Research Article

Research on Aerodynamic Characteristics of Straight-Bladed Vertical Axis Wind Turbine with S Series Airfoils

Fang Feng ^{1,2}, Shouyang Zhao,³ Chunming Qu,³ Yuedi Bai,³
Yuliang Zhang,¹ and Yan Li ^{2,3}

¹College of Science, Northeast Agricultural University, Harbin 150030, China

²Heilongjiang Provincial Key Laboratory of Technology and Equipment for Utilization of Agricultural Renewable Resources in Cold Region, Harbin 150030, China

³College of Engineering, Northeast Agricultural University, Harbin 150030, China

Correspondence should be addressed to Fang Feng; fengfang@neau.edu.cn and Yan Li; liyanneau@163.com

Received 27 October 2017; Revised 12 January 2018; Accepted 13 February 2018; Published 16 May 2018

Academic Editor: Ahmad Sedaghat

Copyright © 2018 Fang Feng et al. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

Background. In order to investigate the effect of aerodynamic characteristics of S series airfoils on the straight-bladed vertical axis wind turbine (SB-VAWT), numerical simulations and wind tunnel experiments were carried out using a small SB-VAWT model with three kinds of blade airfoils, which are asymmetric airfoil S809, symmetric airfoil S1046, and NACA0018 used for performance comparison among S series. The aerodynamics characteristics researched in this study included static torque coefficient, out power coefficient, and rotational speed performance. The flow fields of these three kinds of blade under static and dynamic conditions were also simulated and analyzed to explain the mechanism effect of aerodynamic performance. According to the results, the SB-VAWT with airfoil S1046 has better dynamic aerodynamic characteristics than other two airfoils, while the SB-VAWT with airfoil S809 is better in terms of the static characteristics. As the most suitable airfoil for SB-VAWT, the S series airfoil is worth researching deeply.

1. Introduction

In recent years, as one of vertical axis wind turbines (VAWT), the straight-bladed vertical axis wind turbine (SB-VAWT) has developed rapidly and attracted attention of scientists due to its advantages such as wind direction independence, simple structure, and unique shape [1]. The selection of the blade airfoil was found one of the main factors which has influenced the output characteristics of SB-VAWT. Normally, the airfoils of horizontal axis wind turbine (HAWT) are NACA series airfoils, SERL series airfoils studied by America, S8xx series airfoils, FFA-W series airfoils manufactured by FOI of Sweden, RisΦ-A-XXX series airfoils developed by Denmark, DU series airfoils developed by Delft University, and so on [2]. Common VAWT airfoils refer to NACA series, among which airfoil l0018 is widely used in SB-VAWT due to its better wind energy utilization coefficients. Researchers have great interests in the airfoils comparative analysis and selection. In 2008, Canadian researchers found that airfoils which are suitable for HAWT are not necessarily suitable for

VAWT [3]. Zhang et al. analyzed six different kinds of airfoils including NACA, FFA, and FX series and found that the maximum lift coefficient and the maximum lift-drag ratio of FFA series airfoils which are more suitable for SB-VAWT working environment are better than those of the NACA series airfoils [4]. Liao et al. researched the aerodynamic performance of small SB-VAWT based on different airfoils [5]. In 2012, Mohamed analyzed the performance investigation of VAWT using new airfoil shapes [6]. Xu et al. used nonsymmetrical airfoils DU06-W-200 as the research object to investigate the influence of installation on the performance of SB-VAWT [7]. Xu et al. analyzed the aerodynamic performance of thickened DU series airfoils [8]. Yang and Li studied an improved VAWT airfoil on the basis of airfoil 4418 of NACA series [9]. In 2016, Jia et al. studied three kinds of DU series airfoils including DU25, DU30, and DU35 and found the influence of relative thickness on aerodynamic performance [10].

Based on the past researches mentioned above, it can be found that the researches on SB-VAWT blade airfoils mainly focus on NACA series, DU series, FFA series, and

FIGURE 1: Three kinds of airfoil.

TABLE 1: Main features of the analyzed rotor.

Denomination	Value
Blade number (N)	3
Blade shape	Straight
Blades airfoil (attended)	NACA0018, S809, S1046
Height (H) [m]	0.5
Radius (R) [m]	0.4
Chord (c) [m]	0.125
Solidity (σ)	0.149
Texture	FRP

FX series. However, there is a lack of research on S series airfoils which is widely used in HAWT. Therefore, in this study, two typical kinds of S series including S1046 and S809 were selected to investigate whether this kind of blade airfoil is suitable for SB-VAWT or not. NACA0018 airfoil was also selected for the comparison study. The aerodynamics characteristics researched in this study included static starting torque coefficient, out power coefficient, and rotational speed performance. The flow fields of three kinds of blade under both static and dynamic conditions were also simulated and analyzed. This study can provide a good reference for the blade airfoil research on SB-VAWT.

2. Model Design

2.1. Airfoils. The cross sections of airfoils NACA0018, S809, and S1046 are shown in Figure 1. NACA0018 and S1046 are symmetrical airfoils, and S809 is an asymmetric airfoil. As is shown in the figure, the leading edge of airfoil S809 is thinner than the other two. However, the middle of airfoil S809 is thicker than the other two. NACA0018 and S1046 are symmetrical airfoils. Both the leading edge and the trailing edge of airfoil NACA0018 are thicker than those of airfoil S1046 and the trailing edge of airfoil S1046 is the inner convergence.

2.2. Main Structural Parameters. According to the theory of hydrodynamics and the design method of VAWT, a kind of small blade SB-VAWT is designed [11–13]. For the experimental validation, the geometry considered in the study is summarized in Table 1 based on the size of experimental segment (1 m × 1 m) of the wind tunnel in the laboratory. The blade is rotating counterclockwise; the angle between blade beam and axis Y is azimuth angle θ . The azimuth angle is shown in Figure 2.

FIGURE 2: Structural parameters of wind turbine.

3. Research Methods

In order to explore the aerodynamic characteristics of SB-VAWT with S series airfoils, numerical simulations and wind tunnel experiments were used in this paper.

3.1. Numerical Simulation. A finite volume CFD solver by ANSYS was used in this work, implementing Reynolds averaged Navier-Stokes equations. Because the cross sections of wind turbine blade are exactly the same, this study adopts two-dimensional model numerical simulation method. The calculation of the structure is simplified. The turbulence model based on the pressure solver is the k - ϵ RNG model. The transport equations for k and ϵ are shown in (1). The pressure velocity coupling is the SIMPLEC algorithm, and the flow is unsteady. The turbulent kinetic energy dissipation rate epsilon, K equation, and the momentum equation are the two-order upwind scheme.

$$\begin{aligned}
 \frac{\partial(\rho k)}{\partial t} + \frac{\partial(\rho k u_i)}{\partial x_i} &= \frac{\partial}{\partial x} \left(\alpha_k \mu_{\text{eff}} \frac{\partial k}{\partial x_j} \right) + G_k + G_b - \rho \epsilon \\
 &\quad - Y_M + S_k, \\
 \frac{\partial(\rho \epsilon)}{\partial t} + \frac{\partial(\rho \epsilon u_i)}{\partial x_i} &= \frac{\partial}{\partial x_j} \left(\alpha_\epsilon \mu_{\text{eff}} \frac{\partial \epsilon}{\partial x_j} \right) \\
 &\quad + C_{1\epsilon} \frac{\epsilon}{k} (G_k + C_{3\epsilon} G_b) \\
 &\quad - G_{2\epsilon} \rho \frac{\epsilon^2}{k} - R.
 \end{aligned} \tag{1}$$

The calculation area of the outside wind turbine is a rectangle as is shown in Figure 3, which is 10 times the width and 15 times the length of the radius of wind turbine. The flow is relatively stable before the wind turbine, and after the wind turbine, the flow field changes a lot, so the position of the wind turbine in the computation domain is far from the exit boundary, thus helping to observe the variation of the flow field behind the wind turbine. The flow from the left entry of the graph is the velocity inlet, with the calculation wind speed being 10 m/s, the right side being the pressure outlet, the rectangular upper and lower sides being stationary wall surfaces, and the blade wall moving on the wall surface. In order to guarantee the accuracy of the calculated results and

FIGURE 3: Computational region diagram and boundary conditions.

TABLE 2: Component of the experimental equipment.

Equipment	Function	Precision
Wind tunnel	Provide a stable source of wind	3%
Model of wind turbine	Experimental model	
Torque sensor	Acquisition data	$\pm 0.2\%$
Torque analyzer	Display the data	
Motor	Provide load, stable model speed	3%
Power supply	Control motor speed	
Computer	Process the data	

control the appropriate calculation time, the grid of VAWT was refined. The grid settings are shown in Figure 4.

In order to prove the independence of the mesh number, the static torque coefficient of wind turbine was studied when the azimuth is 5 degrees. Five different mesh numbers are 73765, 110647, 156971, 200432, and 248956, respectively. The fluid computational domain model is chosen for trial calculation. It clearly appears in Figure 5 that using RNG $k-\epsilon$ as the turbulence model for the model meshed by ANSYS gives unstable solution over a wide range of a number of nodes. When the number of mesh increases from 156971 to 248956, the numerical results are not much different. Taken into consideration, the mesh number selected in this study is 156971.

3.2. Wind Tunnel Experiment. In order to verify the influence of eccentricity on the power characteristics of the SB-VAWT, the experiments were conducted at Northeast Agricultural University using the large-scale low-speed opening wind tunnel which is 9.1 m long and 2.3 m wide, its exit size being 1 m $\times$ 1 m wide, and the wind speed being constant at the exit from 1–20 m/s. The wind tunnel experiment system consisted of a low-speed wind tunnel, an experimental model, a speed torque tester, an induction motor, a frequency converter, and a computer. The system diagrams are shown in Figures 6 and 7 and the function of them is shown in Table 2.

In the experiment, the height of wind turbine center is consistent with that of the wind tunnel exit center. The wind turbine is driven by an induction motor, with its speed controlled by a frequency converter. The speed and torque are detected by the speed torque sensor. The speed torque sensor measuring range is 5 N·m, the accuracy is $\pm 0.2\%$, and the original data sampling interval is 0.1 s. The wind generated in the wind tunnel pushes the blades and applies rotation power

to rotor axis, the rotational power can be transferred to the torque meter, and the rotational speed is measured in real time by the topic sensor. When the experiment is carried out, the signal is converted to the voltage level which is used to acquire the power of the wind turbine using a data program.

4. Results and Discussion

The aerodynamic characteristics of the wind turbine investigated in this study are mainly output power coefficients at different tip speed ratio and static torque coefficients at different azimuth angles for SB-VAWT. The definitions of power coefficient, torque coefficient, and tip speed ratio are shown in the following equation:

$$C_p = \frac{P}{(1/2) \rho A U^3},$$

$$C_M = \frac{M}{(1/2) \rho A U^2 R}, \quad (2)$$

$$\lambda = \frac{V}{U} = \frac{\omega R}{U},$$

where C_p is the power coefficient, P is the power absorbed by a wind turbine, ρ is air density, A is the swept area of the wind turbine relative to the current, U is inflow velocity, C_M is the torque coefficient, M is the torque absorbed by a wind turbine, R is the radius of wind turbine, λ is the tip speed ratio, V is the linear velocity of wind turbine, and ω is the rotation speed of wind turbine.

4.1. Dynamic Characteristics

4.1.1. Power Coefficient. In this paper, numerical simulations and wind tunnel tests were carried out, respectively, to reflect the output characteristics of the SB-VAWT with different airfoils. Figure 8 shows that power coefficients vary with the tip speed ratio when wind speed is 10 m/s. Figure 9 shows the maximum power coefficients of the three kinds of SB-VAWT at different wind speeds.

As shown in Figure 8, for simulation results, when λ is in the range from 0.2 to 0.8, the power coefficients are slowly increasing and the growth rate is low. When λ is in the range from 0.8 to 1.8, the power coefficients are obviously increasing, and the value of power coefficients reaches the maximum when λ is up to 1.8. The power coefficient of SB-VAWT with airfoil S809 is the lowest among the three airfoils. When λ is in the range from 0.2 to 1.0, the power coefficients of the SB-VAWT with airfoil S1046 are much close to NACA0018. When the tip speed ratio is in the range from 1.0 to 2.0, the power coefficient of airfoil S1046 is better than those of S809 and NACA0018. The wind tunnel test results and numerical results are in good agreement with the overall trend, except a bit difference in the value. The reasons for the difference between numerical and experimental results are mainly as below: first, there are no shafts, beams, flanges, and other components in the normal numerical simulation model, and when these factors are taken into account in the experiment, the experimental error cannot be ignored. The

FIGURE 4: Grid mesh of computing model.

FIGURE 5: Grid independent verification.

second is that the fluid field of numerical calculation is large, and the range of the experimental wind field is relatively small, which will produce certain errors.

As can be seen from Figure 9, the maximum power coefficient of SB-VAWT increases with the increasing of wind speed. Under the same wind speed, the order of the power coefficient from high to low is S1046, NACA0018, and S809. When wind speed is 10 m/s, the maximum power coefficient of airfoil S1046 wind turbine is 0.32, which is 6.7% higher than that of NACA0018 and 7.1% higher than that of S809. Therefore, the results of Figures 8 and 9 show that, under the experimental conditions, the output characteristics of the

FIGURE 6: Schematic diagram of experimental system.

S1046 airfoil SB-VAWT are better than those of the other two airfoils.

4.1.2. Dynamic Flow Field. In order to further analyze the influence of blade airfoil selection on the output characteristics for SB-VAWT, the torque characteristics and the flow field of the blade were compared and analyzed.

It can be seen from Figure 8 that under the experiment condition of $U = 10$ m/s the power coefficients of the three airfoils wind turbine reach the maximum value when C_P is up to 1.8 according to the results listed above. The power characteristics of the S1046 airfoil wind turbine are better than the other two. Under the experimental conditions, the torque coefficients of SB-VAWT are different from the azimuth angles when the wind turbine rotates in one circle.

FIGURE 7: Physical diagram of experimental system.

FIGURE 8: Power coefficient.

FIGURE 9: Maximum power coefficient.

FIGURE 10: Torque coefficient at different azimuth angle ($\lambda = 1.8$).

Figure 10 shows the curves of the torque coefficients at different azimuth angles when λ is 1.8. As we can see from Figure 10, the torque coefficients of the SB-VAWT with three airfoils have a peak value and a valley value in a circle. Airfoils S1046 and S809 have the lowest torque coefficient at 35 degrees, and the airfoil NACA0018 has the lowest torque coefficient at 45 degrees. The maximum torque coefficients of the SB-VAWT with airfoils S1046 and S809 are near 100 degrees, and the airfoil NACA0018 is near 115 degrees. In conclusion, the torque characteristics of SB-VAWT with S series airfoils are better than NACA series airfoils, the average value of the torque coefficients of airfoil S1046 is the largest, and the output characteristics is the best.

In order to analyze the reasons for the difference in output aerodynamic characteristics of three airfoils SB-VAWT in detail, velocity and pressure distribution flow charts of the blades with three different airfoils are compared when λ is 1.8 and the azimuth angles of 35 and 100 degrees are selected. The influence of airfoils on the flow field of the blade is shown in Figures 11 and 12.

As is shown in Figure 11, for blade, the SB-VAWTs with airfoils S1046 and NACA0018 have a small range of high pressure zone on the windward side of the leading edge. In comparison, the high pressure zone of SB-VAWT with airfoil S809 is larger and there is a wide range of negative pressure zone on the ventral of the blade. The difference on the pressure between the ventral and the back of the blade could generate more aerodynamic forces, thus driving the forward rotation of the wind turbine. Furthermore, the SB-VAWT with airfoil NACA0018 produces a large vortex at the back of the blade, which leads to the loss of energy and lower output characteristics. For blade (b), a large zone of negative pressure is found in the ventral of blades, where the low value area of S809 is more obvious. Therefore, it generates lower power coefficient. For blade (c), three wind turbines with different airfoils all have vortex in the ventral side, among which NACA0018 is the largest, and the energy loss is also greater

than those of other two turbines. In conclusion, among the SB-VAWTs with three different airfoils, the performance of airfoil S1046 is better in the aspects of the pressure difference between the ventral and back of the blade and the energy utilization, and the torque coefficient is slightly higher than the other two airfoils at 35 degrees.

As can be seen from Figure 12, when the azimuth angle is 100 degrees, the variation of the flow field of the blade is obvious. For blade (a), SB-VAWT with three kinds of airfoils has large pressure zone at the leading edge of the blade, and the vortex appears on the ventral, among which NACA0018 has the largest pressure, causing energy loss, producing a great influence on the output characteristics and leading to the smallest torque coefficient. For blade (b), both NACA0018 and S1046 (b) have vortex. However, the blade of airfoil S809 does not appear. The pressure difference between the ventral and the back of the blade is obvious, so there is a great contribution to the output characteristics of airfoil S809. For blade (c), the pressure difference of three kinds of airfoils is not obvious, so the contribution to the output characteristics is small. Comparing with S809 and S1046, the high pressure area of the blade of S809 is smaller, which causes smaller aerodynamic force, so that the torque is slightly smaller.

4.1.3. Rotational Speed Performance. In order to study the rotational speed characteristics and the starting characteristics of SB-VAWT with different airfoils, the change of rotational speed under different wind speeds was investigated by wind tunnel experiments, and the tested wind speed is 6–10 m/s with the interval of 1 m/s. The steady speed of the SB-VAWT and the time required to reach the steady speed were tested at each wind speed. The speed change curve with different wind speeds is shown in Figure 13. When the wind speed is under 7 m/s, the SB-VAWT with airfoil NACA0018 cannot start, so the wind speed change curves are not given.

As can be seen from Figure 13, the steady speed of three different airfoils wind turbines is on the rise with the increase of wind speed, and the time required to reach a steady rotating speed is increasing gradually. When the wind speed is certain, the steady speed from high to low is followed by S1046, NACA0018, and S809. The time required to reach a steady speed from long to short is followed by S1046, NACA0018, and S809. When the wind speed is 10 m/s, three different wind turbine airfoils steady speeds are the highest. For airfoil S1046, the steady rotational speed is 140 r/min, for NACA0018 is 120 r/min, and for S809 is 45 r/min. When the wind speed is less than or equal to 7 m/s, the SB-VAWT with airfoil NACA0018 cannot start itself, which shows that the starting performance is not good. This is one of the important reasons which restricts the development of current NACA series of SB-VAWT. This problem can be overcome to some extent by using S series airfoils.

4.2. Static Characteristics

4.2.1. Static Torque Coefficient. In order to further study different influence of blade on the starting characteristics of SB-VAWT with different airfoils, the static torque of SB-VAWT at different wind speeds was investigated by numerical

FIGURE 11: Flow fields around blade with different airfoils ($\theta = 35^\circ$).

FIGURE 12: Flow fields around blade with different airfoils ($\theta = 100^\circ$).

FIGURE 13: Rotational speed under different wind speeds.

simulation and wind tunnel experiments. Figure 14 shows the simulation and tests results of the curves of static torque coefficients (C_{ts}) change with the azimuth angles when the wind speed is 10 m/s.

As can be seen from Figure 14, concerning simulation results, the torque coefficient of SB-VAWT with three different airfoils in a rotation period namely 0 to 120 degrees shows two peaks and a trough. The value of the static torque coefficient reaches the maximum when the azimuth angle is 15 degrees, the static torque coefficient of SB-VAWT with airfoil S809 is 0.062, airfoil NACA0018 is 0.054, and airfoil S1046 is 0.049. When the azimuth angle is 45 degrees, the minimum value reaches at this moment, and the static torque coefficient of airfoil S809 wind turbine is -0.0075 , airfoil

NACA0018 is -0.0014 , and airfoil S1046 is -0.0091 . The average static torque coefficient of SB-VAWT with airfoil S809 is 0.032, the highest among the three airfoils. For experimental results, the results of wind tunnel experiments and numerical simulations have good consistency in the overall trend except being slightly lower in value, because in the process of torque transmission, there will be some friction loss between the flange and the beam, and the influence of the experimental error. In general, the asymmetric airfoil S809 has bigger static torque coefficients comparing with the other two kinds of symmetric airfoils.

4.2.2. Static Flow Field. In order to analyze the reason of the difference of starting characteristics in SB-VAWT with

FIGURE 14: Static torque coefficients ($U = 10 \text{ m/s}$).

three kinds of airfoils in detail, we selected streamlines and pressure distribution of three kinds of airfoil wind turbine at the azimuth angle of 15 and 45 degrees which are shown in Figures 15 and 16. The influence of airfoils on the flow fields of the blade was analyzed.

As can be seen in Figure 15, for blade (a), the force acting on the blades of the three airfoils is mainly at the leading edge. The negative pressure zone is found at the ventral of the blade, while the positive pressure zone is concentrated at the leading edge of the windward point. The aerodynamic force of the pressure difference causes the wind turbine to rotate counter-clockwise. At the same time, the vortex appears at the trailing edge of airfoils S809 and S1046, which makes a certain energy loss on the upper blade. For blade (b), the trailing edge of the blade of the three airfoils is windward; the positive pressure zone is about 1/2 of the blade size; the back of the blade generates low pressure area; the pressure difference is more obvious than the upper blade; the aerodynamic force is greater, which is the main reason for starting coefficients of the SB-VAWT under this angle. The back of the three airfoils produces varying degrees of vortex, which also results in energy loss. The negative pressure zone of the blade in airfoil S1046 is larger than those of S809 and NACA0018, but its aerodynamic force is relatively small, which is an important coefficient for a minimum starting torque at 15 degrees. For blade (c), the positive pressure zone of three kinds of airfoil appears at the trailing edge of the blade, and the pressure difference is small, so the aerodynamic force is slightly smaller. In general, when the azimuth angle is 15 degrees, the high pressure area of non-symmetrical airfoil S809 is bigger than those of the other two kinds of airfoils. The aerodynamic force is relatively larger, and the starting torque is bigger, so the starting performance is better than those of the other two kinds of SB-VAWT.

As can be seen in Figure 16, for blade (a), three airfoils have a large positive pressure area at the trailing edge of the blade, while the negative pressure zone which generates

from the ventral of airfoil has obvious difference. The negative pressure zone around airfoil S809 accounts for 2/3 of the leeward side which results in great vortex and the energy loss is larger. For blade (b), the flow field of the three airfoils is basically the same. The pressure difference between the windward and leeward surfaces of the trailing edge is found, but the torque is small because of the aerodynamic position. For blade (c), when the positive pressure area is larger, the leeward vortex appears on the different positions of the three airfoils. The vortex appearing in the airfoil NACA0018 is smaller comparing with the other two airfoils. We found that the vortex range of the ventral side of blade S1046 is the largest and the energy loss is the largest, so the torque coefficient is the lowest at this azimuth angle. Overall, when the azimuth angle is 45 degrees, the pressure difference between ventral and the back of the three airfoils is small. The aerodynamic force is small so that the starting torque is small, which leads to the appearance of trough.

5. Conclusions

The main conclusions obtained under the condition of this study are as follows:

- (1) For dynamic characteristics, the power coefficient of the wind turbine model with airfoil S1046 is higher than those of the model with S809 and NACA0018 airfoils. Furthermore, the rotational speed performance of the test model with airfoil S1046 is also better than the other two kinds of airfoils.
- (2) For static characteristics, the static torque coefficient of SB-VAWT with airfoil S809 is higher than the S1046 and NACA0018. The asymmetry of the blade allows the turbine to obtain the forward torque that causes the turbine to rotate under the wide azimuth angle. Therefore, it can be said that the S series airfoils can

FIGURE 15: Flow fields around blade with different airfoils.

FIGURE 16: Flow fields around blade with different airfoils ($\theta = 45^\circ$).

be used for SB-VAWT and as the most suitable airfoil for SB-VAWT, the S series airfoil is worth researching deeply.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

This research is sponsored by the Project 51576037 supported by National Natural Science Foundation of China (NSFC) and Project 12541012 supported by Science and Technology Research Project of Heilongjiang Provincial Department of Education. The authors give thanks to their supporters.

References

- [1] Y. Li, Y. Zheng, S. Zhao et al., "A review on aerodynamic characteristics of straight-bladed vertical axis wind turbine," *Acta Aerodynamica Sinica*, vol. 35, no. 6, pp. 368–382, 2017.
- [2] P. Chen, M.-Y. Du, and J.-P. Liu, "Development status and key aerodynamic problems of wind turbine dedicated airfoils," *Power System and Clean Energy*, vol. 25, no. 2, pp. 36–42, 2009.
- [3] M. Islam, M. R. Amin, R. Cariveau, and A. Fartaj, "Designing straight-bladed vertical axis wind turbine using the cascade theory," in *12th AIAA/ISSMO Multidisciplinary Analysis and Optimization Conference*, American Institute of Aeronautics and Astronautics, Reston, Va, USA, 2008.
- [4] G.-Y. Zhang, W.-M. Feng, and C.-L. Liu, "Numerical simulation on the aerodynamic performance of six kinds of aerofoil of wind turbine blade," in *Renewable Energy Resources*, vol. 2, 2009.
- [5] S.-X. Liao, C. Li, J.-B. Nie et al., "The analysis of aerodynamic performance for small H type VAWT based on different airfoils," in *Machine Design and Research*, vol. 3, 2011.
- [6] M. H. Mohamed, "Performance investigation of H-rotor Darrieus turbine with new airfoil shapes," *Energy*, vol. 47, no. 1, pp. 522–530, 2012.
- [7] Z.-H. Xu, Y. Zhang, B. Yang et al., "Effects of installation method of asymmetric airfoils on performance of H-type wind turbine," *Acta Energy Solaris Sinica*, vol. 34, no. 6, pp. 933–937, 2013.
- [8] H. Xu, H. Yang, and C. Liu, "Numerical value analysis on aerodynamic performance of DU series airfoils with thickened trailing edge," *Transactions of the Chinese Society of Agricultural Engineering*, vol. 17, 2014.
- [9] C.-X. Yang and S.-T. Li, "Study of post stalled airfoil of a H-type vertical axis wind turbine," *Journal of Lanzhou University of Technology*, vol. 41, no. 1, pp. 51–54, 2015.
- [10] Y.-L. Jia, P. Peng, Q.-J. Li et al., "Effects of relative thickness of airfoil on aerodynamics of DU airfoil," *Machinery Design & Manufacture*, vol. 3, 2016.
- [11] F. Feng, Y. Li, L. Chen, W. Tian, and Y. Zhang, "A simulation and experimental research on aerodynamic characteristics of combined type vertical axis wind turbine," *Acta Energiæ Solaris Sinica*, vol. 35, no. 5, pp. 855–860, 2014.
- [12] I. Paraschivoiu, C. Li et al., *The vertical axis wind turbine principle and design*, Shanghai Science and Technology Press, 2013.
- [13] Q.-B. He, *Study on calculation of structure and aerodynamic characteristics for vertical axis wind turbine with double-layer retractile blades*, Northeast Agricultural University, Harbin, China, 2015.