турбіни, що ефективно зменшує вихор навколо лопаті і блокує великий вихор зовні напрямних лопаток в низхідному потоці. Поділ потоку пригнічується концентрованим потоком, що створює велику підйомну силу. В результаті коефіцієнт потужності збільшується на 61,6 %. Це величезне збільшення коефіцієнта потужності досягається при швидкості вітру 5 м/с, хоча стабільне обертання турбіни досягається при меншій швидкості

***Ключові слова:** концентрувати потоки, блокувати вихор, коефіцієнт потужності, Савоніус, напрямна лопатка, вихор Кармана, низхідний потік, обчислювальна гідродинаміка (ОГД)*

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UTILIZATION OF GUIDE VANES TO CONCENTRATE FLOWS TO THE BLADE AND BLOCK VORTEX TO IMPROVE THE POWER FACTOR OF SAVONIUS WIND TURBINE

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1. Introduction

The Savonius wind turbine is a vertical-axis turbine converting wind kinetic energy into motion energy. The advantage of the Savonius turbine is that it can capture wind from any direction, has large static torque, can work at low-speed wind and has a simple design. This turbine is rarely applied as power generator because it has a low power factor when compared to other types of turbines.

Many attempts have been made to increase the performance of the Savonius wind turbine, for example by installing a guide box that directs the flow to the blade so it will increase the power factor by 1.23 times [1]. Installation of flow guides like deflecting plate can increase the turbine power by 24 % [2]. Installation of curtaining in front of the Savonius turbine can increase the power factor by 38.5 % [3–5]. The use of obstacle shielding on the returning blade can increase the power factor by more than 27 %. However, with all these attempts, the increase in power factor is still not optimal.

There is still a lot of potential wind energy that has not been captured because the wind flow has not yet fully passed through the blade. Therefore, studies are devoted to improving the flow toward the blade.

2. Literature review and problem statement

Wind which is cheap and ecofriendly has high energy potential. However, in some countries, this energy potential has not been used due to various difficulties. One of the simple techniques to harvest wind energy is by using the simple Savonius turbine. The paper [6] presents the results of research, the Savonius wind turbine is a simple rotating machine to convert kinetic energy of wind into mechanical energy with a vertical shaft. The Savinous wind turbine is easily built with only two half-cylinder blades. Therefore, it can be very broadly applied and solves energy and environment issues. The Savonius wind turbine is able to capture wind from any direction, has a simple design, large static torque and can function at low wind speed. However, this conventional wind turbine has a low power factor of 15 %. It is because wind cannot be completely accommodated by the blade. Furthermore, the problem of fluid mechanics is also the defining factor which is dominant. In this case, the flow direction often does not follow the blade shape so that the transport of momentum from the wind to the blade is not optimal. The attempts to obtain a greater power factor have been done by previous researchers. The optimum design on the overlap ratio is the comparison of the distance between the blade and the diameter of the blade ($a/(2r)$) of 0.15. The test has been done at an overlap ratio of 0.0, 0.15, 0.30 and 0.5, the greater the overlap ratio, the greater recirculation that occurs. It is produced at the ratio gap ($e/(2r)$ of 0 and aspect ratio (H/D) of 1.0.

The flow observation inside and around the turbine has been done by measuring the pressure of the blade surface and visualization of flow by [6]. The performance that happens is caused by the amount of the Coanda flow in the thrust blade and the flow in the overlap. The overlap increases the recirculation of overlap causing the decrease in performance. The flow inside and around the blade has been observed by [7] at a rest and spinning condition with a pressure measurement on the blade surface. The flow separator area on the blade surface has decreased due to the rotation effect and flow retention occurs in the flow of overlap which causes the decrease in performance. The increase in the turbine performance has been done by installing the turbine in the guide box or Guide-box Tunnel (GBT) by [1]. In addition, this research also reduces the damage risk of strong wind. The maximum speed of the turbine at the GBT area ratio is between 0.3 and 0.7 while the maximum power factor at the GBT area ratio of 0.43 is 1.23 times larger compared to the turbine without GBT. In [2] the effect of end plate shape on the turbine really influences its performance and the contribution of lift force to the performance is huge. In this case, the deflection plate increases power by 24 %. The deflection plate can also be used as speed control or protection to the turbine device. The paper [4] declared at the use of blinds to reduce negative torque on the convex side has been done numerically with fluent 6 and experiment. The turbine with blinds produces better static torque value compared to the one without using blinds. The best result is the use of the longest blinds. Turbine testing with blinds, geometric parameter settings and proper arrangement of blinds can increase the power factor up to 38.5 % compared to the one without using blinds [3]. Numerical testing and experiment are also done under dynamic conditions. The result obtained from three blinds arrangement shows that blinds arrangement 1 has the best performance [5]. Flow simulation using ANSYS Fluent has been done by [8] to observe the turbine using a barrier plate on the turbine with two or three blades. Optimization of arrangement, angle and shape produces an increase in power factor more than 27 % compared to the one without using the barrier plate. The turbine with two blades is better than that with three blades. Optimization of the barrier plate is to increase the power of the turbine to spin itself, which has been done by [9]. Six free parameters are done to optimize by connecting OPAL and ANSYS Fluent. The increase in power factor is almost 40 % at tsr=0.7 compared to the turbine without using the barrier plate. The performance improvement exceeds 30 % in the entire operating range. Static torque is always positive in any angle or torque, which is high enough to start working.

From those studies mentioned previously, although performance improvement is achieved, it can only be done if the wind direction is always from the front. If the wind direction changes, additional equipment is required to adjust the attachment to follow the wind direction. Therefore, it takes time to adjust the direction. In order to overcome that problem, a director that can capture wind from any direction is needed; a guide vane. By installing the guide vanes, the wind coming from any direction can be focused to the center of the turbine so the mass flow through the turbine increases. Therefore, conversion of wind power into mechanical energy in the turbine shaft increases. This research discusses how the guide vane concentrates the flow to the blade, how the centralized flow reduces vortex and blocks Karman vortex downstream of the turbine as well as how the mechanism of flow which is centralized on the blade can increase the power factor (Fig. 1)

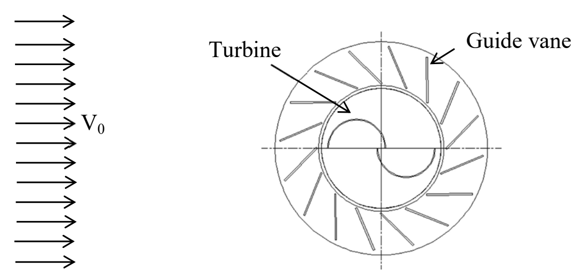


Fig. 1. Schematic diagram of research

3. The aim and objectives of the study

The aim of the study is to observe changes in performance due to the existence of guide vanes.

To achieve this aim, the following objectives have been set:

– to determine the influence of the guide vanes on the air flow to enter the turbine;

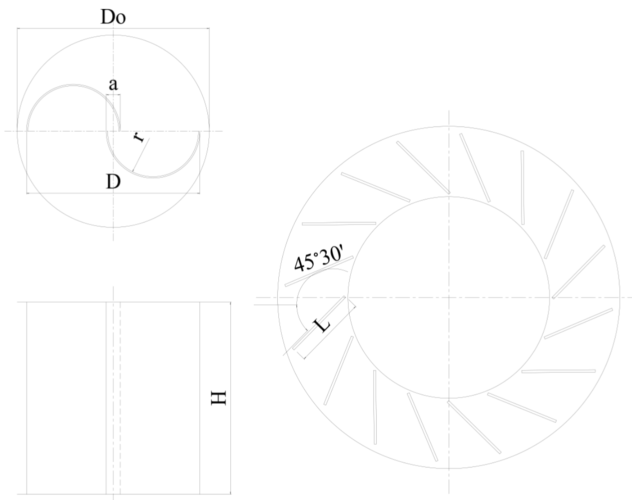
– to study the role of the amount of air mass entering the turbine in the formation of the air flow;

– to study the effect of the increase in mass air flow into the turbines on performance.

4. Material and methods of the research

The structure of the Savonius turbine examined in this research is as shown in Fig. 2. The Savonius wind turbine blade is made of two parts of 8 inch PVC pipe arranged into the turbine with diameter dimensions (D=370 mm), end plate diameter (D_o=1.1D=400 mm), blade radius (r=d/2=

=100 mm), overlap (a=0.15D=30 mm), blade thickness of 3 mm and turbine height (H=400 mm). Director length (L=300 mm), director angle 45°, 16 directors, the distance to the turbine is 6 mm, thickness is 5 mm and height is 400 mm, made of acrylic material.



a *b*

Fig. 2. Dimensions of Savonius wind turbine and guide vane Main signature: *a* — Sketch of the Savonius wind turbine, *b* — guide vane

4. 1. Wind turbine performance testing

The wind turbine is placed in the middle of the wind tunnel with dimensions of 120×120×240 cm. Testing equipment is placed as in Fig. 3.

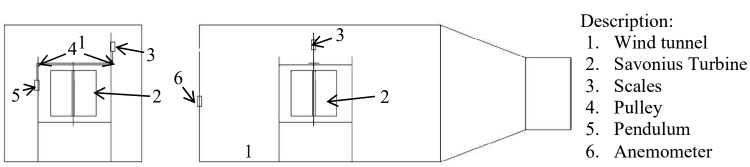


Fig. 3. Scheme of tools

Wind turbine testing is performed at wind speeds of 4 m/s, 5 m/s and 6 m/s. The rotating speed of the turbine (n) was measured using a tachometer from the upper side of the wind turbine. The turbine torque was determined by braking the pulley of the radius (l=50 mm) estimated from the equation (1)

$$T = Fl, \text{ Nm}. \quad (1)$$

F is the brake force measured on the scales minus the pendulum load (N)

Turbine output power was determined by multiplication of torque with angular velocity (ω) as in equation (2)

$$P_{out} = T\omega, \text{ Watt}. \quad (2)$$

The angular velocity was determined by the measurement of the spinning turbine (n) determined by the equation (3)

$$\omega = \frac{2\pi n}{60}, \text{ rad/s}. \quad (3)$$

Input power is the wind's power based on the wind speed estimated by the equation (4)

$$P_{in} = \frac{1}{2}\rho A v^3, \text{ Watt}. \quad (4)$$

ρ is the density of air (=1.25 kg/m^3), A is the frontal area of the turbine (=0.16 m^2), and v is the wind speed (m/s).

Power factor is the ability of a tool to convert the power from wind power into turbine power, arranged in the equation (5)

$$Cp = \frac{P_{out}}{P_{in}} 100\ \%. \quad (5)$$

The power of wind to rotate the turbine is shown by the rotation of tangential tip of the blade (2πR/60) to the wind speed (υ) called the tip speed ratio (*tsr*) determined by the equation (6)

$$tsr = \frac{2\pi R}{60v}. \quad (6)$$

4. 2. Visual Flow Testing

Visual observation is done by using simulation and experiment. Computational Fluid Dynamics (CFD) is used in the simulation. CFD is done with steady settlement, turbulent model k–ε, fluid used is air with ρ=1.225 kg/m^3 and μ=1.7894. 10^{-5}kg/m.s. Operating condition at atmospheric air pressure of 1.01325 bar. The limit conditions used by the inlet are inlet speed, wind tunnel side, turbine and guide vanes as the wall and the outlet is outlet pressure. The control settlement with Semi-Implicit Method for Pressure-Linked Equations (SIMPLE), discretization with first order momentum [10–12]. Meanwhile, experimental work was done by adding thread bundles in the middle of the blade height on all sides of the blade and guide vanes. Shooting is done when the turbine does not move at each angle position with a DSLR camera. Visual observation is done at the wind speed of 5 m/s.

a *b*

Fig. 4. Visualization Main signature: *a* — thread position on the blade; *b* — set up visualization

5. Research Results

5. 1. Comparison of Flow Visualization and Direction from Simulation and Experiment

Visual results are shown by comparing the simulation results (Fig. 5, *a*, *c*) and the experimental results (Fig. 5, *b*, *d*) in Fig. 5. The directions of flows are also shown in Fig. 5.

Fig. 5, *a* shows that the fluid is blocked from the surface of the blade in CFD simulation result in the turbine without guide vanes. In the position of blade 0°, a strong vortex is formed on the concave side of the thrust blade or turning blade which is connected by a very strong vortex on the downstream side. Vortex in the flow tends to absorb energy from the fluid which leads to low torque. At the position of the blade 45°, vortex in the blade is weak and even gone at the turning blade. Some of the vortex shifts to downstream in the form of small Karman vortex sheets. It shows that kinetic energy received by the blade to be torque increases. At the position of the blade 90°, vortex in the downstream of the turbine is getting larger and stronger in the downstream of the turning blade. It indicates that energy in the wind starts to be absorbed back more than that at the position of the blade 45°. At the position of the blade 135°, vortex in the downstream of the turbine is much stronger than at all the positions. It shows that energy absorbed by vortex is the greatest one. Furthermore, the flow speed on the blade surface is faster than on the back side of the blade that leads to negative lift causing negative torque. Fig. 5, *b* shows that the experiment result verifies the CFD result with good agreement. Based on Fig. 5, *c*, the CFD simulation result shows that guide vanes make more fluids enter and concentrate to the blade. Therefore, separation on the entire surface of the blade is getting thinner. The vortex around the blade is reduced and it becomes smaller and the vortex at the downstream of the turbine is blocked outside the guide vanes. The flow speed on the back side of the blade is higher than on the front side. At the higher speed, static pressure is lower and vice versa. Therefore, the lift on the blade is larger. It means that the same wind speed will produce a larger torque compared to the turbine without using guide vanes. Fig. 5, *d* shows that the experimental results of the turbine with guide vanes verify CFD simulation result appropriately.

5. 2. Experimental Results on Turbine Performance

Fig. 6, *a–c* show the influence of guide vanes on static torque at the wind speed of 4 m/s, 5 m/s and 6 m/s. The turbine with guide vanes (GV) has larger static torque compared to the conventional turbine (Conv). This increase occurring due to guide vanes drains more air to the turbine blade so that the vortex is reduced, separation is smaller and fluid is attached to the blade. In addition, the fluid speed on the back side of the blade is faster than that in the front side of the blade so that lift increases.

The charts of the relationship between static torque and blade position (θ) on the turbine with guide vanes on various wind speeds are shown in Fig. 7. The wind speed is getting stronger producing static torque, which is also getting stronger. However, the difference of maximum and minimum torque at the wind speed 5 m/s is similar to at the wind speed 6 m/s which is 0.35 Nm. Meanwhile, at the wind speed 4 m/s, the difference of maximum and minimum torque is 0.24 Nm. The smaller the difference between maximum and minimum torque, the rotating speed of the turbine turns more stable.

Fig. 8 shows the relationship of the power factor and tip speed ratio (tsr) between the conventional turbine (Conv) and the turbine with guide vanes (GV) at the wind speed 4 m/s, 5 m/s and 6 m/s. The power factor of GV is larger than Conv. The increase in power factor at the wind speed 4 m/s is 50 %, 5 m/s is 61.5 % and 6 m/s is 18.7 %. Therefore, the wind speed 5 m/s is very effective for the wind turbine with these guide vanes.

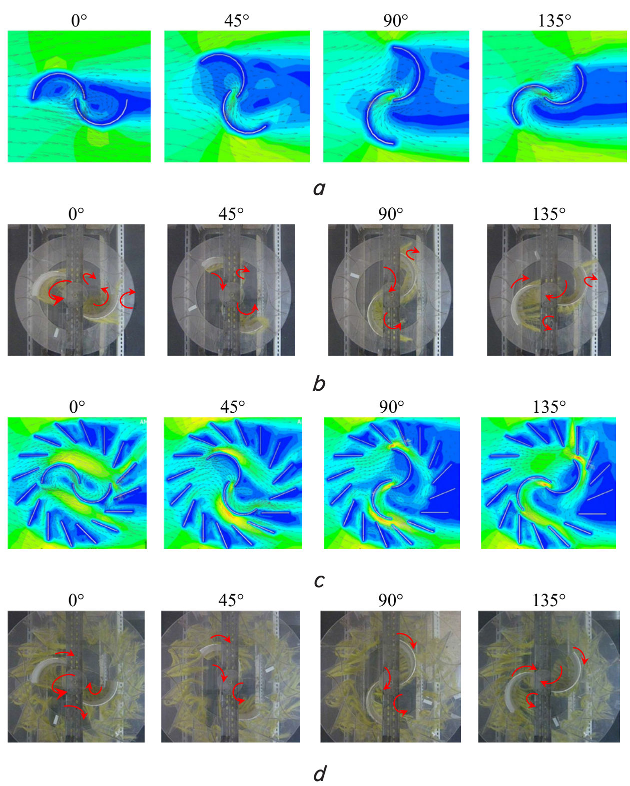


Fig. 5. Flow visualization: *a* – simulation results turbine without guide vanes, *b* – experiment results turbine without guide vanes, *c* – simulation results turbine with guide vanes, *d* – experiment results turbine with guide vanes

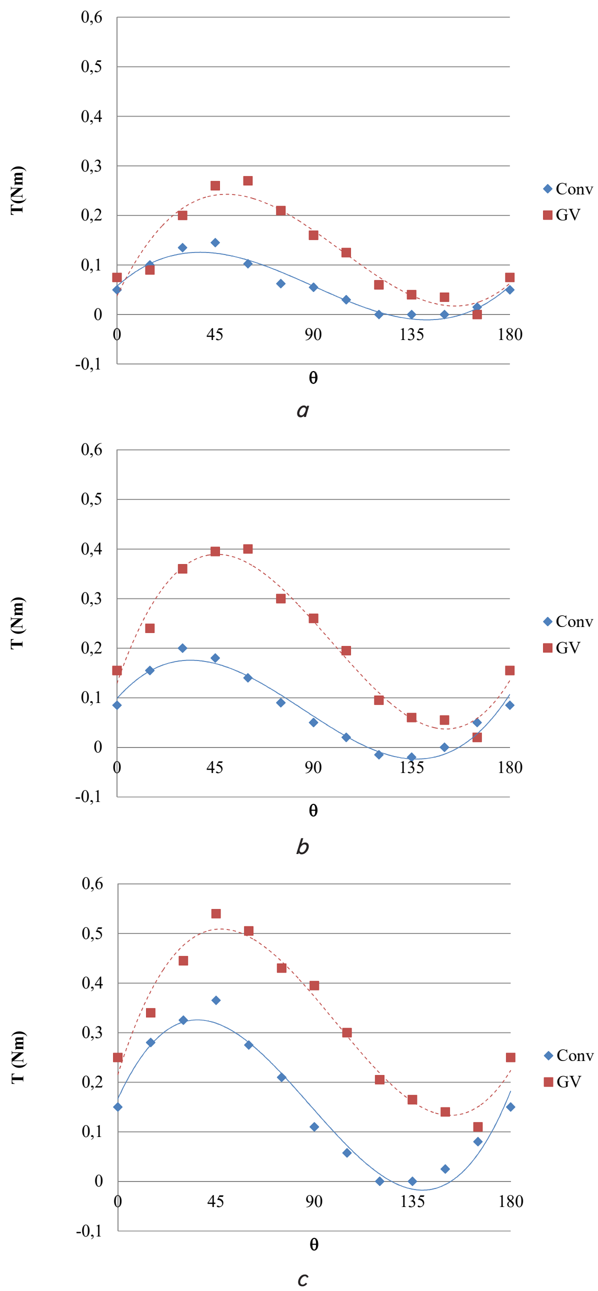


Fig. 6. Influence of guide vanes on static torque at speed: *a* – 4 m/s; *b* – 5 m/s; *c* – 6 m/s

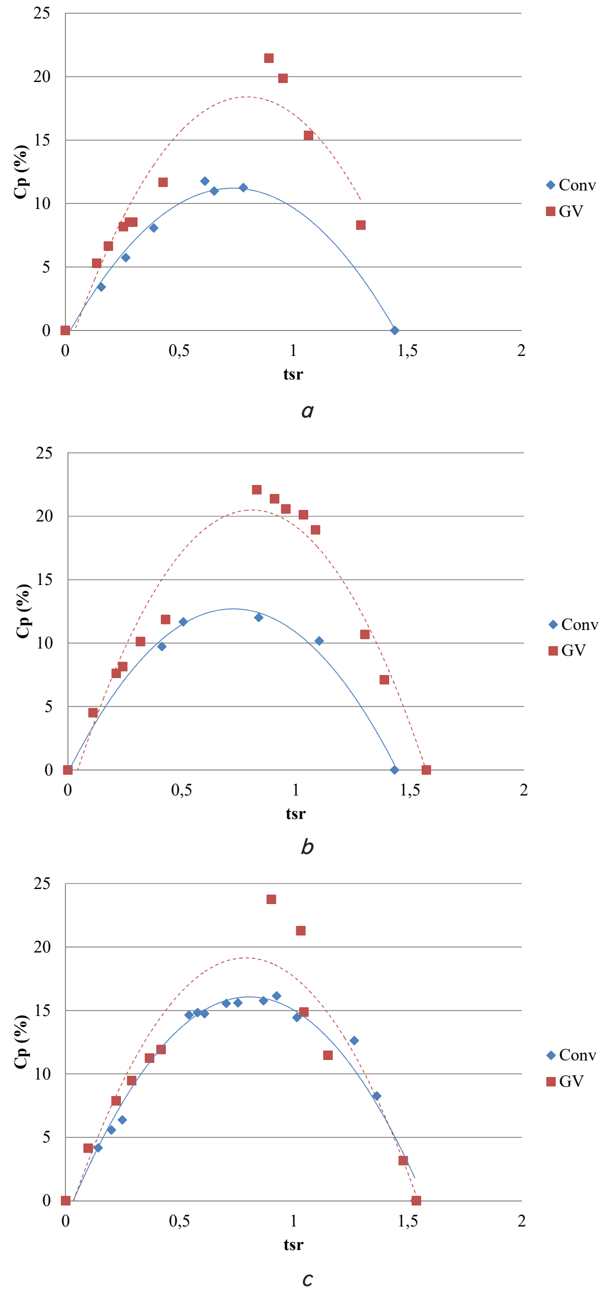


Fig. 8. Comparison of power factor of Conv and GV at the wind speed: *a* – 4 m/s; *b* – 5 m/s; *c* – 6 m/s

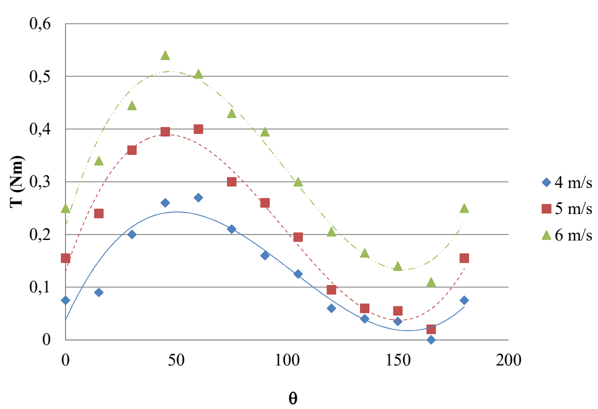


Fig. 7. Static torque to the wind speed at GV

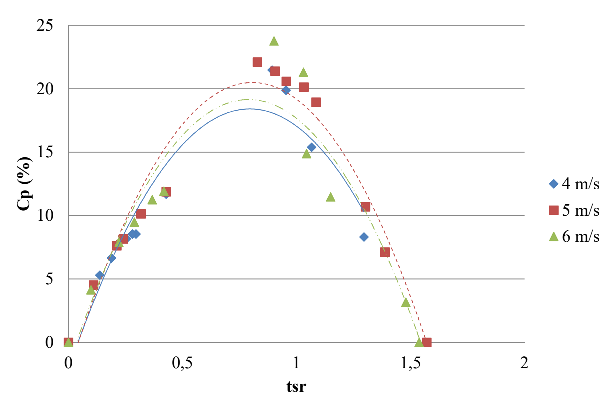


Fig. 9. Relationship between power factor and tsr on GV

Based on the comparison of the power factor of the turbine and guide vanes on tsr, the highest value is achieved at the wind speed 5 m/s. Fig. 9 shows that differences in the wind speed produce the highest power factor at the wind speed 5 m/s although the differences in static torque of the turbine with guide vanes between 5 m/s and 6 m/s are similar. The value of the power factor depends on turbine dimensions, guide vanes and wind speed.

6. Discussion of experimental results

Fig. 5, *c* shows the simulation results of the turbine with guide vanes. At the position of the blade 0°, most of the flow is attached to the blade. Vortex is getting smaller and staying away from the blade wall. On the downstream of the blade, there is almost no vortex. This indicates that energy in the wind can be converted into torque on the turbine shaft. At the position of the blade 45°, the vortex is much smaller, left slightly behind the base of the thrust blade. The difference in speed between the back and the front side of the blade becomes larger which causes the lift increase. It shows that torque increases very much. As shown in Fig. 6, *b*, the maximum static torque increases by 100 % compared to conventional turbines. At the position of the blade 90°, lift on the back side of the blade is still high, however, vortex and separation on the front and back sides of the thrust blade are wider. This shows the decrease in energy taken from the air flow so that torque is reduced. At the position of the blade 135°, vortex and separation on the front and back sides of the thrust blade do not change, but the lift on the turning blade weakens so that torque decreases even more.

Fig. 6, *a–c* show the static torque, the shift in the position of angle (θ) of the maximum and minimum value of around 15° to the right compared to the conventional turbine without guide vanes is caused by changes in wind direction that happens in the turbine. There is a negative static torque at the position of angle 120° to 150° in the conventional turbine. This is because of vortex in the downstream of the blade is very strong which absorbs strong air energy while separation in the blade is getting larger causing the decrease in lift. In this case, lift directly produces torque in the shaft which is weaker due to the energy absorbed by the vortex in downstream of the blade. This negative torque will overload the torque generated at another blade position so that the overall power factor of the turbine is low. Meanwhile, the turbine with guide vanes causes static torque to always be positive. It does not matter when it stops in any condition and when it spins again. Therefore, the power factor is larger. The design developed provides an increase in the power factor at low wind speeds up to Cp=0.23 at tsr=0.8. While at other tsr, the difference in the value of the power factor is relatively small.

Limitations of the wind tunnel that is used, the wind speed that is done is maximum.

The addition of guide vanes works effectively at a certain speed, so if the working wind speed is higher there will be braking itself. Thus, there is no overspeed and the turbine remains safe to operate. It is necessary to develop this research by adjusting the distance of the wheel to the guide vanes.

7. Conclusions

1. Guide vanes direct more air to enter the turbine but it can still receive air flow from any directions.

2. The increase in the amount of air mass entering the turbine reduces vortex that makes it to be smaller even almost gone.

3. The increase in air flow mass entering the turbine reduces separation and increases lift so that torque and power factor increase. An increase in the mass of the air flow entering the turbine increases the lifting force by 61.6 %.

Without guide vanes, the torque produced by the turbine at the position of the blade 135° becomes negative because of big separation which leads to low lift. Vortex on the downstream of the blade is very strong, so that the energy absorbed by the vortex is larger than torque produced by lift. By using guide vanes, air flow mass increases, separation decreases, lift increases, vortex is reduced and Karman vortex on the downstream of the blade is blocked outside the guide vanes. The stability of rotation is achieved at the lower wind speed.

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