Effect of Surface Roughness of Wind Turbine Blade on its Ice Accretion

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***Abstract*— The wind turbine blades' icing often occurs under cold climates when the blades suffer from super-cooling droplets. Ice on blades changes the airfoil profile, reducing the efficiency of wind turbine. In this paper, the icing characteristic of the miniature horizontal-axis rotating wind turbine blade under the conditions of different surface roughness is experimentally studied by establishing the platform of ice wind tunnel in artificial climate chamber. A simulation is performed to reflect the flow field characteristics of the blade profile and different icing conditions. By measuring the ice mass, ice thickness and ice type of the blades, it is found that rough surface significantly increases the ice mass of blades; Ice mass of blades hardly changes under different roughness of rough surface, but a rougher surface leads to a more non-uniform distribution of ice on blades; Surface roughness cannot change the ice type of blades. Surface roughness is largely relative to the collision coefficient and heat transfer coefficient by simulation and numerical calculation.**

Key words: wind turbine blade, surface roughness, flow field, ice mass, ice type, CFD.

I. INTRODUCTION

As the global environment deteriorated, renewable energy, especially wind energy is widely used around the world. Wind energy is rich in north China, but most areas are suffered from icing problem. The super-cooling droplets fall down on the cold wind turbine blades and freeze, which seriously affects the normal operation of wind turbine. Bose[1] experimentally studied the ice of the miniature horizontal-axis wind turbine blade under stationary state. Han[2] studied the ice of a rotating wind turbine by experiment under different environment conditions. His team developed the device AERTS to predict the ice model of wind turbine. Most research institutes tended to pay more attention to the simulation by CFD. The ice model of Turbice[3] from VTT and Lewice[4] from NASA were relatively systematic to study the icing problem. Virk[5] simulated the droplet trajectory to get the collision coefficient of water droplet onto the blade profile and studied the effect of angle of attack(AOA) and profile size on the ice.

At present, studies on surface roughness of wind turbine were few reported. Etemaddar[6] took the ice roughness of the blade into consideration, but he did not focus on the blade surface roughness itself. In this paper, the platform of ice wind tunnel is established in the artificial climate chamber. The icing characteristic of the miniature horizontal-axis rotating wind turbine blade is experimentally studied under the condition of different surface roughness of the blade and large angle of attack. A simulation of flow field characteristics of icing blade profiles is performed as well.

II. EXPERIMENTAL FACILITY AND EXPERIMENTAL PROCEDURE

As shown in Fig. 1, a multifunctional artificial climate chamber, with an internal diameter of approximately 7.6m and an internal height of approximately 11m, can simulate different atmospheric environments. The lowest temperature *T* can reach −45 ℃. Inside the climate chamber, the water nozzle can simulate different Median Volume Diameter (*MVD*) and Liquid Water Content (*LWC*). An ice wind tunnel is designed for the miniature wind turbine, which can provide the maximum wind velocity *V* 10m/s. The miniature horizontal-axis wind turbine is with an output power of 100W, the blade radius *R* of 0.5m, the maximum chord *c* of 0.102m and the minimum chord of 0.028m. To change the output loads keeps the rotate speed of wind turbine in 60r/min.

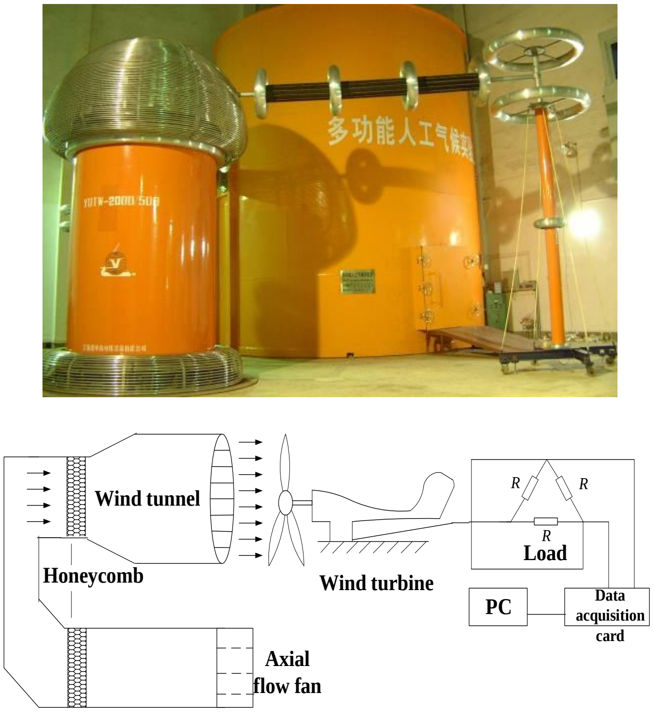


Fig. 1. Experimental schematic diagram

The surface roughness is defined by the equivalent sand grain roughness k_s[7]. The surface roughness of three blades is 0、0.035mm、0.2mm in the experiment. The experimental environment is show in TABLE I.

TABLE I

PARAMETER OF ICING EXPERIMENT IN 30MIN

Test	LWC(g/m^3)	MVD(μm)	T(℃)	V(m/s)	AOA (°)	Ice type
1	1.42	100	-3	5	26.82	Glaze ice
2	1.42	100	-6	5	26.82	Mixed ice
3	1.42	100	-9	5	26.82	Rime ice
4	1.42	100	-6	3	14.80	Glaze ice
5	1.42	100	-6	7	36.03	Glaze ice

III. EXPERIMENTAL RESULTS

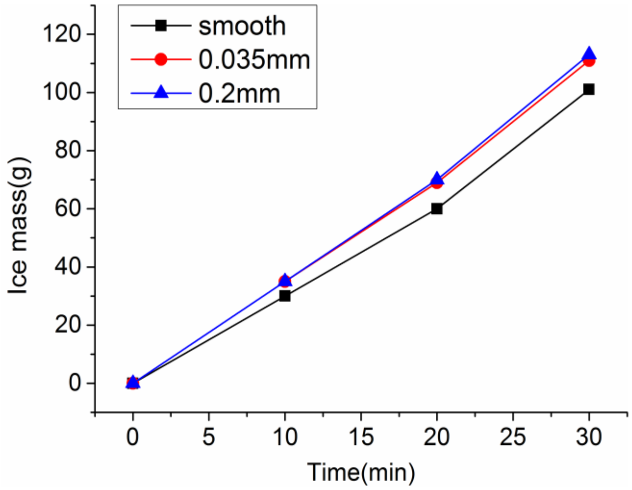
A. Influence of Surface Roughness on Ice Type

The ice type of each group is recorded in TABLE II, which indicates that the surface roughness is hardly relative to the ice type of the blade. Compared with test 1, test 2 and test 3, it is concluded that the ice type is mainly influenced by ambient temperature. If the temperature is around 0℃, it tends to be glaze ice. If the temperature reduces to about or lower than -10℃, it tends to be rime ice.

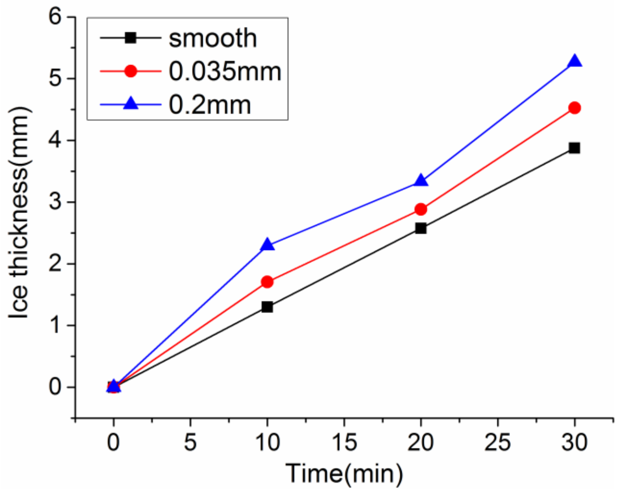
B. Influence of Surface Roughness on Ice Load

Fig. 2 shows the changes of ice thickness and ice mass on the blades with the icing test going on. Both the ice thickness and ice mass on the rough blade are much greater than those on the smooth blade. However, the two rough blades have the same ice mass and different ice thickness. Fig. 3 shows the ice shape at the blade tip under the conditions of different surface roughness when icing time is 30min. It can be seen that the rougher the blade surface is, the less uniformly the distribution of ice on the blade profile exhibits. The ice tends to be uniformly covered on the windward of the smooth blade profile. However, in the condition of 0.2mm surface roughness of the blade, the ice mainly accretes at the leading edge of the windward of the blade profile. This also explains why the two rough blades have the different ice thickness. The non-uniformity of ice distribution keeps rising with the process of ice accretion, and it leads to greater ice thickness. It is noticed that a rougher surface seems not to contribute to more ice accretion.

In addition, when the icing time reaches 10min, most parts of the blades have been covered with ice. It can be seen in Fig.2 that each group has the same ice accretion rate in 10~30min, which means the surface roughness of the blade only influences the ice accretion at the beginning. The surface roughness turns into ice roughness after the blade is covered with ice, and the ice roughness seems to be weakly relative to surface roughness.

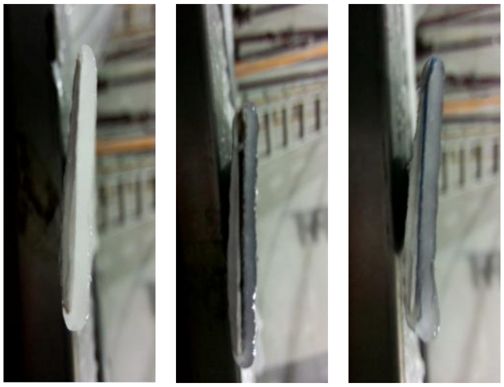


(a) Ice mass



(b) Ice thickness

Fig.2. Ice characteristic of wind turbine blade under different surface roughness



(a) smooth (b) 0.035mm (c) 0.2mm

Fig.3. Ice shape of blade tip under different surface roughness (icing time: 30min)

IV. DISCUSSION

The rate of ice accretion on the blade can be described as[8]:

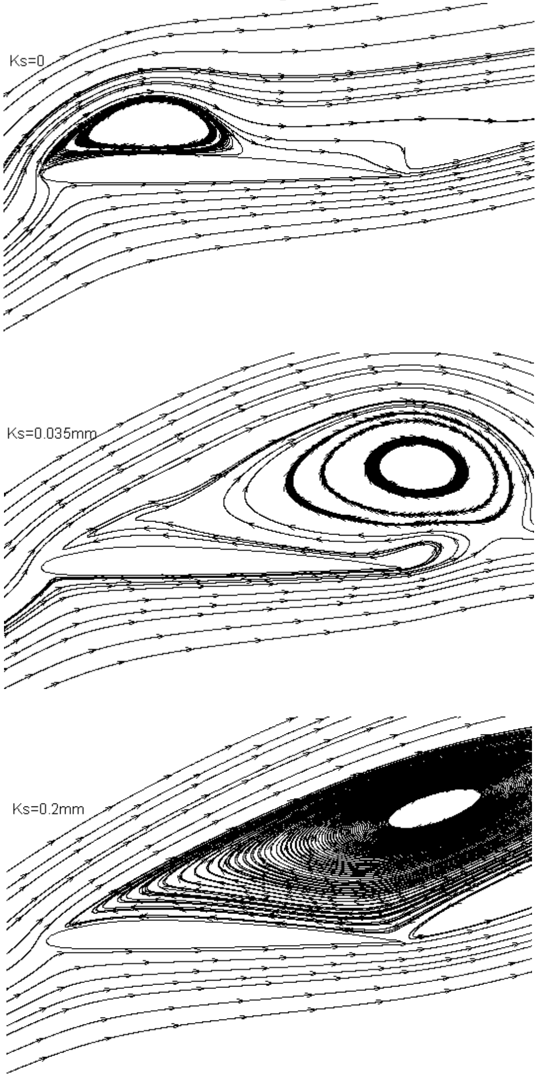
$$\frac{dM}{dt} = \alpha_1 \cdot \alpha_2 \cdot \alpha_3 \cdot LWC \cdot U_e \cdot A \qquad (1)$$

Where, U_e is the relative velocity, A is the cross-sectional area of the object relative to U_e, and α_1, α_2, α_3 are the correction factors with the values ranging from 0 to 1. α_1 is the collision coefficient of the droplet. α_2 is the sticking coefficient. α_3 is the accretion coefficient.

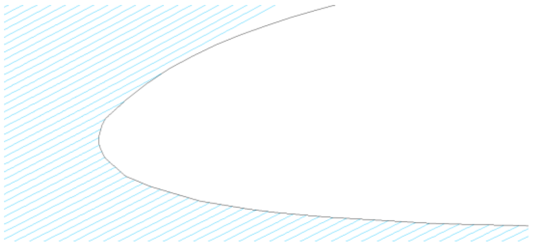
A. Influence of Surface Roughness on the Collision Coefficient

To further explain the experiment phenomenon, a simulation is performed to reflect the pathlines of droplets in the flow field in the cases of different surface roughness.

Numerical studies of the flow field show a significant change in the pathlines of flow field by FLUENT. The flow separation and vortex occur at the leading edge of the leeward of the NACA 2308 profiles under 26 AOA. The vortex area grows larger and moves to the trailing edge as the surface roughness increases. The length of vortex is 0.5c in the flow field of the smooth profile, 0.9c in that of 0.035mm profile and 2c in that of 0.2mm profile.



(a) The pathlines of flow field



(b) The droplet trajectory in the flow field

Fig.4. The pathlines and droplet trajectory in the flow field of NACA 2308 profiles with roughness 0, 0.2mm, 0.035mm

The different flow field changes the droplets trajectory, which leads to different collision coefficient. The local collision coefficient of droplets is defined as[9]:

$$\alpha_1 = dY/dL \qquad (2)$$

Where dY is the initial distance of two adjacent droplets, and dL is their distance on the profile.

It is found that a rougher surface has a lager collision area, especially at the leading edge of the leeward of the profile. The local collision coefficient increases at the leading edge and decreases on the other parts of the profile, as the surface roughness increases.

TABLE II

SIMULATION RESULTS ON COLLISION LOCATION

k_s(mm)	The maximum collision location of windward(x/c)	The maximum collision location of leeward(x/c)
0	1	0.0037
0.035	1	0.0105
0.2	1	0.0173

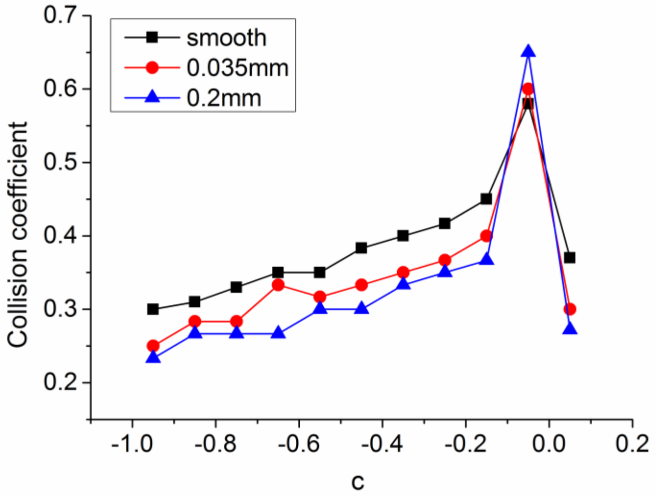


Fig.5. The local collision coefficient of NACA 2308 profiles under AOA 26°(c=0 presents the peak point, c<0 presents the point of the windward)

B. Influence of Surface Roughness on the Accretion Coefficient

The accretion coefficient of the droplet is related to the heat transfer coefficient in the boundary-layer. According to

Chilton-Colburn [10], the heat convection of rough surface is expressed as follows:

$$h = \rho_a \cdot c_a \cdot U_e \cdot St \tag{3}$$

Where ρ_a is the air density, c_a is the specific heat of air, St is the Stanton number. Whether the boundary-layer is in the turbulent area is determined by the roughness Reynolds number Re_k:

$$\mathrm{Re}_k = \frac{U_k k_s}{\upsilon} \geq 600 \tag{4}$$

Where U_k is the speed at the roughness level, v is the kinematic viscosity of air. The heat transfer coefficient could be written respectively in laminar boundary and turbulent boundary as follows:

In laminar boundary-layer:

$$h_c = 0.296 \cdot \frac{\lambda}{\upsilon}[\mathrm{U}_e^{-2.88} \int_0^s \mathrm{U}_e^{1.88}\, ds]^{-1/2} \tag{5}$$

In turbulent boundary-layer:

$$h_c = \frac{\rho_a \cdot c_a \cdot U_e \cdot C_f}{0.8 + 1.13 \cdot C_f^{0.6} \cdot (\frac{U_e k_s}{\upsilon})^{0.2}} \tag{6}$$

Where λ is the thermal conductivity coefficient of air, the friction coefficient C_f is related to k_s and can be obtained by the empirical formula as follows

$$C_f = [0.707 \ln(\frac{x}{k_s}) + 3.476]^{-2.46} \tag{7}$$

Where, x is the arc length from the point of leading edge to the stagnation point. It is concluded from Eqs. (5), (6) that the surface roughness mainly influences the heat transfer coefficient in the turbulent boundary-layer, which is in accordance with the air flow of wind turbine with large AOA. This leads to a lager heat transfer coefficient and a lager rate of ice accretion at the leading edge.

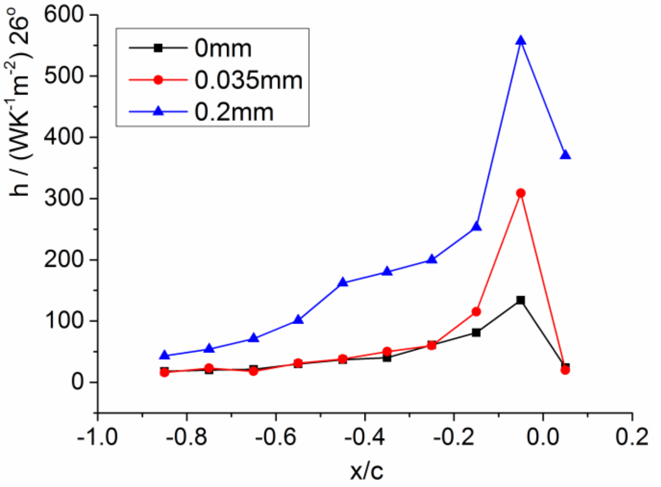


Fig.6. The heat transfer coefficient of NACA 2308 profiles under AOA 26°

V. CONCLUSION

The influence of surface roughness of wind turbine blade with large AOA on icing characteristic is experimentally studied in artificial climate chamber. Surface roughness cannot change the ice type. Rough surface causes more serious ice accretion. Surface roughness hardly changes the ice mass on blades, but it can significantly influence the ice distribution especially at the leading edge of the profile.

A theoretical analysis is made based on the ice accretion model. The collision coefficient and accretion coefficient are related to surface roughness. The collision coefficient decreases while the local collision coefficient of the leading edge increases, in case that roughness grows greater, which causes more serious ice accretion at the leading edge. The heat transfer coefficient in turbulent boundary-layer increases with the rise of surface roughness. Surface roughness does not change the heat transfer coefficient in laminar boundary-layer.

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