

Study on the glaze ice accretion of wind turbine with various chord lengths

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Abstract. Wind turbine icing often occurs in winter, which changes the aerodynamic characteristics of the blades and reduces the work efficiency of the wind turbine. In this paper, the glaze ice model is established for horizontal-axis wind turbine in 3-D. The model contains the grid generation, two-phase simulation, heat and mass transfer. Results show that smaller wind turbine suffers from more serious icing problem, which reflects on a larger ice thickness. Both the collision efficiency and heat transfer coefficient increase under smaller size condition.

1. Introduction

As a renewable energy, wind energy is playing a more important role in the electrical industry. In many places with lots of wind resource, the wind turbines always suffer from serious icing problem. The supercooled droplets freeze on the blades, which change the shape and cause the power losses of wind turbine [1]. Studies indicated that regardless of the ice type, power losses due to icing can reach a maximum of 40% [2].

Studies on the wind turbine icing originated from the aircraft icing, which mainly focused on the simulation model for icing and equivalent reduced-scale testing in the lab or outdoor. Most researches are based on a single specific wind turbine. Besides, the ice tunnel in the lab is only available for small-size airfoil profile, due to the limitation of lab conditions. It is necessary to study the size effects on the ice growth of wind turbine. Matthew [3] studied the relations between chord length and rime on wind turbines by TURBICE. But the glaze ice accretion was not mentioned. In this paper, a 3-D glaze growth model for wind turbine is numerically studied by FLUENT and the glaze ice for various blade sizes are also simulated. This study has important significance for equivalent reduced-scale testing and anti-icing design for wind turbine.

2. Model

Ice accretion for wind turbine is always caused by the impingement of fog droplets (rime ice) and water droplets (glaze ice) [4]. Unlike rime ice simulation [5], water film flowing and heat and mass transfer should be considered in glaze ice. Figure 1 shows the flow chart of glaze ice model for wind turbine.



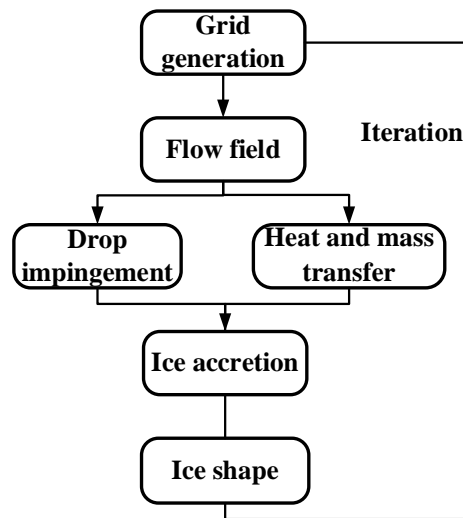



Figure 1. Flow chart of glaze ice model.

2.1. Geometry model

The horizontal-axis wind turbine is NE-100, where most parts of the blade are NACA4409 airfoil profile. The twisted angle and chord length change are also considered in the simulation, as shown in Table 1.

Table 1. Blade geometry parameter.

Blade	Section	r/R	Chord length (m)	Twisted angle (°)	Airfoil profile
	Sec-A	1	0.03	7	NACA4409
	Sec-B	0.8	0.035	10	NACA4409
	Sec-C	0.6	0.045	15	NACA4409
	Sec-D	0.4	0.055	20	NACA4409
	Sec-E	0.2	0.1	25	NACA4409

To reduce the influence of the flow field, the calculation domain is set very large, as shown in Figure 2. The near-wall grid is densified and treated with the wall-strengthening function. The blade surface is set as moving wall with about 35,000 quadrilateral grids. The whole calculation domain is around 1.5 million volume grids and 580,000 nodes. To improve the computing speed, the calculation

domain is only one-third of the cylinder, with a periodic boundary condition. The fluid field is calculated by the k- ε turbulent model in FLUENT, which is capable of accurately simulating the flow field around the profile [6]. The k- ε turbulent model is expressed as follows:

$$\rho \frac{dk}{dt} + \nabla \cdot (\rho k u_i) = \nabla \cdot \left(\frac{\mu_t}{\sigma_k} \nabla k \right) + G_k - \rho \varepsilon \quad (1)$$

$$\rho \frac{d\varepsilon}{dt} + \nabla \cdot (\rho \varepsilon u_i) = \nabla \cdot \left(\frac{\mu_t}{\sigma_\varepsilon} \nabla \varepsilon \right) + \frac{\varepsilon}{k} (G_{1\varepsilon} G_k - G_{2\varepsilon} \rho \varepsilon) \quad (2)$$

where k is the turbulent kinetic energy, ε is the turbulent dissipation rate, ρ and u_i are the mixture density and velocity, μ_t is the turbulent viscosity. To improve both the convergence accuracy and the convergence efficiency, both the relaxation factor and the finite difference scheme are variable during the calculation.

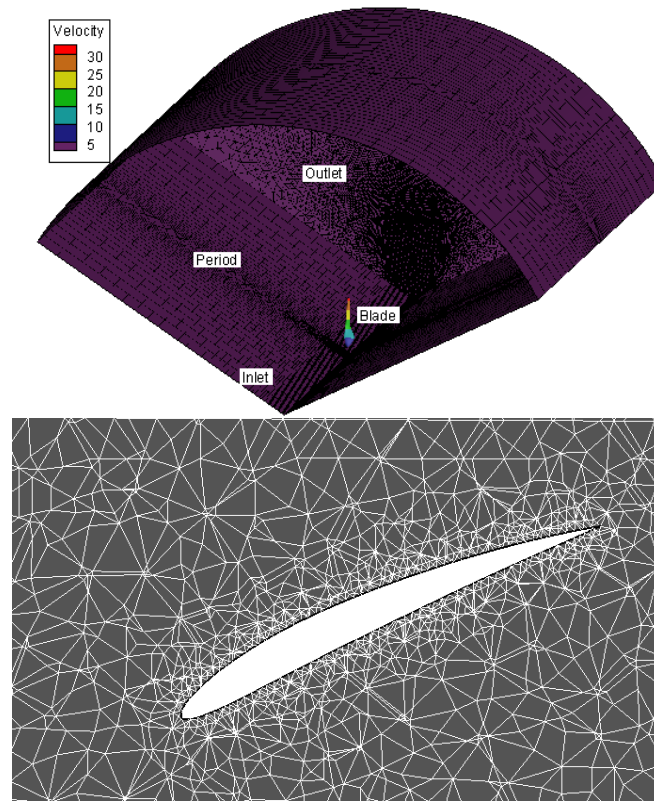


Figure 2. Calculation domain and near-wall grid.

2.2. Droplets impingement

Both the Eulerian–Lagrangian method and Eulerian–Eulerian method can simulate the droplets impingement on the profile. Eulerian–Lagrangian method has often been used in 2-D icing problem, which simulates the droplets trajectory in the flow field. But in 3-D case, it is hard to track so many droplets to get the collision efficiency in each cell [5]. In this paper, the droplets impingement is simulated by the multi-phase Eulerian model in the FLUENT, as shown in Figure 3. The droplets are set as secondary phase and shown by volume fraction α . The local collision efficiency β is related to the volume fraction α and can be expressed as follows:

$$\beta = \frac{\alpha}{\alpha_\infty} \cdot \frac{|\vec{V} \cdot \vec{n}|}{V_\infty} \quad (3)$$

where α/α_∞ denotes the volume fraction of the droplets phase, V denotes the local velocity of the droplets, n denotes the local normal vector and V_∞ denotes the freestream velocity.

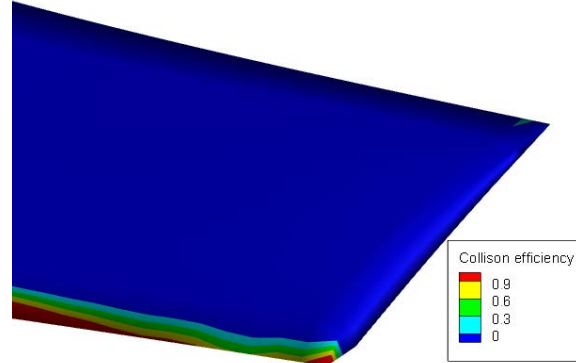


Figure 3. Eulerian–Eulerian method for the simulation of droplets trajectory.

2.3. Heat and mass balance

Based on the Messinger model [7], the mass balance in each cell can be expressed as:

$$m_{im} + m_{in} = m_{out} + m_{eva} + m_{ice} \quad (4)$$

where m_{im} denotes the mass of droplets impinging onto the blade profile. m_{in} and m_{out} denote the previous water into the cell and the water flowing out to the next one respectively. m_{eva} denotes the evaporating water and m_{ice} denotes the ice mass of the cell.

Droplets impingement process denotes included in m_{im} , which can be described as [8]:

$$m_{im} = \beta \cdot LWC \cdot V_\infty \cdot A \quad (5)$$

where LWC denotes the liquid water content, A denotes the cross-sectional area of the object relative to V_∞ . Freezing fraction f [9] denotes introduced to denote the ratio of freezing water in the cell. If $f=0$, water does not freeze; If $0 < f < 1$, both water and ice are existed in the cell, which denotes glaze ice; If $f=1$, all the water freezes into ice, which denotes rime ice. f can be expressed as follows:

$$f = \frac{m_{ice}}{m_{im} + m_{in}} \quad (6)$$

The heat balance in each cell can expressed as follows:

$$Q_{im} + Q_{in} = Q_{eva} + Q_i + Q_{out} + Q_f + Q_c \quad (7)$$

where Q_{im} denotes the impingement energy of supercooled water, Q_{in} denotes the energy of the incoming water, Q_{eva} denotes the evaporation heat, Q_i denotes the heat released from icing, Q_{out} denotes the outgoing water, Q_f denotes the friction heat, Q_c denotes the convective heat. The radiation heat denotes ignored in this equation considering a low temperature of both the ice-covered surface and environment.

3. Discussion

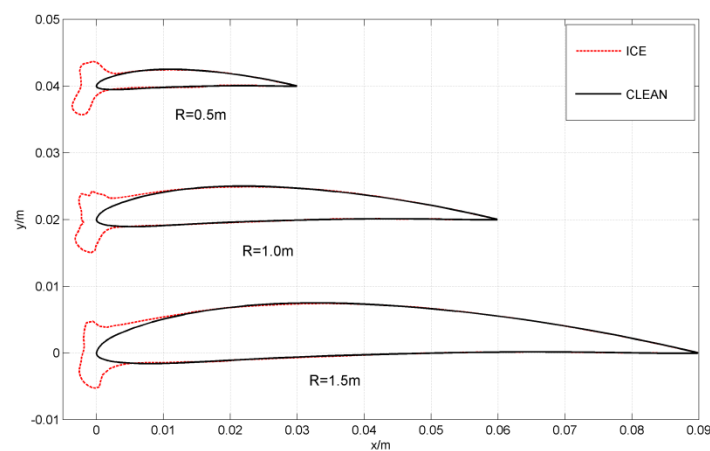
The blade size is designed larger with the increase of wind turbine output. Matthew [3] pointed a trend of reduced rime ice for larger wind turbines. The glaze ice for various blade sizes is numerically analyzed. Taking the tip speed ratio as a constant, the changes of blade size and rotate speed are shown in Table 2.

Figure 4 shows a trend of more glaze ice for smaller wind turbine. The trend is more obvious than that of the rime ice. Collision efficiency at the tip averagely increases by 32.48% when the blade length changes from 1.5m to 0.5m. Besides, heat transfer coefficient also averagely increases by 28.68%

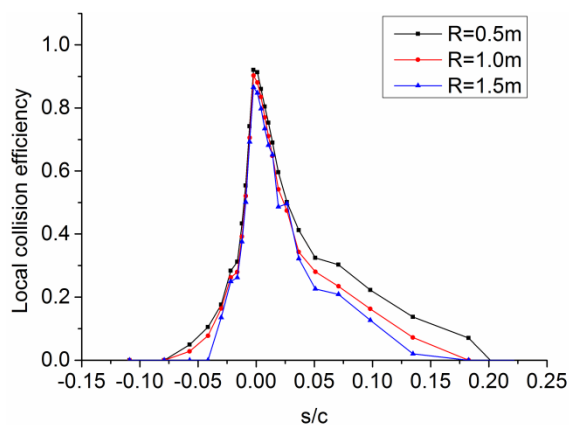
with a decreasing blade size. The glaze ice accretion largely depends on both collision efficiency and heat transfer coefficient, which means glaze ice is more sensitive to the blade size.

Table 2. Simulation conditions with various blade sizes.

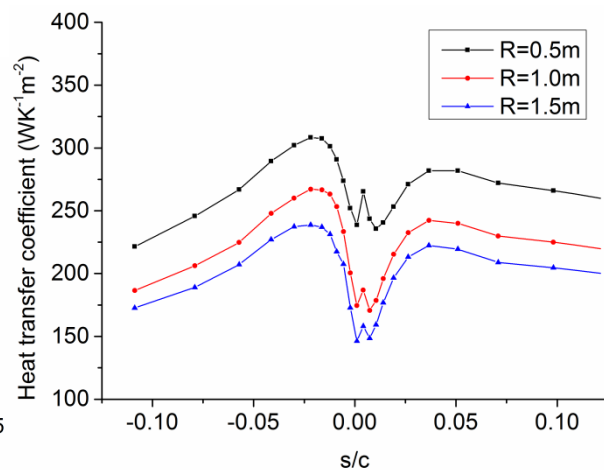
Parameter	Value
V_{wind} (m/s)	5
R (m)	0.5, 1.0, 1.5
c (m)(at the tip)	0.03, 0.06, 0.09
n (r/min)	494, 247, 165



(a) Ice shape (5min)



(b) Local collision efficiency



(c) Heat transfer coefficient

Figure 4. Effect of chord lengths on glaze ice accretion (blade tip).

4. Conclusion

A glaze ice model for horizontal-axis wind turbine is proposed in the paper. The model consists of 3-D rotating geometry, two-phase simulation, heat and mass balance. According to the simulation with different blades, the glaze ice growth accelerates with a smaller blade. This can be attributable to the larger collision efficiency and heat transfer coefficient.

Acknowledgment

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