Effect of Wind Turbine Blade Profile Surface Roughness on Ice Accretion – A Numerical Case Study

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Abstract. A parametric numerical study of wind turbine blade profile surface roughness has been carried out to investigate its effects on boundary layer characteristics and accreted ice growth. DU96-W-180 blade profile is used in this paper. Multiphase numerical analysis has been performed at glaze ice conditions for three different surface roughness values: Shin et al. surface roughness model and two specific roughness values (0.03m and 0.0003m). Study shows that surface roughness considerably effects the shear stresses as well as heat fluxes, which results a variation of ice accretion in rate and shape. Results show that accreted ice mass and ice thickness increases with the increase of surface roughness.

Keywords: Wind turbine; Surface roughness; Atmospheric ice; CFD; Sheer stress; Heat flux.

1. Introduction
Cold regions have good resources of wind energy due to the high potential wind resource and low temperature. However, environmental challenges such as atmospheric icing on wind turbine blades has been recognized as a hindrance limiting the proper use of these good wind resources at elevated icing regions [1]. Ice accretion on wind turbine blade affects wind turbine aerodynamic performance and resultant power production. Such Annual Energy Production (AEP) losses have been reported to lead up to a 17% decrease, in which 20% to 50% of the aerodynamic performance [2]. The installed wind energy capacity in cold climate regions was 86.5 GW in 2015, and it expected to reach 123 GW in 2020 [3]. With the aim to improve safety and reduced the Capital Expenditure (CAPEX) and Operational Expenditure (OPEX) related to wind turbine operations in cold regions, therefore, the importance of wind resource of cold region is to better understanding of ice accretion process on wind turbine blades. Ice accretion physics on wind turbine blade influences the geometric features, which contribute to the aerodynamic performance losses. Ice accretion on wind turbine blade relies on both geometric (turbine size, shapes, and surface roughness) and operating (air temperature, wind velocity, Liquid Water Content (LWC) and Medium Volume Diameter (MVD) conditions. [4]. Different temperatures and heat flux along the blade profile result in different ice growth [5]. Duncan et al. [6] identified the difference between glaze and rime ice causing different levels of production losses. Surface roughness of the blade profile changes during the process of ice accretion. Surface roughness change affects the shear stresses and heat fluxes, which effects the ice accretion in rate and shape [7] [8]. The numerical methods, especially Computational Fluid Dynamics (CFD) have begun to play an important role both in simulating and determining the performance of wind turbine blades under different icing conditions [9]. Generally for the wind turbine blade profile surface roughness evaluation, two analytical models are being mostly used; NASA sand-grain roughness model and Shin et al. sand-grain model [10]. NASA sand-grain roughness model is computed with an empirical NASA correlation
formula for icing, whereas shin et al. sand-grain roughness model modified the NASA correlation with shin and Bond correlation formula [11].

During the process of ice accretion, the blade profile surface roughness leads to changes in the boundary layer growth, which influences the droplet sticking efficiency and the heat transfer. Shin[12] and Anderson [13] show that the characterization of ice surface roughness could have three main zones, which develops along the leading edge of blade for both glaze and rime ice cases - the smooth zone, rough zone and feather region, shown in Figure 1. Guy et al. [14] have developed a model, which combines ice mass and heat balance equations to calculate the surface roughness and mass of remaining, runback and shedding water over the airfoils.

This paper carried out a numerical case study to better understand the effect of vary of blade profile surface roughness during icing along a DU96-W-180 airfoil at glaze ice conditions.

2. Numerical Study

CFD-based multiphase numerical analysis are implement to study the effect of surface roughness on the ice growth and the simulations are carried out using ANSYS FENSAP ICE. Structured O-grid [15] with 48450 cells is used for this study. Detailed mesh sensitivity study are carried out to accurately determine the boundary layer characteristics (shear stress and heat flux), where y+ values of less than 1 is used near the wall surface. Number of mesh elements and y+ value are selected based upon the heat flux calculations, where a numerical check was applied that the heat flux computed with the classical formulae, whereas dT/dn should be comparable with the heat flux computed with the Gresho’s method. Figure 2 shows the grid of numerical study.

Atmospheric ice accretion on blade profile can be numerically simulated by means of integrated thermo-fluid dynamic models, which involve the fluid flow simulation, droplet behaviour, surface thermodynamics and phase changes. The numerical study of airflow behaviour is carried out by solving Partial Differential Equations (PDE) for the conservation of mass, momentum and energy.

\[
\frac{\partial \rho_a}{\partial t} + \nabla (\rho_a \vec{v}_a) = 0
\]

\[
\frac{\partial \rho_a \vec{v}_a}{\partial t} + \nabla (\rho_a \vec{v}_a \vec{v}_a) = \vec{g} \sigma_{ij} + \rho_a \vec{g}
\]

\[
\frac{\partial \rho_a E_a}{\partial t} + \nabla (\rho_a \vec{v}_a H_a) = \vec{g} (k_a \vec{v}_a T_a) + \nu_i \nu_{ij} + \rho_a \vec{g} \vec{v}_a
\]

where \(\rho\) is the density of air, \(\vec{v}\) is the velocity vector, subscript \(a\) refers to the air solution, \(T\) refers to the air static temperature in Kelvin, \(\sigma_{ij}\) is the stress tensor and \(E\) and \(H\) are the total initial energy and enthalpy, respectively. There are three different surface roughness values that are simulated in this study; two specified sand grain roughness values and one is using Shin and al. roughness model, by solving the following equations.

\[
\left[ \frac{k_s/c}{(k_s/c)_{base}} \right]_{MVD} = \begin{cases} 1, & MVD \leq 20 \\ 1.667 - 0.0333 (MVD), & MVD \geq 20 \end{cases}
\]

Figure 1. Features of ice roughness.[13]  
Figure 2. Grid around DU96-W-180 airfoil.
where MVD is the droplet mean diameter (in microns), and the corresponding value of sand-grain roughness is obtained:

\[ k_s = 0.6839 \left( \frac{k_s}{c} \right)_{base} LWC \left( \frac{k_s}{c} \right)_{base} T_s \left( \frac{k_s}{c} \right)_{base} MVD \left( \frac{k_s}{c} \right)_{base} C \]  

(5)

Two-phase flow \((\text{air and water droplets})\) is calculated using the Eulerian approach, where the supercooled water droplets are assumed to be spherical. The Eulerian two-phase flow model is composed of the Navier-Stokes equation with the continuity and momentum equation of the water droplets. The drag coefficient of water droplet is depends on the empirical correlation for the flow around the water droplets described by Clift et al. [16]

\[
\frac{\partial \alpha}{\partial t} + \nabla \cdot (\alpha \mathbf{V}_d) = 0
\]  

(6)

\[
\frac{\partial (\alpha \mathbf{V}_d)}{\partial t} + \nabla \cdot (\rho \alpha \mathbf{V}_d \mathbf{H}_d) = C_D \frac{\mathbf{V}_a}{24} \alpha (\mathbf{V}_a - \mathbf{V}_d) + \alpha \left( 1 - \frac{\rho a}{\rho d} \right) \frac{1}{(F_r^2)} \mathbf{g}
\]  

(7)

Where \(\alpha\) is the water volume fraction, \(\mathbf{V}_d\) is the droplet velocity, \(C_D\) is the droplet drag coefficient and \(F_r\) is the Froude number. The numerical approach is present for Lang-D droplet distribution at a fixed water droplet median volume diameter (MVD), sets as 20 microns. Iced surface thermodynamics is calculated using the mass and energy conservation equations, which considering the heat flux due to convective and evaporative cooling, heat of fusion, viscous and kinetic heating.

\[
\rho_f \left[ \frac{\partial h_f}{\partial t} + \nabla \cdot (\mathbf{V}_f h_f) \right] = V_\infty LWC \beta - \dot{m}_{\text{evap}} - \dot{m}_{\text{ice}}
\]  

(8)

Equation 9 expresses the conservation of energy:

\[
\rho_f \left[ \frac{\partial c_f c_f T_f}{\partial t} + \nabla \cdot (c_f \mathbf{V}_f \mathbf{T}_f) \right] = \left[ c_f \left( \bar{T}_\infty - \bar{T}_f \right) + \frac{\| \mathbf{V}_d \|^2}{2} \right] V_\infty LWC \beta - L_{\text{evap}} \dot{m}_{\text{evap}} + 
\]  

\[ (L_{\text{fusion}} - c_s \bar{T}_f) \dot{m}_{\text{ice}} + \sigma \varepsilon (\bar{T}_\infty^4 - T_f^4) - c_h (\bar{T}_f - \bar{T}_{\text{ice,rec}}) + Q_{\text{anti-icing}} \]  

(9)

The coefficients \(\rho_f, c_f, c_s, \sigma, \varepsilon, L_{\text{evap}}, L_{\text{fusion}}\) are physical characteristics of the fluid. The reference conditions \(\bar{T}_\infty, V_\infty, LWC\) are the airflow and droplets parameters. ALE (Arbitrary Langrangian Eulerian) formulation is used for the mesh displacement because of ice accretion in time. This method adds the grid speed terms to the Navier-Stokes equations to account for the mesh velocity [17]. The roughness height for the iced blade profile surface was measured using Shin et al. model as reference and two other specified roughness values. In addition, one equation Spalart-Allmaras turbulence model is used and numerical simulations are carried out at operating and geometric conditions specified in Table 1.

| Table 1. Numerical setup |
|---------------------------|
| **Airfoil**               | DU96-W-180          |
| **Chord length (meter)**  | 0.5                 |
| **Wind velocity (m/s)**   | 77                  |
| **AOA (Celsius)**         | 0                   |
| **Temperature (°C)**      | -5 (Glaze ice)      |
| **LWC (g/m³)**            | 0.35                |
| **MVD (microns)**         | 20 (Lang-D)         |
| **Reynolds number**       | \(3 \times 10^6\)   |
| **Simulation time step**  | 15 min              |
| **Surface roughness model** | Shin et al. sand-grain model |

Specified sand-grain model (0.0003m and 0.03m)


3. Results and Discussion

3.1. Effect of Surface Roughness on Boundary Layer Conditions

3.1.1. Shear stress. Change in the surface roughness affects the shear stress along blade surface. This is mainly a change of the friction in viscous boundary layer. Analysis shows that shear stresses changes significantly with the change of surface roughness. Figure 3 shows that the fluctuation of shear stress in shin et al. roughness model is much more than specific values and the lower surface of the blade profile has higher shear stress than upper surface for Shin et al. roughness model, whereas for the specific values the upper surface has opposite tendency. In addition, the common for these three surface roughness models, shear stress values show that the most fluctuations occurred around stagnation points (range from -0.02m to 0.03m in Y-axis).

![Image 3. Shear stress comparison.](image)

3.1.2. Heat flux. A thermal boundary layer will develop during ice accretion, which is similar to the viscous boundary layer, where it has a significant variations in fluid temperature and also caused different heat transfer characteristics along the blade profile surface. Figure 4 shows that the fluctuation of heat flux in shin et al. roughness model is much more than specific values, similar to Figure 3. In addition, the upper surface has higher Gresho heat flux than lower surface for both in Shin et al. model and 0.0003m roughness model, whereas for 0.03m roughness model, the lower surfaces have higher heat transfer than upper surface. The common for these three surface roughness models of heat flux shows that the most fluctuations occurred similarly as shear stress, around the stagnation points (range from -0.02m to 0.03m in Y-axis).

![Image 4. Gresho heat flux comparison.](image)

3.2. Effect of Surface Roughness on Ice Accretion

3.2.1. Ice Shapes. To study the effect of surface roughness on ice accretion, accreted ice shape is one of the most important parameter that shows the comparison. Figure 5 shows the different ice shapes under three different surface roughness models and Figure 6 shows the roughness height and velocity magnitude around three different roughness models. For the higher roughness value (0.03m), more ice accreted along the stagnation points, whereas in case of smaller roughness values (0.0003m), less ice was accreted along stagnation point, but have humps along both upper and lower sides. In other word, the smaller surface roughness lead more uneven ice surfaces than bigger roughness model.
3.2.2. Ice growth and ice thickness. Ice growth and ice thickness are two important parameters for ice accretion. Figure 7 and Figure 8 show ice growth and ice thickness, respectively. The most fluctuation for both cases occurred around stagnation points (range from -0.02m to 0.02m in Y-axis). However, the bigger roughness value (0.03m) get the highest ice growth, whereas the Shin et al. get the highest ice thickness. Values of total ice mass accreted in 15 mins are shown in Table 2, which also indicate that Shin et al. roughness model has lowest total mass of ice.

| Total mass of ice (Kg) | 0.0003m | 0.003m (Shin et al. Model) | 0.03m |
|------------------------|---------|---------------------------|-------|
|                        | 0.004509 | 0.004362                  | 0.004675 |
4. Conclusion

This preliminary study provides a good insight of surface roughness effects on ice accretion physics. Multiphase numerical analysis shows that surface roughness has significant influence on ice accretion of DU06-W-180 airfoil at glaze ice condition. The change of surface roughness effects the shear stresses along the blade surface. Moreover, the Gresho heat flux in-case of the smaller roughness values (0.003m and 0.0003m) has positive correlation with the surface roughness and shear stress, while for the bigger roughness values (0.03m) shows the opposite. Analysis shows that smaller surface roughness resulted in more uneven surfaces than bigger surface roughness value. In addition, the most fluctuation for ice growth and ice thickness occurred around stagnation points due to maximum shear stress and heat flux variation.

Acknowledgments

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