1. Introduction

Wind turbines in cold climate regions often suffer from severe blade icing events during winter operations. Ice accretion changes the blade shape and the surface roughness, thereby greatly deteriorating the aerodynamic performance and affecting the power production (Hu et al., 2017). Therefore, a better understanding of blade icing characteristics is necessary in order to mitigate the energy power loss.

In this paper, a 3D numerical method based on Lagrangian approach is developed to simulate rime ice accretion on the rotating wind turbine blade. The main contents are as follows: First, a detailed description of the numerical simulation method is given and validated against experimental result. Then, a comprehensive analysis of the airflow behavior and ice mass distribution along the blade radial direction is carried out.

2. Numerical method

2.1 Air flow

A semi-cylindrical domain is used for air flow calculation, with a single blade placed in the center. The Moving Reference Frame is employed to predict the flow around the blade. An unstructured mesh is generated using Gambit. The inlet is specified as a velocity inlet and outlet is specified as a pressure outlet. The turbulence around the blade is simulated using standard k-ε turbulence model. The pressure-velocity coupling is solved using the SIMPLE method. The second order upwind is employed for the discretization schemes.

2.2 Droplet trajectory

The Lagrangian description is adopted to calculate droplet trajectories and impingement characteristics. The governing equation of water droplet motion is expressed as

\[ m_d \frac{d^2 \mathbf{r}_d}{dt^2} = \mathbf{F}_d = -0.5 \frac{C_D A_d \rho_d}{\rho_a} \mathbf{U} \times \mathbf{U} + \mathbf{F}_{\text{drag}} + \mathbf{F}_{\text{stall}} \]

where \( \rho_a \) is the air density, \( A_d \) is the cross section of water droplet. The drag coefficient \( C_D \) is determined by

\[ C_D = 24 \left( 1 + 0.15 R e^{0.5} \right) \]

where \( R e \) denotes the Reynolds number.

Approximately 120,000 droplets are arranged with equidistant spacing at around one blade radius upstream of the wind turbine. The initial speeds of the droplets are identical to the local air speeds.

The motion equation is solved using the fourth order Runge-Kutta scheme until the impingement occurs, by which the trajectory is obtained.

2.3 Ice accretion calculation

This study is aimed at rime ice accretion simulations rather than glaze ice. The blade surface is divided into several units, and the corresponding area of each unit is marked as \( \Delta s \). According to the number of droplets impacting on each unit, the ice mass and ice thickness can be obtained by the following equations

\[ m_i = A \cdot V_0 \cdot \rho_{\text{ice}} \cdot \left( \frac{n_i}{N} \right) \cdot t \]

\[ d_i = m_i / \rho_{\text{ice}} \Delta s \]

where \( A \) is the sweeping area of blade, \( R \) is the blade length, \( V_0 \) is the wind speed, \( t \) is icing time, and \( \rho_{\text{ice}} \) is the ice density. To get a smoother ice shape, a reasonable smoothing treatment is necessary.

3. Method validation

An untapered and untwisted blade equipped with S809 airfoil (Han et al., 2012) is selected as the objective of this work. The predicted ice shape agrees well with the experimental result of Han et al. (2012), which indicates the correctness of the numerical method, as illustrated in Fig. 1.

![Figure 1. Comparison of ice shape for the 99% radial section.](image1)

4. Result and discussion

Fig. 2 illustrates the pressure coefficient contours and streamlines on the blade suction surface at the wind speed of 12m/s. The radial flow extends to a larger part of the blade surface, indicating a significant 3D rotating effect.

![Figure 2. Pressure coefficient contour and streamlines.](image2)

The ice mass distribution affected by different parameters is shown in Fig. 3. The ice mass is found to increase approximately linear along the radial direction of the blade. For a specific section, more severe icing is observed with the increase in wind speed and droplet size.

![Figure 3. Effects of icing parameters on ice mass distribution.](image3)

References
