International Journal of Smart Grid and Clean Energy

Experimental study on aerodynamic characteristics of vertical-axis wind turbine

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Abstract

This paper firstly introduces some parameters for the design of vertical-axis wind turbine including sweeping area, blade aspect ratio, number of blades, airfoil type, turbine solidity, blade shape and height/diameter ratio. Models of Cup-Rotor, Φ-Rotor and H-Rotor vertical-axis wind turbine were made and aerodynamic experiments were carried out in a wind tunnel laboratory on these typical vertical-axis wind turbines. Experimental results are analyzed, which reveal the influence of the structural parameters on the aerodynamic performance of these wind turbines. When a baffle plate is put in front of the Cup-Rotor wind turbine, its rotational velocity and tip-speed ratio will be higher, and the tip-speed ratio will be over 1.0. Airfoil type has little influence on the minimum steady running speed of Φ-Rotor wind turbine and some influence on the turning point speed. Initial triggering could greatly enlarge the rotational velocity and the tip-speed ratio of the Φ-Rotor vertical-axis wind turbines and improve its working efficiency. The H-Rotor wind turbine has higher minimum steady running speed and lower tip-speed ratio, which needs more attention and carful optimization.

Keywords: Aerodynamic analysis; renewable energy application; vertical-axis wind turbine; wind tunnel test

1. Introduction

Due to its simple structure, low working noise, high working stability, simple maintenance and fine appearance, vertical-axis wind turbine has been more and more widely used in wind energy application [1]-[6]. But its aerodynamic performance is quite puzzling and its structural design is more difficult [7], which somehow limits its application to some extent.

There are two types of vertical-axis wind turbines including drag type and lift type wind turbines according to their working principle of wind turbine blades. Drag type wind turbine mainly uses air resistance force to rotate its blades while air flowing through them. These asymmetrical blades produces different aerodynamic resistance forces in the upwind direction, which results in a moment round a central axis driving the wind turbine such as cup-Rotor wind turbine. Lift type wind turbine uses lift force generated by the air blowing through the blades. There are two kinds of lift type vertical-axis wind turbine as Φ-Rotor vertical-axis wind turbine and H-Rotor vertical-axis wind turbine. They have relatively simpler structures, lower cost, higher rotational velocity, bigger rotational inertia and are suitable for large-scaled wind turbine. Because of its small windward area, Φ-Rotor vertical-axis wind turbine has poor starting-up performance and should be equipped with a starting mechanism and a clutch, which increases the complexity of structure and investment.

Aerodynamic experiments were carried out in a wind tunnel laboratory on three typical vertical-axis wind turbines. The experiment results reveal the influence of structural parameters on the aerodynamic performance of these wind turbines and lay foundation of practical application of these vertical-axis wind turbines.

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*Manuscript received November 20, 2016; revised January 20, 2017.
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doi: 10.12720/sgce.6.2.104-113

2. Structural Design of Vertical-Axis Wind Turbine

Some important structural parameters could influence the performance of vertical-axis wind turbine including sweeping area, blade aspect ratio, number of blades, airfoil, solidity, blade shape and height /diameter ratio.

2.1. Sweeping area

The sweeping area of wind turbine is the swept area by blades within one revolution perpendicular to wind direction, which directly determines the total amount of captured wind energy. The sweeping area is determined by the radius and height of wind turbine. This sweeping area could be estimated from rated power, rated speed and wind energy utilization coefficient of wind turbine. This parameter is then used to determine the overall size of wind turbine and to design its components.

2.2. Blade aspect ratio

The blade aspect ratio is the ratio of blade height to its chord. When the wind turbine runs at a certain velocity, the air pressure on pressure side is higher than that on suction side, resulting in upward lift force from its pressure difference. Due to this pressure difference on blade surface, the air on pressure side will orbit up from both ends of blade, which generates wing tip vortex. The normal flow on both ends will be disturbed by this vortex and lift force will be reduced. The larger the lift coefficient is, the larger the wing tip vortex will be, and a series of vortex will be formed near the wing tip behind the blade end and increase the blade resistance. If the aspect ratio is large enough, the lift loss and increased resistance caused by the wing tip vortex could be ignored; if the aspect ratio is relatively small, this influence will be obvious. Due to the limited blade length, the larger the aspect ratio is, the narrower the blade will be, resulting in smaller blade area and total lift force. In addition, narrower chord will result in smaller Reynolds number, smaller stall attack angle of the blade, smaller lift coefficient and larger drag coefficient. Sometime a end plate is installed on the blade tip to reduce the influence of circling flow.

2.3. Number of blades

The number of blades directly determines the total cost, aerodynamic performance and load distribution of wind turbine. At present, Darrieus type wind turbine mostly has two or three blades. Three-blade wind turbine is the most widely used, which has small torque disturbance, good aerodynamic performance. Two-blade wind turbine is also used with less material and investment. The comparisons between these two kinds of wind turbine are shown in Table 1.

Table 1. Comparison between two-blade and three-blade wind turbines

Performance index	Two-blade wind turbine	Three-blade wind turbine
Manufacture technology	Poor	Good
Material cost	Low	High
Installation cost	Low	High
Torque disturbance	Poor	Good
Mechanical properties	Poor	Good
Strength/mass ratio	Good	Poor

2.4. Airfoil type

Airfoil type could directly determine energy transformation coefficient, blade cost, load distribution of wind turbine. Lift/drag ratio is an important index to indicate the performance of airfoil. NACA00XX type airfoil is usually adopted by Darrieus wind turbines with high lift, low drag and good stall characteristics [8]. The NACA0015 type airfoil drawn by ProfiliV2 is shown in Fig. 1.

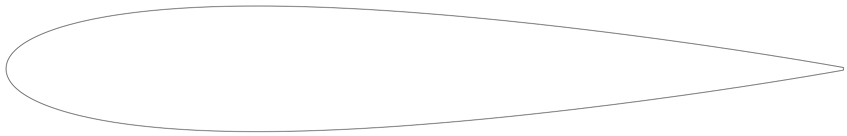


Fig. 1. Section view of NACA0015 airfoil.

2.5. Turbine solidity

Turbine solidity is an important parameter of vertical-axis wind turbine, which is the spreading surface of blades divided by the sweeping area as indicated in formula (1) as.

$$\sigma = \frac{Bcl}{S} \tag{1}$$

where
σ——turbine solidity
B—— number of blades
c——blade chord (m)
l——blade length (m)
S——sweeping area (m2)
For simplicity, it could be also calculated as:

$$\sigma = \frac{Bc}{R} \tag{2}$$

where
R——rotor radius (m)
The energy transformation coefficient of vertical-axis wind turbine could be reduced when the turbine solidity is too large or too small. Larger turbine solidity could increase larger drag force and decrease wind velocity onto the blades, resulting in the moving of high rotating torque attack angle on blades to low tip-speed ratio area. So the vertical-axis wind turbine with small solidity could have higher tip-speed ratio than that with large solidity [9]. But the vertical-axis wind turbine with larger solidity has better starting-up feature than that with smaller solidity. Some other parameters should be taken into account such as number of blades, blade chord and tip-speed ratio in the design of vertical-axis wind turbine. To reduce the cost of wind turbine, small turbine solidity is a better choice.

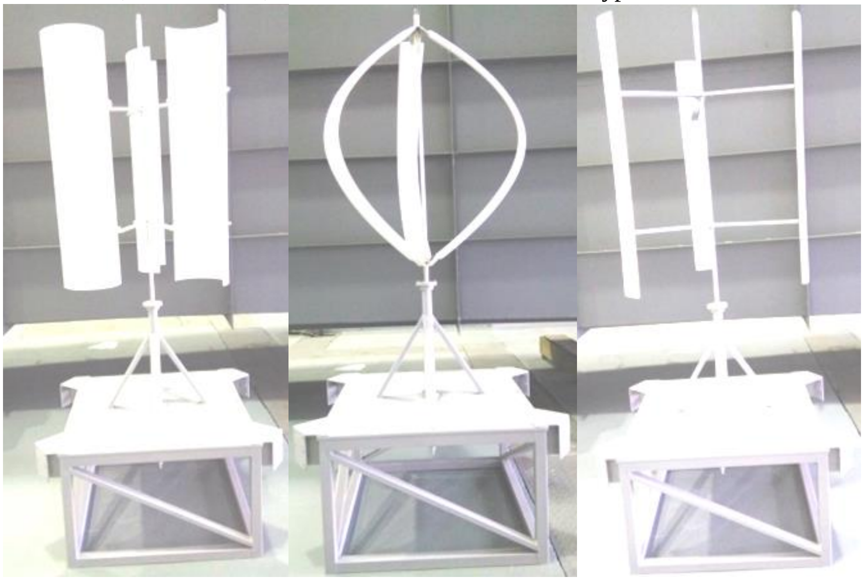
2.6. Blade shape

Different wind turbine has different blade shape. Drag type cup-Rotor wind turbine is made from bent semi-circled iron plate, which is enforced by ribs and brackets. After years' research and practice, blade shape of Φ-Rotor wind turbine has been gradually developed into several curves including troposkien, sandia, catenaries and parabola type. The troposkien type blade is flexible and fixed at tow ends, which rotates around a fixed axis and is naturally bent into curve by its centrifugal force. The sandia type blade is simplified from troposkien blade with arc segment in the middle and straight parts at two ends symmetrically distributed by equatorial plane. The catenaries curve is a line with uniform material and constant cross-section hung at its two ends on the horizon with gravity. The parabola type is a kind of catenaries. Parabolic type Φ-Rotor wind turbine and H-Rotor wind turbine with vertically straight blades of NACA00XX airfoil were made models for the experiments.

2.7. Height /diameter ratio

Height/diameter ratio of the wind turbine is the height to its diameter. Under the same sweeping area the wind turbine is usually designed with small height /diameter ratio in order to minimize the length of blade and the height of central pole. But it has large rotating torque under low speed, higher stress on blade from gravity, higher cost for driving mechanism. Modern design of vertical-axis wind turbine tends to be larger height/diameter ratio, which could capture more amount of and more stable wind energy. But it needs carefully material and strength design and supporting structure. Generally speaking, the height/diameter ratio of the vertical-axis wind turbine is better between 0.5 and 3.0 [9].

Models of Cup-Rotor, Φ-Rotor and H-Rotor vertical-axis wind turbine were made as shown in Fig. 2 (a), (b), (c). Cup-Rotor wind turbine has semicircle blade and Φ-Rotor, H-Rotor wind turbines use NACA0012, NACA0015, NACA0018, NACA0021 and NACA0024 type airfoils.



(a) (b) (c)

Fig. 2. Three types of vertical-axis wind turbine models: (a)semicircle Cup-Rotor, (b)Φ-Rotor, (c)H-Rotor.

3. Wind Tunnel Test

The experiments were carried out respectively on those three kinds of vertical-axis wind turbine models in a wind tunnel laboratory of Shanghai Maritime University with a velocity measuring device in a tunnel tank.

The wind tunnel is a low-speed, recycling wind system. The flow field parameters are shown below:

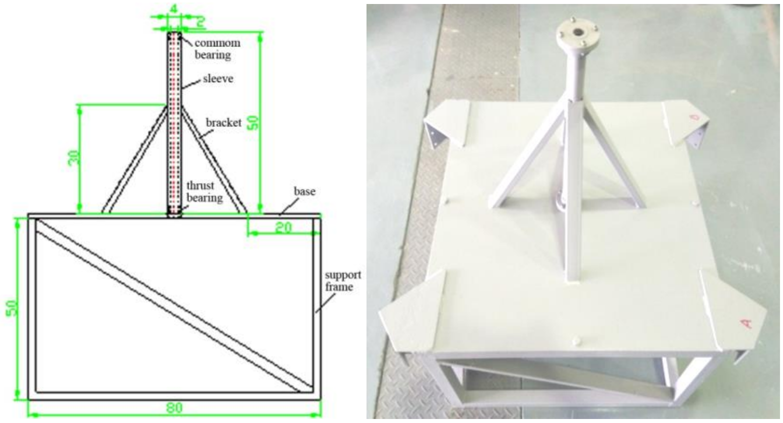
- Wind speed range: 1~40 m/s;
- Airflow stability: < ±0.4%;
- Airflow deflection: < ±0.5°;
- Airflow turbulence intensity: <0.5%;
- Airflow unevenness: < ±0.4%;

3.1. Velocity measuring device

A velocity measuring device is designed according to the wind tunnel size, tunnel tank and vertical-axis wind turbine model structure as shown in Fig. 3 (a), (b). The device is composed of common bearing, thrust bearing, sleeve, bracket, base and support frame.

According to the size of the wind tunnel, inner tank and the structure of vertical-axis wind turbine, a velocity measuring device of the wind turbine is designed; its structure size and physical map are shown in Fig. 3 (a), (b). The device is composed of common bearing, thrust bearing, sleeve, bracket, base and support frame. The shaft of vertical-axis wind turbine model is inserted into the sleeve and its rotational velocity will be measured by photoelectric sensor as shown in Fig. 4.

The photoelectric velocity measuring device is mainly composed of rotating member, reflecting sticker and reflecting photoelectric sensor with measuring range of 1~60000 r/min and operating temperature from 0 to 70 ℃ as shown in Fig. 4.



(a) (b)

Fig. 3. Rotational velocity measuring device :(a) device drawing,(b) device picture.

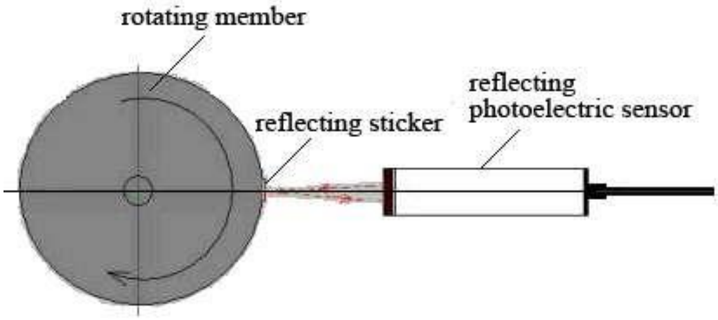


Fig. 4. Working principle of the photoelectric sensor.

3.2. Experimental results

● Semi-circle cup-Rotor vertical-axis wind turbine

Rotational velocity of semi-circle cup-Rotor wind turbine under different wind speeds are shown in Fig. 5. It could been seen that the semi-circle cup-Rotor wind turbine has good starting-up feature because it could be rotated in the slight breeze of between 1.6 and 3.3m/s. ,The velocity increases with wind speed. The increasing rate is larger when wind speed is between 8 and 12m/s than that between 1.6 and 7.5m/s and reaches its maximum when wind speed is between 7.5 and 8.5m/s.

Tip-speed ratio of semi-circle cup-Rotor wind turbine is calculated from its rotational velocity as compared in Fig. 6. As seen that the tip-speed ratio of wind turbine increases relatively faster when wind speed is between 1.6 and 3.7m/s, and gets to its maximum when between 8.0 and 9.0 m/s. Here the tip-speed ratio λ is ratio of the linear speed at blade tip point to wind speed.

To improve its aerodynamic characteristics, a baffle plate was placed half way in front of the wind turbine model. The rotational velocity of the wind turbine model with or without baffle plate is shown in Fig. 7. It could be seen that the rotational velocity of wind turbine with baffle plate is obviously larger than that of without baffle plate, and increases approximately linearly. It has lower started speed, better starting-up feature and more smooth running stability. It is proved that plate in front of wind turbine could greatly improve the aerodynamic characteristics of vertical-axis wind turbine.

Tip-speed ratios of semi-circle cup-Rotor wind turbine with baffle plate are shown in Fig. 8. As seen that the tip-speed ratios of wind turbine with baffle plate are all larger than 0.9, much larger than that of without baffle plate, and change smoothly within range between 1.3 and 1.4.

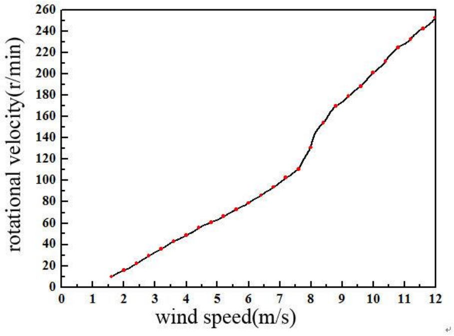


Fig. 5. Rotational velocity of semi-circle cup-Rotor wind turbine under different wind speeds.

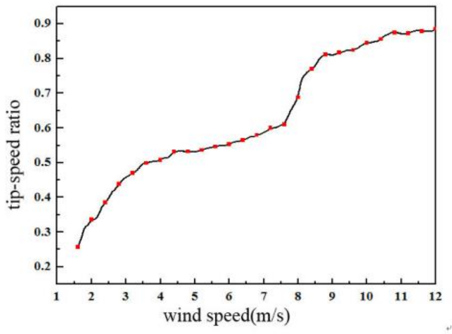


Fig. 6. Tip-speed ratio of semi-circle cup-Rotor wind turbine under different wind speeds.

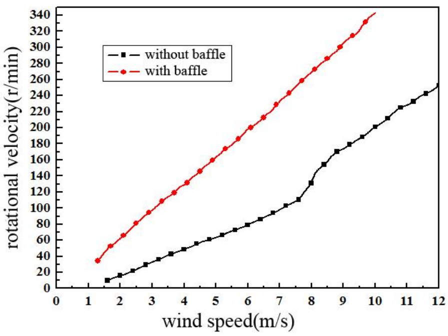


Fig. 7. Rotational velocity of semi-circle cup-Rotor wind turbine with or without baffle plate.

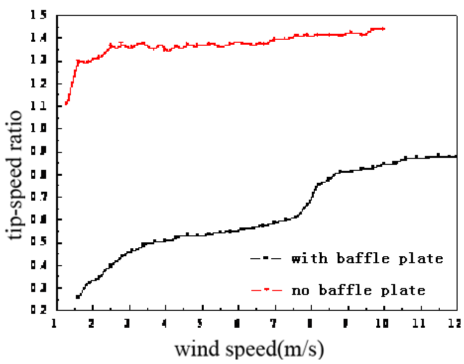


Fig. 8. Tip-speed ratio of semi-circle cup-Rotor wind turbine with or without baffle plate.

● Φ-Rotor vertical-axis wind turbine

The rotational velocities of Φ-Rotor vertical-axis wind turbine models with the same height and diameter and different airfoil type as NACA0012, NACA0015, NACA0018, NACA0021, NACA0024 are shown in Fig. 9.

The rotational velocity was measured when the Φ-Rotor wind turbine run steadily under some a wind speed. As seen from the Fig. 9 that without initial Triggering, rotational velocities of these five types of wind turbines increase linearly with wind speed under lower wind speed range, but then increase dramatically at a certain speed, indicating a turning point where low speed turns to high speed. The steady running speeds of five airfoil wind turbines are quite different, where NACA0024 airfoil has the lowest minimum steady wind speed around 7.4 m/s and NACA0012 airfoil gas the highest minimum steady wind speed around 8.6 m/s. The steady running speed and turning point of the five airfoils are listed in Table 2.

Table 2. The steady running speed and turning point of the five airfoils

Airfoil type	NACA0012	NACA0015	NACA0018	NACA0021	NACA0024
Minimum steady running speed(m/s)	8.6	7.4	8.3	7.8	7.4
Turning point speed，m/s	14.9	12.3	13.5	9.5	9.0

Among these five different airfoils without initial trigging, the thicker the blade is, the lower the turning point speed will be and the corresponding rotational velocities all below 250 r/min. When all the wind turbines were trigged to an initial rotational velocity 250 r/min, the experimental results are shown in Fig. 10. As seen that the velocities of these five different airfoils increase with wind speed linearly, where NACA0015 airfoil has the lowest steady wind speed and NACA0012 airfoil has the highest steady wind speed. The minimum steady wind speed of all the five airfoils are between 3.0 and 4.0 m/s as listed in Table 3. It could be seen from the comparison between Fig. 9 and Fig. 10 that when Φ-Rotor wind turbine is trigged at an initial velocity 250 r/min, its velocity is higher than that of without initial velocity. So the initial Triggering of Φ-Rotor wind turbine is necessary for its higher working efficiency.

Table 3. The minimum steady wind speed and rotational velocity under the 10m/s wind speed

Airfoil type	NACA0012	NACA0015	NACA0018	NACA0021	NACA0024
Minimum steady running speed, m/s	3.9	3.3	3.4	3.5	3.8
Rotational velocity under 10m/s wind speed, r/min	1091.4	1088.0	1040.2	987.8	1004.8

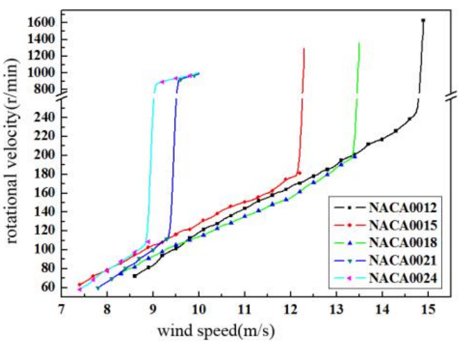


Fig. 9. Rotational velocity of Φ-Rotor wind turbine without initial trigging.

The calculated tip-speed ratios under different wind speed are shown in Fig. 11 and Fig. 12 respectively. As seen from Fig. 11 that when the airfoils are not initially trigged at 250 r/min the tip-speed ratio increases with wind speed before the turning point. As seen from Fig. 12 that with or without initial triggering the tip-speed ratio increase with wind speed and NACA0015 has the largest stability. But all the tip-speed ratios present a fluctuation from 4.5 to 5.5 m/s wind speed, especially the NACA0012 has two big fluctuations.

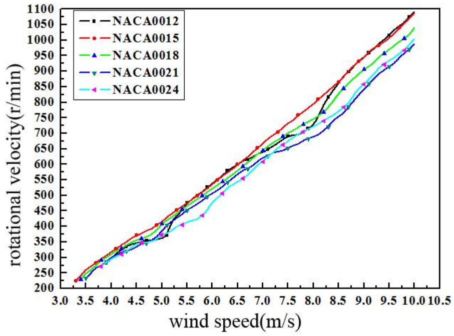


Fig. 10. Rotational velocity of Φ-Rotor wind turbine with 250r/m initial trigging.

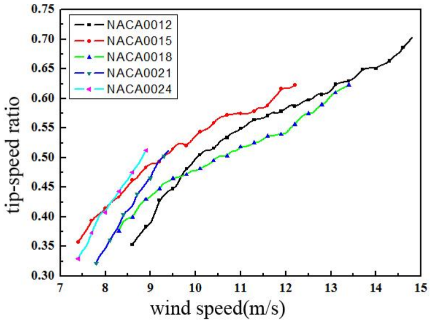


Fig. 11. Tip-speed ratio of Φ-Rotor wind turbine without initial trigging.

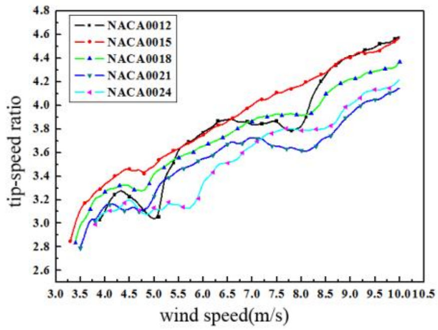


Fig. 12. Tip-speed ratio of Φ-Rotor wind turbine with 250r/min initial Triggering.

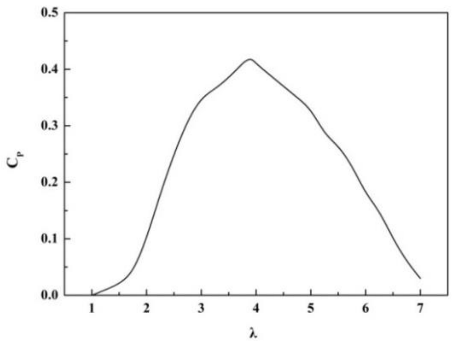


Fig. 13. Relationship between Tip-speed ratio λ and power co efficiency Cp of Φ-Rotor wind turbine.

Fig. 13 indicates the relationship between power coefficient C_p and tip-speed ratio λ. Here the power coefficient is the ratio of the wind turbine power to its encountered wind power. From Fig. 11 and Fig. 13 it could be seen that power coefficients are almost zero before turning point without initial trigging. From Fig. 12 and Fig. 13 it could be seen that the power coefficients are all above 0.3 when power coefficient is between 2.7 and 5.2 while wind turbine was initially trigged at 250 r/min velocity and all these wind turbines reach their highest power coefficient. So the Φ-Rotor wind turbine could have higher working efficiency and higher wind power coefficient at the low wind speed if initially trigged at 250 r/min velocity.

● H-Rotor vertical-axis wind turbine

In the case of same structure parameters such as height and diameter of wind turbine, rotational velocities of five H-Rotor vertical-axis wind turbines with different airfoils of NACA0012, NACA0015, NACA0018, NACA0021 and NACA0024 were measured as shown in Fig. 14.

The rotational velocity of the H-Rotor wind turbine was measured, respectively when five different wind turbine models run steadily. As seen from Fig. 14 that all the H-Rotor wind turbines run steadily under high wind speed above 15.0 m/s, except that with NACA0024 airfoil type which could run above 9.5 m/s. Their rotational velocity all increase with wind speed nearly linearly.

The tip-speed ratio of H-Rotor wind turbine is calculated as shown in Fig. 15. All the tip-speed ratios of H-Rotor wind turbines increase with wind speed gradually, most of which are below 0.20 even under strong wind.

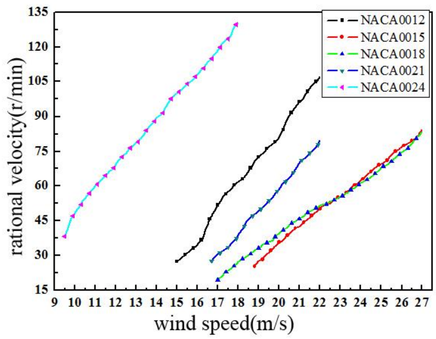


Fig. 14. Rotational velocity of five different H-Rotor airfoils wind turbine.

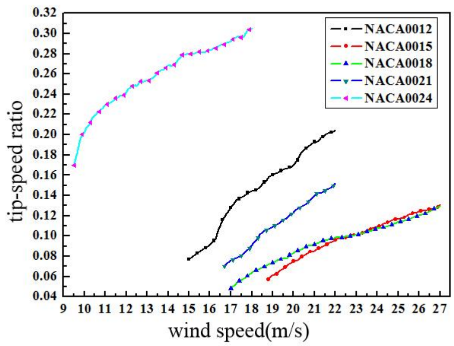


Fig. 15. Tip-speed ratio of five different H-Rotor airfoils wind turbine.

4. Conclusion

Through theoretical analysis and experimental study, some conclusions are drawn out as below:

- The starting-up wind speed of semi-circle Cup-Rotor vertical-axis wind turbine is about 1.6 m/s, the rotational velocity and the tip-speed ratio increases with wind speed from 1.6 m/s to 12m/s. When a baffle plate is put in front of windward convex part of the Cup-rotor wind turbine, its rotational velocity and tip-speed ratio will be higher, and the tip-speed ratio will be over 1.0.

- The rotational velocities of the five Φ-Rotor vertical-axis wind turbines gradually increase approximately linearly with wind speed within a certain range of wind speed, and then increase rapidly after a certain turning point when they were initially trigged. Airfoil type has little influence on the minimum steady running speed of Φ-rotor wind turbine and some influence on the turning point speed. When the Φ-Rotor vertical-axis wind turbine is initially trigged at 250 r/min the rotational velocity and tip-speed ratio will be much larger and increase with wind speed approximately linearly, which indicates that initial triggering could greatly enlarge the rotational velocity and the tip-speed ratio of the Φ-Rotor vertical-axis wind turbines and finally improve its working efficiency. At this time, airfoil type has little influence on their minimum steady running speed and performance.
- Compared with the semi-circle Cup-Rotor and Φ-Rotor vertical-axis wind turbine, the H-Rotor wind turbine has higher minimum steady running speed and lower tip-speed ratio, which indicates that the aerodynamic design and structure manufacture of H-Rotor wind turbine needs more attention and carful optimization.

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