Numerical Estimation of Anti-icing Heating Power for NREL 5MW Wind Turbine Blades in Cold Climate

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Abstract. This work aims to give an estimate of the heating power used in the anti-icing system of the NREL 5MW wind turbine rotor operating in a cold climate in the presence of suspended water particles in the air. In this work, the turbine blade was simulated using an in-house code implemented in OpenFOAM framework that uses compressible Lagrange-Euler approach to simulate water particles transport from the atmosphere to the blade surface. On the water film side, Shallow-Water Icing Model (SWIM) is used to simulate the icing and anti-icing process. The results show that at least 3\% of the rated power of the rotor should be used just to keep the water film from freezing. It shows also that most of the heating power should be concentrated on the leading edge, lower surface of the blade, and the middle sections of the blade.

1. Introduction
In many areas of the world, especially in Europe, wind farms are located in cold regions and high altitude areas. Such locations are selected to benefit from the fact that wind speeds generally increase with the increase in altitude due to wind shear. However, during operation in such areas, turbines are exposed to harsh operating conditions with very low ambient temperatures that can result in ice accretion on its parts. In case of ice accretion on blades, problems like power losses, due to change of the aerodynamic profile of the blades, the increased mechanical and fatigue loads on the turbine, and safety hazards of ice shedding occur. Such icing problems usually make turbine shutdown inevitable. To avoid the effects of ice formation like turbine tripping, wind turbines are equipped with anti-icing and/or de-icing systems. In case of using anti-icing techniques, additional icing sensors should be added to control the operation of the anti-icing system [1]. Otherwise, the anti-icing system should be operational for unnecessarily long time periods, which costs more heating energy [2]. In case the design depends on using active anti-icing and de-icing systems, there are different strategies to heat the blade. One strategy is to add heating layers between the layers of wind turbine blade [3], mainly on the leading edge. The main problem with such a system is that it complicated to apply and it can attract lighting [1]. Another strategy is to use warm air. In this case, the heater is placed at the root of the blade and air is injected through the blade. This
of course implies on the problem of none-localized heating. This makes this option much more expensive in operation than the electric heating option, especially with Glass-fibre reinforced plastics (GRP) that is known to be good thermal insulator [2]. Despite being effective, active anti-icing de-icing systems can consume energy up to 15% of turbine generated power [4]. Barber et al. [5] predicted that ice formation can lead to up to 17% loss in Annual Energy Production (AEP) for NREL phase VI rotor operating at 800-1500 m altitude. Regarding mechanical and fatigue loads, Lehtomäki et al. [6] performed two measurement campaigns for two different sites and analyzed production losses and fatigue loads. They found that for wind turbines with a hub height of 80 m and rotor diameter of 92 m, around 180 kg of ice was formed on a single blade and caused an increase in fatigue loads. Also, Battisti et al. [4] showed using Monte-Carlo simulations that the probability of being hit by ice block shed from a rotating turbine for moderate icing site is around 10%.

CFD techniques have proven over that last few decades that they can be a good approach to simulate and anticipate many physical and engineering problems. Accordingly, more researches have focused on the simulation of ice accretion on 3D rotating wind turbine blades to predict ice accretion profiles on the blades and hence can predict the performance drop and change of loads. An example of these researches is the work of Ibrahim et al. [7] that studied the effect of blade airfoil geometry and different Mean Volumetric Diameter (MVD) and Liquid Water Content (LWC) values on the ice accretion shape and hence on the overall power loss. They concluded that the profile thickness and its location relative to the leading edge is highly impacting the ice profile. Wang et al. [8] simulated the ice accretion of NREL Phase VI turbine under different atmospheric conditions and icing durations and concluded that ice grows significantly more near the lead edges and the tip of the blade. Shu et al. [9] studied ice accretion on NREL Phase VI turbine rotor under different wind speeds and concluded that iced blades are subject to more airfoil stall and this stall, and hence more power loss, increase with the increase of wind speed. The main objective of this work is to computationally estimate the heating energy used in anti-icing system of the NREL 5MW wind turbine rotor operating in a cold climate and in the presence of suspended water particles in the air. In this work, the turbine rotor was simulated using an in-house code implemented in OpenFOAM®v7 framework based on Lagrangian approach to simulate the transport of water particles from the atmosphere to the blade surface. This in-house code also is based on using the Shallow Water Icing Model (SWIM) to simulate calculate mass, momentum and energy conservation of the water-ice film on the blade surface. This study is made to show how much heating energy is consumed relative to the AEP to overcome the ice accretion problems which is interesting for both research and industry.

In the next section, a brief about of the used methodology is made with a justification of using the selected approaches rather than other possible approaches. In Section 3 a description of the case study is made. the last two sections, namely Sections 4 and 5 are to show the simulation results and analyze them to draw conclusions.

2. Methodology
To simulate the process of transport of water particles from the atmosphere to the blade surface, full simulation of flow fields, namely pressure field (p), velocity field (U), and temperature field (T), should be simulated. However, in this OpenFoam code, Lagrange-Euler approach is used to simulate water particles flowing around the blade and hitting its surface. After calculating the mass of water impinging on the surface and its distribution over the surface, SWIM model is applied to the water film on the surface. SWIM model enables the calculations of the ice mass and thickness on each surface element of the blade walls or to calculate the minimum amount of energy required to prevent water from freezing i.e. keep it at 273.16° K which in this work is called anti-icing heat.
2.1. Turbulence Model:

k-ω SST Turbulence Model is a two-equation model that can calculate both turbulence kinetic energy (k) and turbulent frequency (ω) using the equations [10]:

\[
\frac{\partial \rho k}{\partial t} + \frac{\partial \rho u_j k}{\partial x_j} = \frac{1}{\nu} \left( \frac{\partial}{\partial x_j} \left[ \left( \mu + \sigma_k \mu t \right) \frac{\partial k}{\partial x_j} \right] \right) - \beta \rho \omega k + \frac{\partial}{\partial x_j} \left[ \left( \mu + \sigma_k \mu t \right) \frac{\partial k}{\partial x_j} \right] (1)
\]

\[
\frac{\partial \rho \omega}{\partial t} + \frac{\partial \rho u_j \omega}{\partial x_j} = \gamma \left( \frac{\partial}{\partial x_j} \left[ \left( \mu + \sigma_\omega \mu t \right) \frac{\partial \omega}{\partial x_j} \right] \right) + 2(1 - F_1) \rho \sigma_\omega \frac{k}{\omega} \frac{\partial k}{\partial x_j} \frac{\partial \omega}{\partial x_j} (2)
\]

where

\[
P = \tau_{ij} \frac{\partial u_i}{\partial x_j}, \quad \tau_{ij} = \mu t \left( 2 S_{ij} - \frac{2}{3} \frac{\partial u_k}{\partial x_k} \delta_{ij} \right) - \frac{2}{3} \rho k \delta_{ij}, \quad S_{ij} = \frac{1}{2} \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right), \quad \mu_t = \frac{\rho a_1 k}{\max(a_1 \omega, 2 \sqrt{S_{ij} S_{ij} F_2})}
\]

and the above constants have values of:

\[
\gamma_1 = \frac{\beta_1}{\beta^*}, \quad \gamma_2 = \frac{\sigma_{\omega 2} \kappa^2}{\beta^*}, \quad \sigma_{k1} = 0.85, \quad \sigma_{\omega 1} = 0.5, \quad \beta_1 = 0.075, \quad \sigma_{k2} = 1.0
\]

\[
\sigma_{\omega 2} = 0.856, \quad \beta_2 = 0.0828, \quad \beta^* = 0.09, \quad \kappa = 0.41, \quad a_1 = 0.31
\]

2.2. Lagrangian flow simulation approach:

To calculate the amount of impinging water \( \dot{m}_{\text{imp}} \), impingement locations and its kinetic energy, Lagrangian particle tracking is used. The trajectory of each droplet is calculated using Newton’s second law which take the form:

\[
m_p \frac{dU_p}{dt} = -\frac{1}{2} |U_p - U| (U_p - U) \frac{\pi d^2}{4} C_D + F
\]

where \( F \) represents any other forces that affecting on the droplet. In OpenFOAM, modules for Lagrangian partial tracking and film calculation are already existed. The additional modules that should be implemented in OpenFOAM are \( \dot{m}_{\text{ice}} \) and \( \dot{Q}_{\text{ice}} \) that are applied as a phase change model and solved along with other film conservation equations.

2.3. Shallow-Water Icing Model (SWIM):

SWIM is a thermodynamic model that consists of conservation equations of the three thermodynamic quantities, namely: mass, momentum and energy, of the liquid film on the blade surface in partial differential equations form. After simplification of the conservation equations and applying boundary conditions, the equations as stated in [11]:

\[
\frac{\partial W}{\partial t} + \nabla . F = S
\]

where

\[
W = \rho_w \left( \frac{h_w}{h_w C_{p,w} T} \right), \quad F = \rho_w \left( \frac{\bar{u} h_w}{\bar{u} h_w C_{p,w} T} \right), \quad S = \left( \dot{Q}_{\text{drop}} + \dot{Q}_{\text{ice}} + \dot{Q}_{f} - \dot{Q}_{\text{evap}} - \dot{Q}_{\text{conv}} + \dot{Q}_{\text{cond}} \right), \quad \bar{u} = \frac{\dot{m}_{\text{imp}}}{2 \mu_w \tau_w}
\]
Figure 1. Comparison between CFD and experimental simulation results of case 27 [12]

To apply the above equations, compatibility relations must be satisfied, which are

\[ h_f \geq 0 \]  
\[ \dot{m}_{\text{ice}} \geq 0 \]  
\[ h_f \bar{T} \geq 0 \]  
\[ \dot{m}_{\text{ice}} \bar{T} \leq 0 \]

where \( \bar{T} = T_w - T_{\text{ref}} \).

by forcing \( T_w = 273.16 \) K, i.e. \( \bar{T} = 0.01 \) which is the temperature lower limit of liquid state of water at 1 bar, into the equations and also by setting \( \dot{m}_{\text{ice}} = \dot{Q}_{\text{ice}} = 0 \), anti-icing heating power, \( \dot{Q}_{\text{cond}} \) in this case, can be calculated.

2.4. Validation of the solver:
To make sure that the in-house code implemented in OpenFOAM v7 is working properly, validation with experimental results has been carried out. In this validation, rime ice formation over NACA0012 airfoil was simulated and compared with wind tunnel results of case 27 done by NASA [12]. In this case, ice accretion on NACA0012 airfoil with 0.53 m chord length at 58.1 m/s at angle of attack (AoA) = 4° was tested. The wind tunnel experiment in this case was carried out and ambient temperature of 245.2°K and the water spray achieved LWC = 1.3 gm/m³ and MVD = 20 µm. The in-house code showed good agreement with the resulted ice profile indicated in the report of the results [12] as shown in Fig. 1.

3. Case study: NREL 5MW wind turbine blade
In this work, the anti-icing heating power required to keep the NREL 5MW wind turbine blade ice-free was simulated. As indicated in its definition documents [13], this blade is 61.5 m long and rotates with 12.1 rpm at 11.4 m/s as rated rotor and wind speeds respectively. The rated tip speed, in this case, is found to be 80 m/s.

To simulate the anti-icing heating power required to keep the blade ice-free, the NREL 5MW wind turbine blade was first simulated using NREL FAST v8 to calculate the AoA and inflow velocity at each radial station of the blade. For each of the blade stations, the anti-icing power was calculated using 2D simulations of airfoil profiles of each station. After that, the resulting heat is multiplied by the station width and all power values are summed together to result in
Figure 2. Cross section of 2D airfoil mesh generated

the total blade heating power.

The anti-icing heat was simulated at 11.4 m/s and 12.1 rpm. For atmospheric conditions, ambient temperature is set at 263.15°K which is within the operation range of low-temperature climate wind turbines which has a minimum of 243.15°K [16]. Also, liquid water content (LWC) was taken at 1.3 gm/m^3 and mean volumetric diameter (MVD) was set at 20µm. These operation conditions were selected to represent highly probable conditions to give a realistic estimate of anti-icing heat.

4. Simulation Results and Discussion

After applying the methodology from Section 2 on case study from Section 3, The anti-icing heat was calculated as shown in Fig. 3. In this figure, the radial distribution of heating power over the blade was shown.

From Fig. 3, it can be noticed that there are two different parameters that are highly affecting the anti-icing heat:

- Tangential velocity of the airfoil: the higher the relative velocity of air carrying water particles the higher the mass of water particles hitting the blade surface. Accordingly, higher tangential velocities at higher radial positions should need higher heating powers.
- Surface area of the section: The higher the surface section area the higher the collection efficiency and the required heating power.

In wind turbine blades, it is known blade sections’ chord lengths decrease with the increase of radius of rotation. Accordingly, the aforementioned two parameters are inversely proportional with each other. However, the middle sections of the blade, specifically between 0.5-0.8 R, have relatively high values of both chord lengths and tangential velocities. this results in higher required anti-icing heat for these sections. This can be seen obviously in Fig. 3.

Another important outcome of the simulations of this work is the distribution of required heating over the blade sections as can be seen in Fig. 4. From this figure, it can be noticed that most of the required heating power is required for the lower surface of the airfoil. This happens due to the positive angle of attack of airfoils during operation in rated conditions. It also can be seen that not only the required heating peaks at stagnation point, that corresponds to angle of attack, but also there is required heating downstream on the lower surface of the airfoil due to the run-back phenomenon. These results gives indication of where the anti-icing heat should be applied or concentrated to give effectiveness against ice formation. This should be very important in case of applying localized heating, using electric heaters embedded in blade materials, or applying special coatings that delays the ice formation process.

By summing all heating power resulted from the simulations on all control surfaces, the mini-
The minimum required heating power sums to 146.7 kW. This value represents almost 3% of rated power which is 5000 kW. This can give an indication of how the icing phenomenon entails losing some of the generated power of the turbine to prevent the problems occurring due to ice formation on the blades.

As mentioned in Section 1, usually composite materials, like GRP, are good thermal insulators. This means that the calculated anti-icing power should be higher to ensure that the required heat will reach the surface. To ensure that the required heat flux for each control surface can be delivered to the blades’ surfaces, this entails additional technical details and simulation techniques that highly dependent on the used anti-icing technique and blade material. Also additional simulation process of conjugate heat transfer (CHT) should be added to this study.
Figure 5. Particles’ sizes distribution and locations around blade station at \( r/R = 0.5 \)

to see the effect of different material properties. But it can be expected that, the higher the thermal conductivity of the blade material, the lower the required heating power to ensure no ice formation and accordingly the higher the anti-icing or deicing system efficiency.

5. Conclusions and Future Work

In this work, the required anti-icing heating power for the NREL 5MW wind turbine blades at the rated wind and rotational speeds and typical icing atmospheric conditions. This simulation case study was carried out using in-house code within OpenFOAM®v7 that uses Lagrange-Euler approach to simulate airflow field water particles transport to the blade and SWIM model to simulate water flow on the surface of the blade and required anti-icing heat. The aforementioned simulation case study resulted in requiring at least 3% of the rated power of the NREL 5MW rotor to be dissipated in the form of anti-icing heat to ensure that no ice will form on the blades at rated wind and rotor speeds. Also, the simulation has given a prediction of the areas on the blade surfaces that requires most of the heating power. For radial distribution of anti-icing heat, it is found that sections between 0.5-0.8R have the highest heat demand due to their high tangential velocities, and accordingly high relative wind velocity, and their high surface area as well. Also through the simulation’s results, it can be predicted that the heating power demand is the highest at stagnation point and on the lower surface of the airfoil section due to run-back of water film that needs to be heated to avoid freezing.

Since the simulations calculate only the required heating power for each control surface on the blade, these results do not take into consideration material properties or heating distribution over the blade that depends on the heating technique. Accordingly, the simulated heating distribution is the minimum heating that should reach the surface to prevent ice formation. However, the actual required heating power will be more than the values of the simulations. Since this work is a preliminary work in this field, it is intended to include other physical phenomena in the simulation process like different modes of heat and mass transfer. These
additionally simulated phenomena shall provide a more accurate estimation of anti-icing heating power.

6. Acknowledgement
This work is part of project OptAnIce: Optimales Anti-Icing für Rotorblätter im kalten Klima, funded by the German Federal Ministry for Economic Affairs and Energy (BMWi), fund No.: 0324232C. The simulations were performed using the HPC Cluster EDDY, a part of WIMS-Cluster project and funded by the BMWi.
The first author would like to thank Dr Hassan Kassem and Leo Hönig from Fraunhofer IWES for valuable discussions about OpenFOAM implementation.

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