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Numerical investigation on the flow and power of small-sized multi-bladed straight Darrieus wind turbine

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Abstract: Straight Darrieus wind turbine has attractive characteristics such as the ability to accept wind from random direction and easy installation and maintenance. But its aerodynamic performance is very complicated, especially for the existence of dynamic stall. How to get better aerodynamic performance arouses lots of interests in the design procedure of a straight Darrieus wind turbine. In this paper, mainly the effects of number of blades and tip speed ratio are discussed. Based on the numerical investigation, an assumed asymmetric straight Darrieus wind turbine is proposed to improve the averaged power coefficient. As to the numerical method, the flow around the turbine is simulated by solving the 2D unsteady Navier-Stokes equation combined with continuous equation. The time marching method on a body-fitted coordinate system based on MAC (Marker-and-Cell) method is used. O-type grid is generated for the whole calculation domain. The characteristics of tangential and normal force are discussed related with dynamic stall of the blade. Averaged power coefficient per period of rotating is calculated to evaluate the eligibility of the turbine.

Key words: Small-sized, Straight Darrieus wind turbine, Multi-bladed, Power coefficient
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INTRODUCTION

Wind turbines are now widely set up all over the world. Mostly they are divided into two kinds: horizontal axis wind turbine (HAWT) and vertical axis wind turbine (VAWT). Compared with HAWTs, VAWTs have their obvious advantages. They can accept wind from any direction without mechanisms to turn the blades into the wind. Straight Darrieus turbine is a typical kind of VAWT. It is simple and easy to be constructed, but also known for its complex aerodynamics with dynamic stall phenomenon. The authors (Jiang and Doi, 2005; Jiang *et al*., 2004; Jiang, 2005) studied the dynamic stall phenomenon, single-bladed wind turbine performance and principal parameters such as mounting position of blade, radius of turbine, tip speed ratio and number of blades. Eriksson *et al*.(2007) and Islam *et al*.(2007) reviewed aerodynamic models for straight Darrieus wind turbines especially for the computational model of momentum, vortex and cascade model in the past decades. Ishimatsu *et al*.(1995) studied solidity and tip speed ratio of a Darrieus turbine by 2D simulation. When concerning the solidity, they studied the one blade and two blades cases. But the turbulence model is not included. Horiuchi and Seki (2003) mainly discussed the flow passed the wind turbine and the distance downstream where the flow restored its natural wind velocity. This may be helpful for setting up a wind turbine farm. Paraschivoiu (2002) mentioned consideration of the design parameters. However more detailed discussion based on flow analysis is needed for the more efficient design of straight Darrieus turbine. Although blade section is also an

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important parameter, selection of blade section is not discussed in detail here as most of the set-up turbines adopted NACA-series sections. As the research of authors is initially validated with experiment data (Oler *et al.*, 1983), NACA-0015 section is selected for the present study.

In this paper, the effects of number of blades including solidity and wake effect, and tip speed ratio are discussed. Based on the numerical investigation, an assumed asymmetric straight Darrieus wind turbine is proposed to improve the averaged power coefficient.

NUMERICAL METHOD

The outline of the motion of 2-bladed straight Darrieus turbine is shown in Fig.1. U_∞ is an oncoming velocity on the outer boundary of the computational domain; c is chord length of the blade of a Darrieus turbine; ω is angular velocity; r is radius of the blade; $\beta=\omega r/U_\infty$ is tip speed ratio and θ is the instant rotating angle of blade from the initial position based on Blade 1 of the turbine. Reynolds number is defined as $Re=U_\infty c/\nu$, where ν is kinematic viscosity.

The governing equations for the flow around the wind turbine are given by the non-dimensional Navier-Stokes equation and continuity equation. The normalization is based on the oncoming velocity and the chord length of blade.

$$\begin{cases} \frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=-\frac{\partial p}{\partial x}+\frac{1}{Re}\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right)+R_x, \\ \frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}=-\frac{\partial p}{\partial y}+\frac{1}{Re}\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}\right)+R_y, \end{cases} \tag{1}$$

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0. \tag{2}$$

here, x and y are the non-dimensional coordinates in the fixed coordinate system, u and v are the corresponding non-dimensional velocity components towards x and y directions, p is the non-dimensional pressure at the position (x,y), t is the nondimensionalized time.

In the Navier-Stokes equation as shown in Eq.(1), R_x and R_y are Baldwin-Lomax-Smagorinsky (BLS) (Camelli, and Löhner, 2002) Reynolds stress components. They can be expressed as follows:

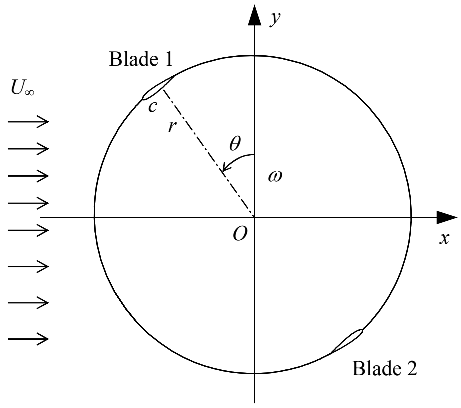


Fig.1 Outline of 2-bladed rotating straight Darrieus wind turbine

$$\begin{cases} R_x=\{\nu_t(u_x+u_x)\}_x+\{\nu_t(u_y+v_x)\}_y, \\ R_y=\{\nu_t(v_x+u_y)\}_x+\{\nu_t(v_y+v_x)\}_y, \end{cases} \tag{3}$$

here ν_t is BLS eddy viscosity. The BLS turbulence model is discussed in former papers of authors (Jiang and Doi, 2005; Jiang *et al.*, 2004; Jiang, 2005). Concerning the calculation of both single-bladed and multi-bladed wind turbines, except the areas near each blade before flow separation where Baldwin-Lomax model (B-L model) is applied, SGS (Sub-Grid Scale) turbulence model is applied.

In the present computation, both oncoming velocity U_∞ on the outer boundary of the domain and the rotating angle velocity ω have an accelerating stage within the non-dimensional time t=1.0. No-slip boundary condition is imposed on the blade. In order to investigate the aerodynamic performance of the straight Darrieus turbine, normal force coefficient C_N, tangential force coefficient C_T, torque coefficient C_{T_q} and power coefficient C_P are selected. $\overline{C}_P$ and $\overline{C}_{T_q}$ are time-averaged power and torque coefficients for one period.

$$C_N=N/(\rho U_\infty{}^2 c/2),\ \ C_T=T/(\rho U_\infty{}^2 c/2), \tag{4}$$

$$C_{T_q}=T_q/(\rho U_\infty^2 r^2),\ \ \overline{C}_{T_q}=\int_0^{2\pi} T_q \mathrm{d}\theta/(2\pi\rho U_\infty^2 r^2), \tag{5}$$

$$C_P=T_q\omega/(\rho U_\infty^3 r),\ \overline{C}_P=\frac{\int_0^{2\pi} T_q\omega \mathrm{d}\theta}{2\pi\rho U_\infty^3 r}=\frac{\int_0^{T_0} T_q\omega^2 \mathrm{d}\tau}{2\pi\rho U_\infty^3 r}. \tag{6}$$

here C_{T_q} is the torque coefficient, T and N are the tangential and normal force. T_0 is the period of the rotating blade.

NUMERICAL CALCULATION AND INTERPRETATION

Number of blades

As most of setup VAWTs have 2 or 3 blades, the number of blades of straight Darrieus turbine is firstly investigated. For single-bladed case, a turbine with Re=26800, r/c=4.0 running at tip speed ratio β=5.1 gets the best-averaged power coefficient, the corresponding angular velocity ω=1.275. Cases with Re=26800, r/c=4.0, ω=1.275 and different number of blades N=1, 2 and 3 respectively are investigated.

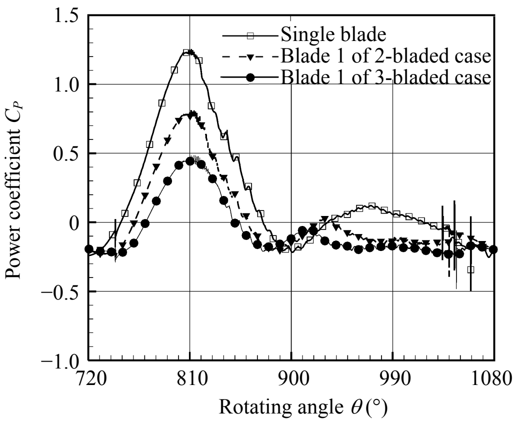


Fig.2 Power coefficient versus rotating angle for single and Blade 1 of multi-bladed turbines (Re=26800, β=5.1, r/c=4.0)

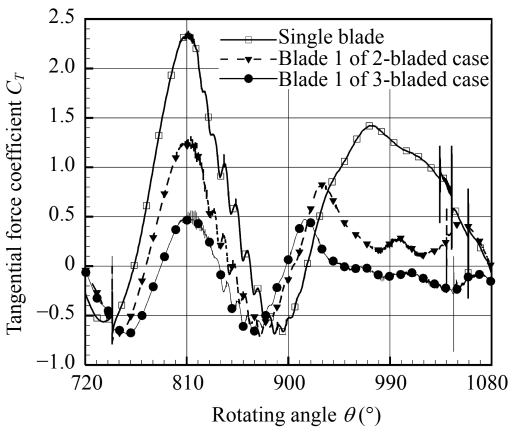


Fig.3 Tangential force coefficients for single-bladed turbine and Blade 1 of multi-bladed turbines (Re=26800, β=5.1, r/c=4.0)

Power coefficients for single-bladed turbine and Blade 1 of the 2-bladed and 3-bladed turbines are shown in Fig.2. It is noticed that the magnitude of power coefficient of Blade 1 of multi-bladed cases decreases when the number of blades increases near the position around θ=180°. At the position near θ=990°, the tendency is similar. At position θ=811°, it is noticed that all the power coefficients of three cases reach the peak, while the magnitude differs much from each other. The tangential force coefficients and normal force coefficients are demonstrated in Figs.3 and 4. From the time history of tangential force coefficients shown in Fig.3, which contributes to the output power coefficients, it is clear that when the number of blade increases, the magnitude of tangential force decreases obviously if the radius and chord length of the blade are fixed. By studying on the streamlines near the blade of single-bladed turbine and Blade 1 of multi-bladed cases, it is noticed that the oncoming flow for the blade of multi-bladed turbine is affected especially in the downwind area. The total averaged output power coefficients are shown in Table 1.

From Table 1, the single-bladed turbine at β=5.1, r/c=4.0, Re=26800 has higher averaged power coe-

Table 1 Averaged power coefficients of the multi-bladed turbines (β=5.1, r/c=4.0, Re=26800)

Type of turbine	Solidity σ	Averaged power coefficient $\bar{C}_P$
Single-bladed	0.125	0.194
2-bladed	0.250	0.064
3-bladed	0.375	−0.2026

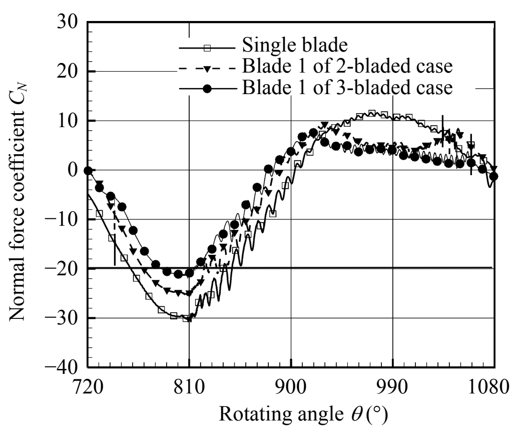


Fig.4 Normal force coefficients for single-bladed turbine and Blade 1 of multi-bladed turbines (Re=26800, β=5.1, r/c=4.0)

fficient than 2-bladed turbine and 3-bladed turbine. For a 3-bladed turbine, the output averaged power coefficient is even negative, that is to say, the 3-bladed turbine cannot generate power under this condition. This result seems to be absurd. In order to characterize this phenomenon, the solidity σ is introduced:

$$\sigma = nc/(2r), \tag{7}$$

where n is the numbers of blades, c is the chord length of each blade, r is the radius of the turbine. The solidities of three cases are included in Table 1 too.

As shown in Table 1, it is noticed that for the 2-bladed straight Darrieus wind turbine with the same chord length, radius and rotating at the same angular velocity as the single-bladed straight Darrieus wind turbine, the averaged power coefficient decreases from 0.194 to 0.064. As the solidities are different, it is still not so clear what kind of contribution will be brought by increasing the number of blades without increasing solidity to the output averaged power coefficient of the turbine. In order to explore it, another assumed 2-bladed straight Darrieus wind turbine with the same angular velocity ω=1.275, solidity σ=0.125, radius r, but half chord length c with corresponding Re=13400 and r/c=8.0 is investigated. The parameters for the focused three cases and resultant averaged power coefficients are collected in Table 2. Parameters are nondimensionalized by the chord length and oncoming velocity of turbine with case code SDWT 1. The time history of power coefficients of SDWT 1 and Blade 1 of SDWT 3 is shown in Fig.5.

As the chord lengths of SDWT 1 and SDWT 3 are different, it may be easier to use the tangential force coefficient, which mainly contributes to the output power coefficient, to characterize the wake effect. Fig.6 shows the time history of the tangential force coefficient of SDWT 1 and Blade 1 of SDWT 3. It is clear that in the range from θ=930° to θ=1020°, the tangential force coefficient is decreased due to the wake effect while others are very similar.

Tip speed ratio

For the single-bladed case with Re=26800, r/c=4.0, the turbine gets a maximum averaged power coefficient at β=5.1. As noticed, for a 2-bladed turbine with the same Reynolds number and r/c, it gets a lower averaged power coefficient of 0.064. For the 2-bladed case, its solidity is σ=0.250, higher than single-bladed case; the relative tip speed ratio where the maximum averaged power coefficient is obtained

Table 2 Wake effect investigation of straight Darrieus wind turbine with NACA0015 blade(s)

Case code	Chord length (c)	Radius of turbine (r)	Oncoming velocity (U_∞)	Tip speed ratio (β)	Number of blades (n)	Solidity (σ)	Re by c and U_∞	Averaged power coefficient $\bar{C}_P$
SDWT 1	1	4	1	5.1	1	0.125	26800	0.194
SDWT 2	1	4	1	5.1	2	0.250	26800	0.064
SDWT 3	0.5	4	1	5.1	2	0.125	13400	0.130

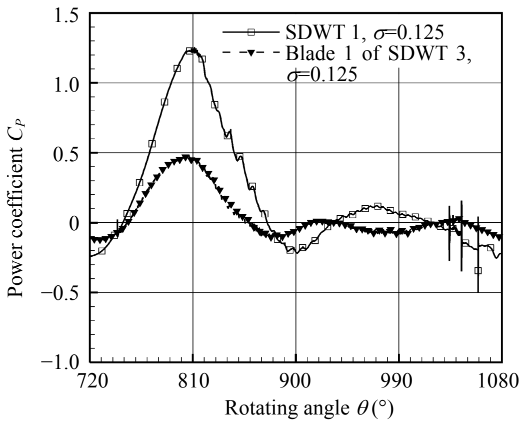


Fig.5 Power coefficient of SDWT 1 and Blade 1 of SDWT 3 versus rotating angle at Re=26800, ω=1.275, r/c=4.0

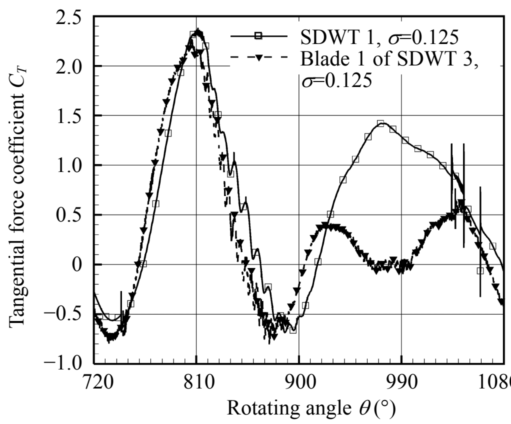


Fig.6 Tangential force coefficient of SDWT 1 and Blade 1 of SDWT 3 versus rotating angle at Re=26800, ω=1.275, r/c=4.0

depending on solidity is investigated. Three cases with β=2.0, 3.5 and 5.1 are investigated, the averaged power coefficient are shown in Table 3. From the calculation of the three cases, it is noticed that running at tip speed ratio β=3.5 will get a highest averaged power coefficient of 0.179. The averaged power coefficients for different tip speed ratios of both single-bladed straight Darrieus wind turbine with solidity of 0.125 and 2-bladed one with solidity of 0.250 are shown in Fig.7. It is concluded that when the solidity increases, the tip speed ratio where the maximum averaged power coefficient obtained will decrease.

From the analysis of dependency on solidity and tip speed ratio, there are two direct ways to improve aerodynamic performance of the 2-bladed straight Darrieus wind turbine with Re=26800, σ=0.250 and running at β=5.1 by decreasing either solidity or tip speed ratio. Decreasing the solidity from 0.250 to 0.125 will get a higher averaged power coefficient as 0.130. Decreasing the tip speed ratio from 5.1 to 3.5 will get even a better one as 0.179. As to an installed turbine, decreasing the tip speed ratio is more effective and practical. What is more, as small-sized straight Darrieus wind turbines are designed to be set up on roofs and gardens instead of rural area, running at a lower tip speed ratio will be safer, too. During the design procedure, careful and overall consideration of size of turbine blades is also necessary according to both space consideration and better performance.

Asymmetric 2-bladed straight Darrieus wind turbine

As discussed above, even with same solidity as 0.125 and rotating at the same tip speed ratio of 5.1, 2-bladed straight Darrieus wind turbine has a lower averaged power coefficient compared with single-bladed one. It is concluded that wake effect holds back the aerodynamic performance. From above, the averaged power coefficient of 2-bladed straight Darrieus wind turbine with solidity as 0.250 running at β=3.5 will obtain best output averaged power coefficient as 0.179. As conventional straight Darrieus wind turbines are all with the same radius, the after blade is running by tracking the same orbit of the frontal blade, so we try to reduce the wake effect by change the radius of each blade. The assumed turbine is described as an asymmetric straight Darrieus wind turbine. Turbine 2B04B is an asymmetric straight Darrieus wind turbine described in Table 4. Turbine 2B22C is assumed to have an almost same solidity as 2B04B for comparison.

Table 3 Averaged power coefficient for 2-bladed SDWT rotating at different β with Re=26800, r/c=4.0, σ=0.250

Tip speed ratio β	Averaged power coefficient $\overline{C}_P$
2.0	−0.023
3.5	0.179
5.1	0.064

For the asymmetric straight Darrieus wind turbine, because the radius for each blade is different, when the torque coefficient and power coefficient are considered, a non-dimensional procedure based on each blade itself is necessary. For a 2-bladed asymmetric straight Darrieus wind turbine with radius r_1 and r_2, the torque coefficient and power coefficient and corresponding averaged ones are dealt with in the following way:

$$C_{T_q} = C_{T_{q_1}} + C_{T_{q_2}} = \frac{T_{q_1}}{\rho U_\infty^2 r_1^2} + \frac{T_{q_2}}{\rho U_\infty^2 r_2^2}, \tag{8}$$

$$C_P = C_{P_1} + C_{P_2} = \frac{T_{q_1}\omega}{\rho U_\infty{}^3 r_1} + \frac{T_{q_2}\omega}{\rho U_\infty{}^3 r_2}, \tag{9}$$

$$\overline{C}_{T_q} = \overline{C}_{T_{q_1}} + \overline{C}_{T_{q_2}} = \frac{\int_0^{2\pi} T_{q_1}\mathrm{d}\theta}{2\pi\rho U_\infty{}^2 r_1{}^2} + \frac{\int_0^{2\pi} T_{q_2}\mathrm{d}\theta}{2\pi\rho U_\infty{}^2 r_2{}^2}, \tag{10}$$

$$\begin{aligned}\overline{C}_P = \overline{C}_{P_1} + \overline{C}_{P_2} &= \frac{\int_0^{2\pi} T_{q_1}\omega\mathrm{d}\theta}{2\pi\rho U_\infty^3 r_1} + \frac{\int_0^{2\pi} T_{q_2}\omega\mathrm{d}\theta}{2\pi\rho U_\infty^3 r_2} \\ &= \frac{\int_0^{T_0} T_{q_1}\omega^2\mathrm{d}\tau}{2\pi\rho U_\infty^3 r_1} + \frac{\int_0^{T_0} T_{q_2}\omega^2\mathrm{d}\tau}{2\pi\rho U_\infty^3 r_2}.\end{aligned} \tag{11}$$

Table 4 Parameters for investigation of asymmetric straight Darrieus wind turbine

Case code	Blade section	Chord length (c)	Radius of Blade 1 (r_1)	Radius of turbine (r_2)	Oncoming velocity (U_∞)	Angular velocity (ω)	Number of blades (n)	Solidity (σ)	Re by c and U_∞
2B00A	NACA 0015	1	4	4	4	0.875	2	0. 2500	26800
2B04B	NACA 0015	1	4	4.4	4	0.875	2	0.2386	26800
2B22C	NACA 0015	1	4.2	4.2	4.2	0.875	2	0.2381	26800

The time history of power coefficient for each blade of the focused turbines is shown in Fig.8. From Fig.8, the amplitudes of power coefficient for each blade of symmetric straight Darrieus wind turbine 2B00A and 2B22C are almost the same in the third period. So the analysis below will focus on the third period. The averaged power coefficients for each blade of straight Darrieus wind turbines 2B00A, 2B04B and 2B22C concerned are listed in Table 5. From Table 5, it is noticed that the asymmetric turbine 2B04B obtains the highest averaged power coefficient. Compared with turbine 2B00A, the averaged power coefficient has an augment of 8.7%. Compared with turbine 2B22C, the averaged power coefficient also has an augment of 7.7%. As 2B04B is asymmetric, comparison of averaged power coefficient for each blade is necessary. To make it clearer, the time histories of each blade for the three turbines in the third period are shown in Figs.9 and 10. Now that the wake effect is more severe when the blade is in downwind half of rotation, mainly the performance of blade in the downwind half of rotation is focused.

Table 5 Averaged power coefficient for straight Darrieus wind turbines with *Re*=26800, rotating at ω=0.875

Turbine code	$\bar{C}_{P_1}$ of Blade 1	$\bar{C}_{P_2}$ of Blade 2	$\bar{C}_P$ total
2B00A	0.0900	0.0892	0.1792
2B04B	0.0926	0.1022	0.1948
2B22C	0.0903	0.0905	0.1808

Fig.9 is the time history of power coefficients of Blade 1 of each straight Darrieus wind turbine in the third period. For the downwind half of rotation of Blade 1, it is noticed for most part, the power coefficient of Blade 1 for straight Darrieus wind turbine 2B04B is a bit higher than that of 2B00A. Flow patterns for Blade 1 of straight Darrieus wind 2B04B and 2B00A are analyzed in detail. Pressure distributions with streamlines around Blade 1 of straight Darrieus wind turbine 2B00A and 2B04B at position θ=1035° are shown in Figs.11a and 11b respectively. The streamlines are also observed from Blade 1. By investigation of the flow patterns shown in Figs.11a and 11b, it is noticed that there are flow separations from the trailing edge of both blades, but for Blade 1 of turbine 2B04B, the flow separation is a bit weakened. Resultantly the power coefficient is a bit improved. The wake effect from the upwind blade is partly improved.

Fig.10 is the time history of power coefficients of the third period of Blade 2 of each straight Darrieus wind turbine. As the definition of rotating angle θ is based on Blade 1, there is a half period of phase difference for Blade 2. From Fig.10, it is noticed that during the range from θ=720° to θ=900°, the time histories of power coefficient for Blade 2 of straight Darrieus wind turbines 2B04B and 2B22C are similar. During the range from θ=800° to θ=900°, power coefficient of Blade 2 of straight Darrieus wind turbine 2B00A is smaller than the power coefficients of turbine 2B04B and 2B22C. Flow patterns for Blade 2 of straight Darrieus wind 2B04B and 2B00A are analyzed in detail. Figs.12a and 12b are the local pressure distributions with streamlines for Blade 2 of turbine 2B00A and 2B04B at position θ=847°. The streamlines are observed on Blade 2. At this position, Blade 2 is in the downwind half and in the wake of Blade 1. It is also noticed that the flow separation from the outer surface of Blade 2 is improved for Turbine 2B04B compared with Turbine 2B00A. Resultantly, the wake effect from Blade 1 to Blade 2 is weakened for straight Darrieus wind turbine 2B04B.

CONCLUSION

In this paper, mainly the effects of number of blades including solidity and wake effect, and tip speed ratio are discussed. Wake effects will hold back the aerodynamic performance of multi-bladed turbine especially when the blade is in the downwind half of rotation. For the straight Darrieus wind turbine with higher solidity, the corresponding tip speed ratio where the averaged power coefficient of turbine obtained is smaller than the cases of low solidity. Based on the numerical investigation, an assumed asymmetric 2-bladed straight Darrieus wind turbine is proposed to improve the averaged power coefficient. It is proved that the wake effects for both blades are weakened due to the arrangement of different radius from numerical investigation.

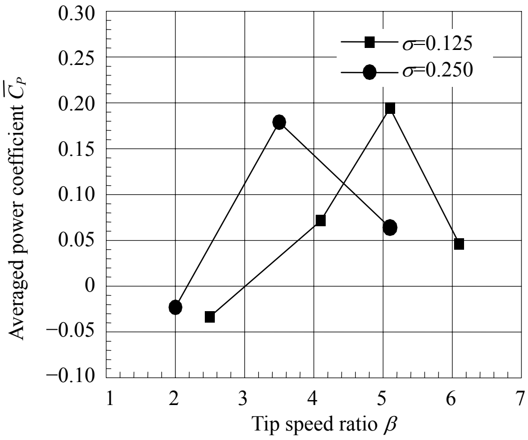


Fig.7 Averaged power coefficient versus tip speed ratio with *Re*=26800, *r*/*c*=4.0 for SDWTs with different solidities

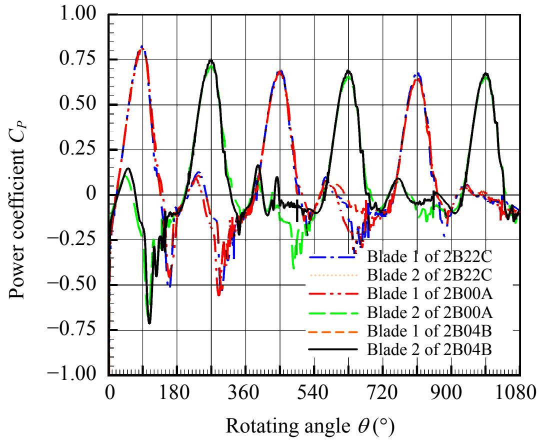


Fig.8 Power coefficient for each blade of SDWTs 2B00A, 2B04B and 2B22C versus tip speed ratio with *Re*=26800, *ω*=0.875

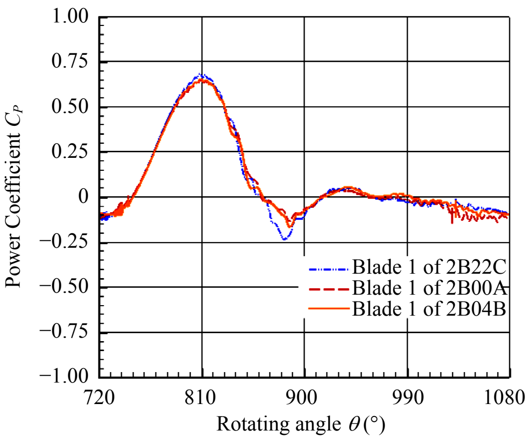


Fig.9 Power coefficient for Blade 1 of SDWTs 2B00A, 2B04B and 2B22C versus rotating angle with *Re*=26800, *ω*=0.875

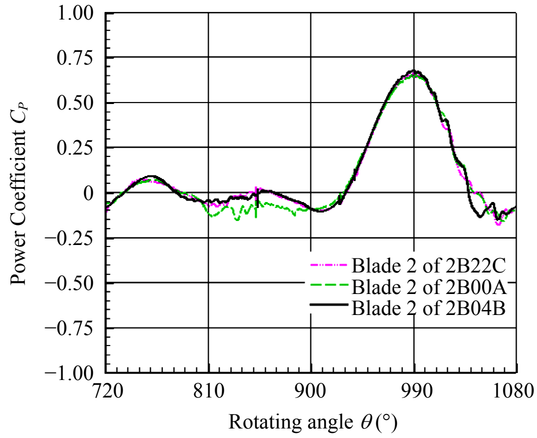
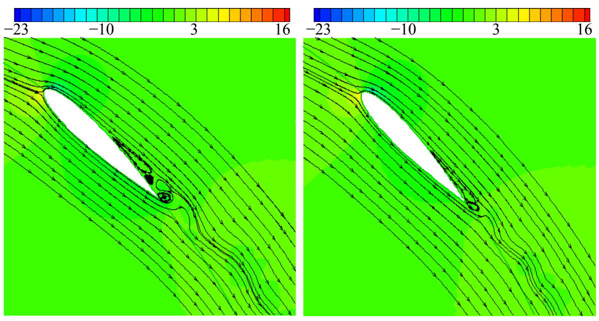
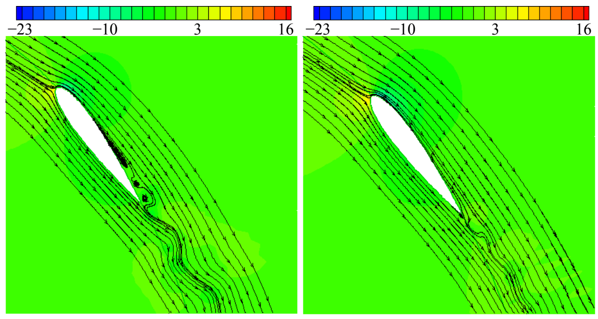


Fig.10 Power coefficient for Blade 2 of SDWTs 2B00A, 2B04B and 2B22C versus rotating angle with *Re*=26800, *ω*=0.875



(a) (b)

Fig.11 Pressure distribution with streamlines around Blade 1 of 2-bladed SDWT 2B00A (a) and 2B04B (b) at position *θ*=1035°, *Re*=26800, *ω*=0.875, r_1/c=4.0 in blade-fixed coordinate system



(a) (b)

Fig.12 Pressure distribution with streamlines around Blade 2 of 2-bladed SDWT 2B00A (a) and 2B04B (b) at position *θ*=847°, *Re*=26800, *ω*=0.875, r_2/c=4.0 in blade-fixed coordinate system

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