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Efficiency of Different Spaces between the Blade and Hood for Vertical Axis Wind Turbine

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ABSTRACT

This paper presents the efficiency of three kinds of vertical axis wind turbines with different spaces between the blade and hood by using three-dimensional numerical simulation. The IDDES method with SST *k-w* turbulence was used to predict the flow field around those turbines under the inlet velocity of 25m • s^{-1}. Results show that mean torque provided by the turbine with the space width of 0.01m is 4.5% more than that of 0.02m and is 14.8% more than that of 0.03m. Furthermore, the pressure, velocity vectors and vorticity around the turbine were investigated to analyze the phenomenon qualitatively.

1. INTRODUCTION

Wind energy, a clean and pollution-free renewable energy, is a kind of unconventional energy with large-scale industry development Fogelbergm (2017). The utilization of wind energy has received a lot of attentions. Generally, a convenient way to utilize the wind energy is to convert it into mechanical energy by turbines. There are two kinds of turbines in the mainstream. However, parallel with the horizontal axis wind turbine (HAWT), the vertical axis wind turbine (VAWT) maintains a lower starting wind speed and less aerodynamic noise, which makes it to be widely used all over the world. Therefore, considerable researches, such as Lee (2015), Liu (2015), etcetera, aiming at increasing the efficiency of turbines by optimizing the form of the blades. Fans of the VAWT are generally exposed in the air when it is working. However, turbines need to be protected by hoods when working in some special occasions, for instance, under extreme weather conditions. So the form of above hoods will be another parameter that impacts on the efficiency of turbines. Besides, there would be a little space between the tip of the blade and the hood. In the present work, the efficiency of three different spaces between the blade and hood for a kind of VAWT has been analyzed by using numerical method.

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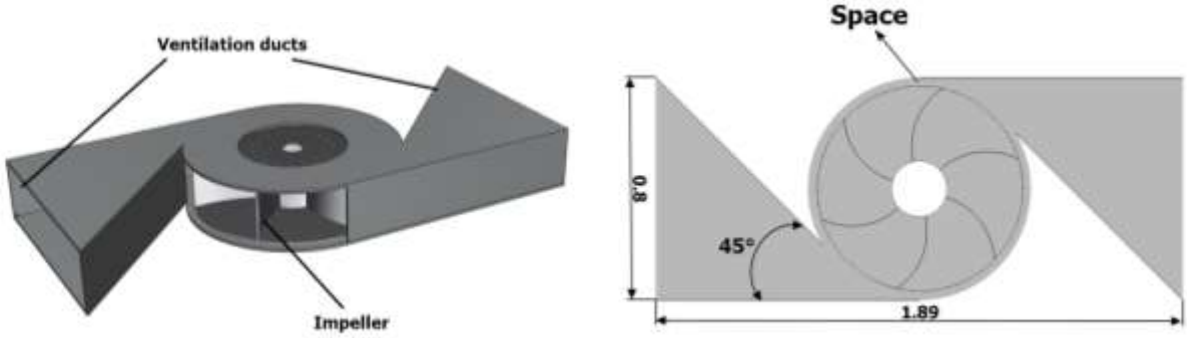
2. METHODOLOGY

2.1 Physical Models

A three-dimensional model of VAWT with six blades and two ventilation ducts on hoods which guides the inflows and outflows is shown in Fig 1(a). The sectional dimension of the numerical model and the sketch of the space analyzed in the present are shown in Fig 1(b). In addition, the space with the width of 0.01m (Case 1), 0.02m (Case 2) and 0.03m (Case 3) were studied in the present work.



(a) (b)

Fig. 1 Model of the turbine: (a) three-dimensional; (b) sectional, unit: m

2.2 Method of Simulation

The governing equations of the flow fields include continuity, motion and energy equations. These equations are as follows:

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i}(\rho u_i) = 0 \tag{1}$$

$$\frac{\partial}{\partial t}(\rho u_i) + \frac{\partial}{\partial x_i}(\rho u_i u_j) = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}[\mu(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3}\delta_{ij}\frac{\partial u_i}{\partial x_i})] \tag{2}$$

$$\frac{\partial}{\partial t}(\rho E) + \frac{\partial}{\partial x_i}[(u_i(\rho E + \rho)] = \frac{\partial}{\partial x_j}(k\frac{\partial T}{\partial x_j} + u_i \tau_{ij}] \tag{3}$$

Where, ρ is the air density, t is the time, u_i is the velocity vector, τ_{ij} stands for the time-averaged Reynolds stresses, which are related to the mean velocity gradients, can be written as:

$$\tau_{ij} = \mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) - \frac{2}{3}\mu\delta_{ij}\frac{\partial u_i}{\partial x_i} \tag{4}$$

The IDDES method, which is a model consisting of two sub-branches, namely, Wall Modelling LES (WMLES) and Delayed Detached Eddy Simulation (DDES) Šekutkovski (2016), is adopted in the present work to predict the flow field around the turbine. The IDDES method combines the advantages of both RANS and LES, distinguishing them in each node by the discriminant function $\tilde{d}$ Shur (2008), which is:

$$\tilde{d} = \tilde{f}_d(1 + f_c)d_{\mathrm{RANS}} + (1 - \tilde{f}_d)d_{\mathrm{LES}}, \tag{5}$$

Where $\tilde{f}_d$ is the empirical blending function, d_{RANS} is the length scale of RANS, d_{LES} is the length scale of LES, and f_c is the elevating function. In addition, the SST *k-ω* turbulence model Menter (2003) which is a suitable model for the simulation of the flow fields around the turbine Jubori (2017), is used for the part of the RANS model.

2.3 Boundary conditions and mesh

The computational domain consists a turbine is shown in Fig 2. Where **d**=0.8m stands for the diameter of the rotating region which contains the blades. The fluidity is defined as ideal gas, then a mass-flow inlet is defined as the entrance of the air with the velocity of $25\text{m} \cdot \text{s}^{-1}$. The exit of the flow is defined as pressure outlet. The hood, blades and axis are defined as wall. However, other faces are defined as symmetry.

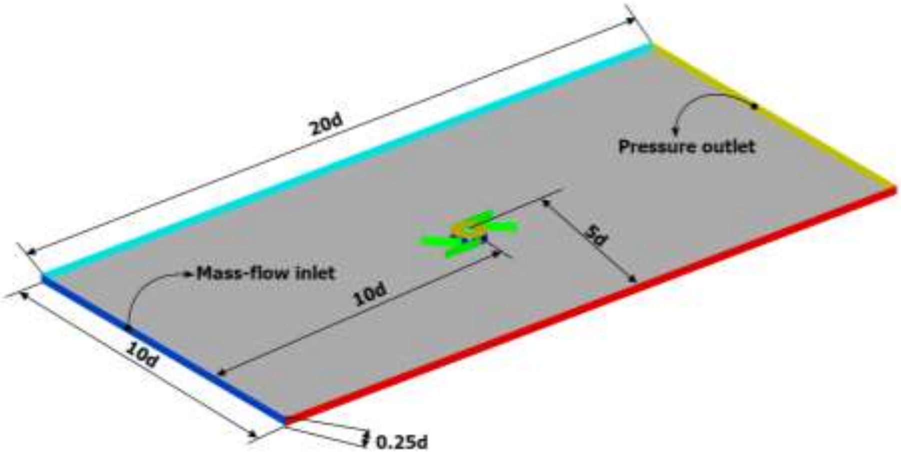


Fig. 2 Computational domain

The structured mesh contains more than 2.0×10^{6} cells used in the present work is shown in Fig. 3. The meshes are fine when they are close to the boundary layer of the blades, while the maximum value of equiangular skewness is 0.65.

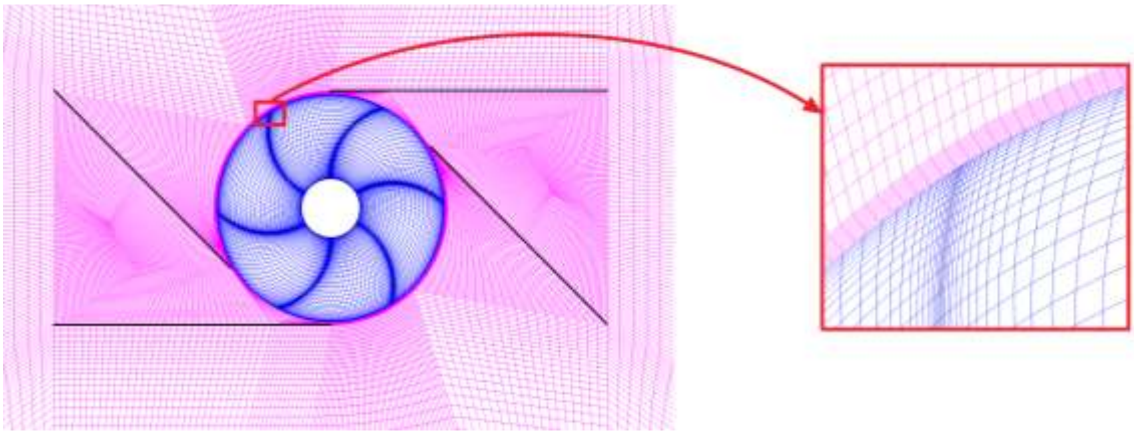


Fig. 3 Mesh of the flow field

A slip mesh technique was used in the present work, which means, meshes are distributed into rotation region and stationary region. Two regions can exchange data by the interface between them, as shown in Fig. 4.

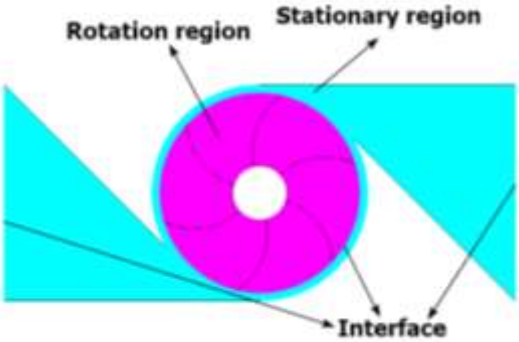


Fig. 4 Sketch of slip region

According to the study of Tabatabaeikia (2016), time step should be less than 1°ω^{-1}, which is to ensure a reliable result when simulating flow fields around turbines. In this paper, rotating speed is defined as 2 rot • s^{-1}, it means that the blades rotate with the speed of 720° per second. Therefore, the time step is supposed to be set no more than 1 • 720^{-1}. In fact, the time step in the present work is defined as 0.001, which meets the requirement.

2.4 Grid independence

A test of grid independence was performed by using three different meshes to predict the flow field around the turbine, which are: Coarse mesh, containing only 6.7×10^{-5} cells with 10 cells distributed along the thickness direction; Medium mesh, containing 2×10^{-6} cells with 30 cells distributed along the thickness direction; Fine mesh, containing only 3.3×10^{-6} cells with 50 cells distributed along the thickness direction. The torque curves of blades are shown in Fig. 5. The results show that the changing law of the three curves is consistent. The error of mean torque between the coarse mesh and medium mesh is 4.9% while that between the medium mesh and fine mesh is 0.5%, which indicates that he method of generating the mesh in the present work is appropriate and accurate for the simulation.

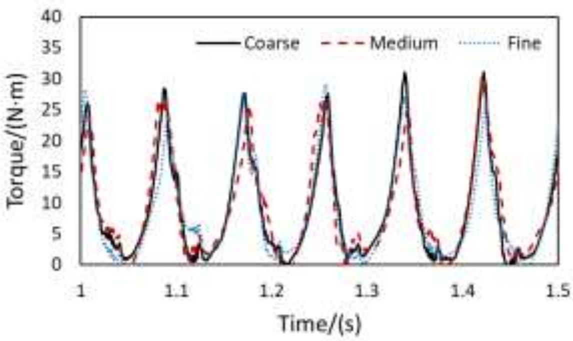


Fig. 5 Comparison of meshes

3. Analysis

3.1 Torque

The torque history of three cases with different spaces is shown in Fig. 6. It shows that the changing trend of these waveforms are in a basic agreement during computing time from 1.0s to 1.5s. All the blades revolved around a whole circle in this period and generated 6 torque peaks owing to 6 blades. Nevertheless, there still are certain differences in some peaks, in especial, torques of Case 1 are higher than those of Case 2 and Case 3 at the peaks in the periods from 1.05s to 1.1s and from 1.3s to 1.3s (in red circles).

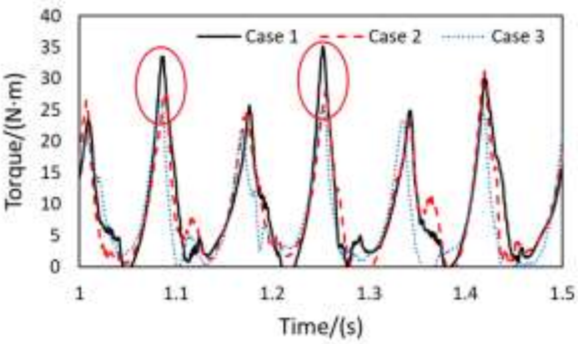


Fig. 6 Curves of torques history

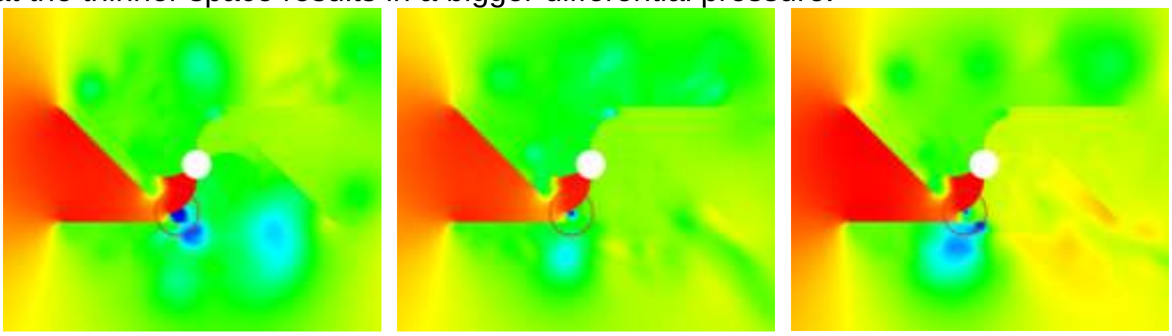
The mean torque is listed in Tab. 1, which shows that Case 1 provides the highest mean torque, which is 4.5% more than that of Case 2 while 14.8% more than that of Case3. It illustrates that the thinner the space, the higher efficiency of the turbine.

Tab. 1 Mean torque of Case 1~3

	Case 1	Case 2	Case 3
Mean torque/(N • m)	9.24	8.84	8.05

3.2 Pressure

The pressure at the time of 1.25s, at which an exceedingly obvious difference of three cases emerges, is chosen to be analyzed. The pressure on the slice which is located on the middle position in the direction of thickness is shown in Fig. 7. Obviously, the main differential pressure in all the three cases to drive the turbine is generated at two sides of the blade which is closest to the entrance of the ventilation duct (in red circles). The negative pressure region on the leeward side of the blade in the case 1 is the biggest, then, the one in the case to is bigger than that in the case 3. Which means that the thinner space results in a bigger differential pressure.

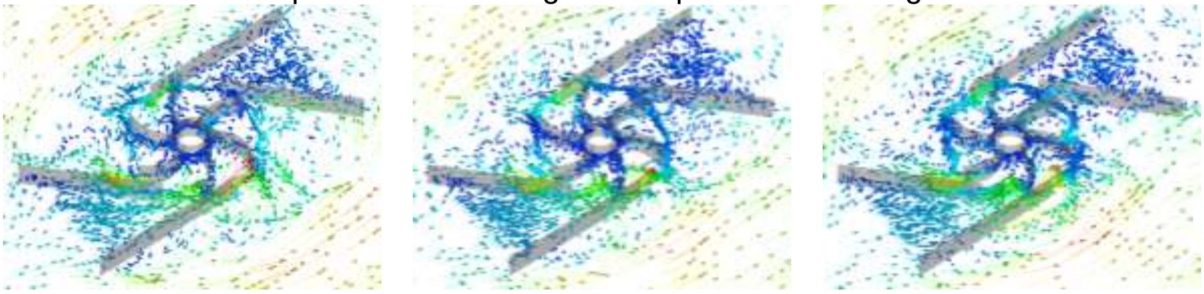


(a) (b) (c)

Fig. 7 Pressure nephogram of: (a) Case 1; (b) Case 2; (c) Case 3

3.3 Velocity

Similarly, Velocity vectors on the slice which is located on the middle position in the direction of thickness at the time of 1.25s is shown in Fig. 8 to reveal the flows around the turbine. There is little difference in the trends of three airflows. While, some faster airflows emerge in the regions between the blades and the hood in all three cases. The thinner space leads to a higher air speed in those regions.

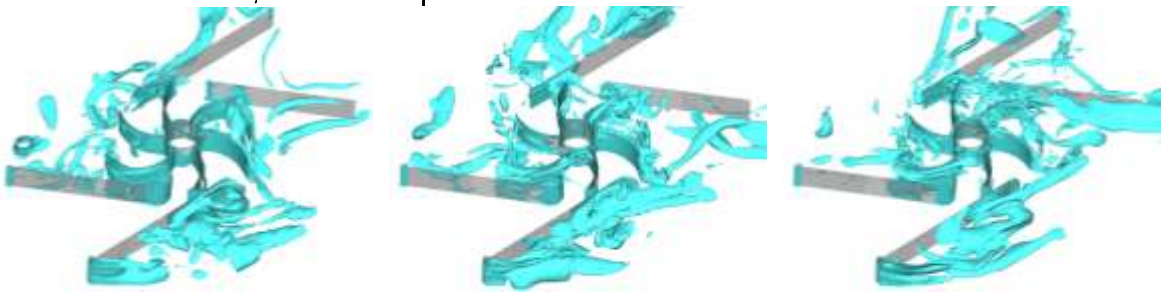


(a) (b) (c)

Fig. 8 Velocity vectors of: (a) Case 1; (b) Case 2; (c) Case 3

3.4 Vorticity

Isosurface of vorticity when Q=500 at the time of 1.25s is shown in Fig. 9. There are plenty of vorticities generated in the region of blades in all three cases. However, the evidence that the vorticity in the blades region of case 1 is less than that of case 2 and case 3 manifests that the aerodynamic viscous resistance in the blades region of case 1 is the least, which can provide a faster flow rate.



(a) (b) (c)

Fig. 9 Vorticity isosurface at Q=500 of: (a) Case 1; (b) Case 2; (c) Case 3

4. Conclusions

The IDDES method with SST *k-w* turbulence was adopted to simulate the flow field around three kinds of turbines with different spaces between the blades and hood. Results of the simulation show that:

1. Though the changing trends of the torque history curves are in a well obvious agreement, the efficiency of three turbines are distinct because of the different mean torques. The mean torque provided by the turbine with the space width of 0.01m is 4.5% more than that of 0.02m and is 14.8% more than that of 0.03m.

2. The negative pressure region on the leeward side of the blade with the thinnest space is the biggest, which means that the thinner space results in a bigger differential pressure.

3. Some faster airflows emerge in the regions between the blades and the hood and a thinner space leads to a faster airflow in those regions.

4. A thinner space provides less vorticity in the region of blades, which makes a less aerodynamic viscous resistance and a faster air speed.

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