Investigation of ice accretion effect on the aerodynamic characteristics of a wind turbine blade tip after a short icing event

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Abstract. The paper investigates the flow behavior near the NACA 64-618 airfoil profile of the blade tip section of a wind turbine for electric power production after a short icing event. The flow simulation considering the rotation speed of the wind turbine blade is performed to assess the effect of icing on the aerodynamic characteristics. Degradation of aerodynamic characteristics affects the electrical energy production of the wind turbine. The aerodynamic lift and drag coefficients are calculated for different angles of attack. The flow velocity fields near the airfoil are analyzed. The pressure coefficient distributions along the profile surface are obtained. The points of flow stall and changes of aerodynamic characteristics at different angles of attack are determined.

1. Introduction

The demand for energy resources in the world is growing, and therefore renewable energy sources, which are a cleaner and more affordable alternative to fossil energy sources, are becoming increasingly important. Wind energy has a leading position among renewable energy sources [1].

The reduction of negative environmental impacts from the energy sector is related to the increase of total global wind power capacity. Limiting global warming to below 2°C compared to pre-industrial levels requires installing an average of 180 GW of new wind power annually, and from 2030 onwards up to 280 GW will need to be installed annually to maintain a pathway consistent with achieving net zero by 2050 [2].

Northern territories have substantial wind energy resources and could become an area for expanding the use of renewable wind energy to meet the world's energy needs [3-4]. Another way of using wind energy in the north is energy supply for remote northern settlements that are not connected to the central energy supply systems and are dependent on imported fuel [5].

However, weather conditions are a limiting factor for the widespread use of wind energy in the north. Wind turbine structures, especially the blades, are prone to ice formation [6]. Blade icing leads to aerodynamic degradation due to changes in airfoil shape and increased surface roughness [7]. Ice formation on the blades causes a decrease in lift and at the same time an increase in drag force, resulting in reduced power output from the wind turbine [8-9]. In addition, the ice accretion on the wind turbine structures can lead to partial or complete mechanical destruction, errors in measurements, and a threat to human health and life due to ice falling from the blades [10-11]. Consequently, the operation of wind turbines in northern weather conditions requires additional technical solutions and in-depth knowledge of the ice formation process.

In a previous paper, the authors investigated the effect of icing on the performance of a wind turbine [12]. Four cases with inflow velocities of 10, 15, 20 and 25 m/s were considered to assess the effect of 60-minute icing event on the performance of the wind turbine and to build a power curve after icing. In addition to inflow velocities, the rotation speed of the sections, relative flow velocity considering inflow velocity and blade rotation speed, axial and tangential induction coefficients were considered and calculated for each considered blade section. This allowed to simulate the flow conditions for each blade element close to the real conditions of the wind turbine and rotor rotation, except for the three-dimensional influence of the sections on each other. The blade geometry of the NREL 5MW wind turbine was used as a reference for the study. The calculation of the aerodynamic characteristics showed that the greatest losses are observed near the tip of the blade due to the formation of large amounts of ice.

This paper is devoted to the study of the aerodynamic characteristics of the blade tip airfoil of a wind turbine after a short icing event. The airfoil NACA 64-618 is chosen for the study as one of the blade tip sections of the NREL 5MW wind turbine. Seven cases with different angles of attack (AoA) are considered in the article to assess the effect of the ice shape on the aerodynamics of the blade.

2. Materials and methods

The blade geometry of the NREL 5MW wind turbine was used in this study (figure 1). NREL 5MW blade is divided into 17 sections and consists of 8 different airfoils [13]. The main characteristics of the NREL 5MW are presented in the table 1.

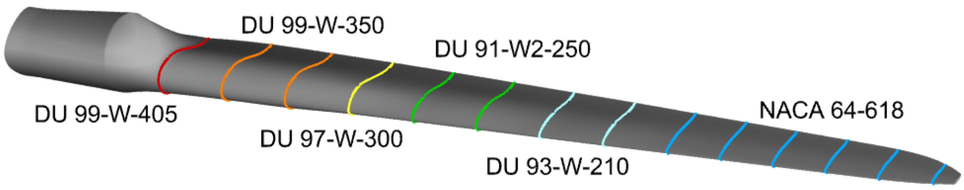

Figure 1. Blade geometry of the NREL 5MW wind turbine.

Table 1. Characteristics of the NREL 5MW.

Characteristic	Value
Rated power	5 MW
Rotor diameter	126 m
Hub diameter	3 m
Blade length	61.5 m
Hub height	90 m
Cut-in, rated, cut-out wind speed	3 m/s, 11.4 m/s, 25 m/s
Cut-in, rated rotor speed	6.9 rpm, 12.1 rpm

The blade tip of a wind turbine is most prone to icing. Therefore, its sections are of most interest for studying the effect of icing on the performance of a wind turbine. The NACA 64-618 airfoil is used for the blade tip sections of the NREL 5MW wind turbine. Airfoils of the NACA family are widely used in the design of wind turbine blades [14-16]. The profile selected for the study has the following characteristics: NACA 64-618 airfoil, r/R = 0.98, chord length = 1.419 m, twist angle = 0.106°. The research uses the icing geometry of the airfoil obtained by the authors in a previous paper [12] as a result of simulation of wind turbine blade icing with an inflow velocity of 10 m/s, which corresponds to the relative velocity of the flow for the selected section of the blade – 68.9 m/s (figure. 2).

The simulation was performed in the ANSYS Fluent finite volume method solver. The SST k-w turbulence model was used for flow simulation [17-18]. This model is widely used, in particular for flow calculations near wind turbine blades, and provides reliable flow calculations [19-21]. The Coupled scheme was chosen to solve the pressure-velocity coupling. Seven cases with angles of attack from -15° to 15° with 5° step were simulated to evaluate the effect of icing on the aerodynamic characteristics of the blade section. An inflow velocity of 10 m/s was chosen for all cases. The relative flow velocity, considering the inflow velocity and the rotation velocity of the blade, is 68.9 m/s.

Two-dimensional structured grid was created for the study. The wall distance was calculated considering the fluid parameters, flow velocity, profile size and the desired value of the function Y+ less than 1 [22-23]. The distances from the airfoil to the mesh boundaries were chosen with consideration of no influence of the walls on the result: the boundary after the airfoil is 25 chord lengths, the other directions are 15 chord lengths (figure 2).

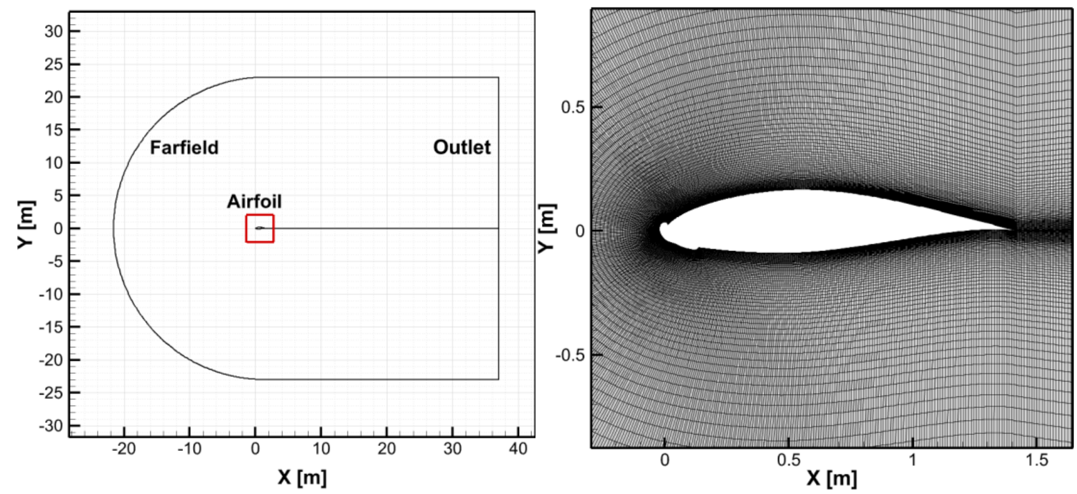

Figure 2. Numerical domain (left) and mesh near the airfoil (right).

The study of the independence of simulation results from the quality of the mesh model was performed for the aerodynamic profile of a wind turbine in order to provide an optimal balance between the accuracy of the obtained results and the waste of computational resources and time per simulation. Six different grid models with different number and configuration of cells were created to determine the minimum required number of cells. For this estimation, simulations were performed and aerodynamic coefficients of lift and drag forces were calculated at an angle of attack of 0° and Reynolds number of 6 million. A comparison of the results showed that a 153,000 cells mesh provides a sufficient level of accuracy with a reasonable use of computational resources.

3. Results and Discussion

The simulation resulted in the computation of the flow near the NACA 64-618 airfoil with ice formation. Aerodynamic lift and drag coefficients were obtained. Figure 3 shows that the lift coefficients have negative values at negative angles of attack. The lift coefficient increases as the positive angle of attack increases up to 10°. There is a decrease in the lift coefficient at 15°, which may indicate flow stall.

Figure 4 shows the change in the drag coefficient at different angles of attack. The lowest drag coefficient values are observed at angles of attack between -10° and 5°. Angles of attack above and below this range are characterized by increasing drag coefficient, especially for the case of AoA 15°.

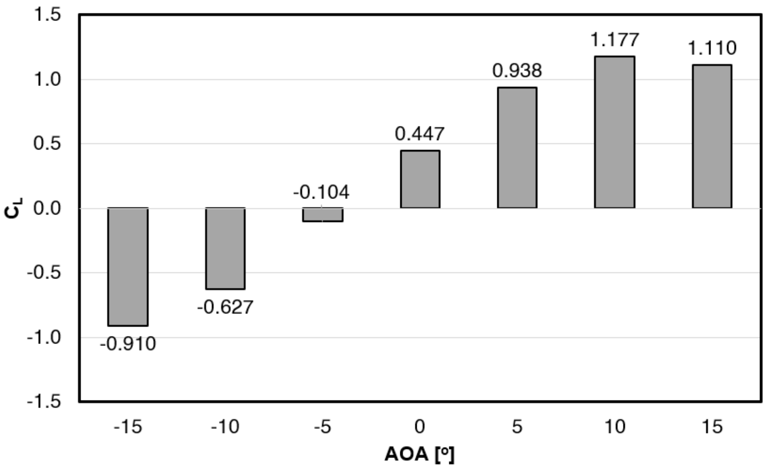

Figure 3. Lift coefficients C_L for NACA 64-618 iced airfoil at different angles of attack.

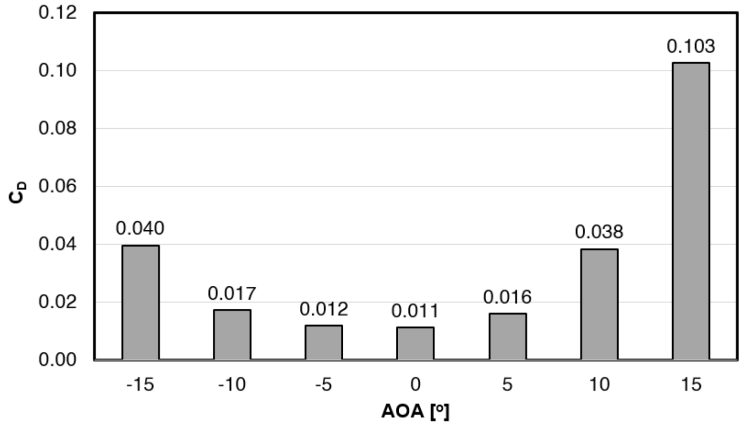

Figure 4. Drag coefficients C_D for NACA 64-618 iced airfoil at different angles of attack.

Figure 5 shows the flow velocity fields for the NACA 64-618 iced airfoil for the inflow velocity of 10 m/s (relative velocity – 68.9 m/s) and at the angles of attack from -15° to 15°. All cases show flow disturbance near the ice formation at the leading edge. The slightest changes in flow are found for cases with AoA -5°, 0°, and 5°. Flow stall at positive angles of attack is noticeable at 10°, and deep stall is observed at 15°. The flow stall at negative angles of attack is noticeable at -15° and absent at -10°. This confirms the previously described results of calculating the lift and drag coefficients.

The pressure coefficient distributions along the NACA 64-618 iced airfoil surface at angles of attack of 0°, 5°, 10° and 15° are shown in figure 6. Disturbance at the leading edge is common to all presented cases, which is caused by the influence of icing on the airfoil shape and leads to a degradation of its aerodynamic characteristics. It is observed that the pressure difference at the leading edge increases with increasing angle of attack. But cases AoA 10° and 15° have a smaller pressure difference along the pressure side compared to other cases due to the flow stall, which leads to a reduction of the aerodynamic characteristics.

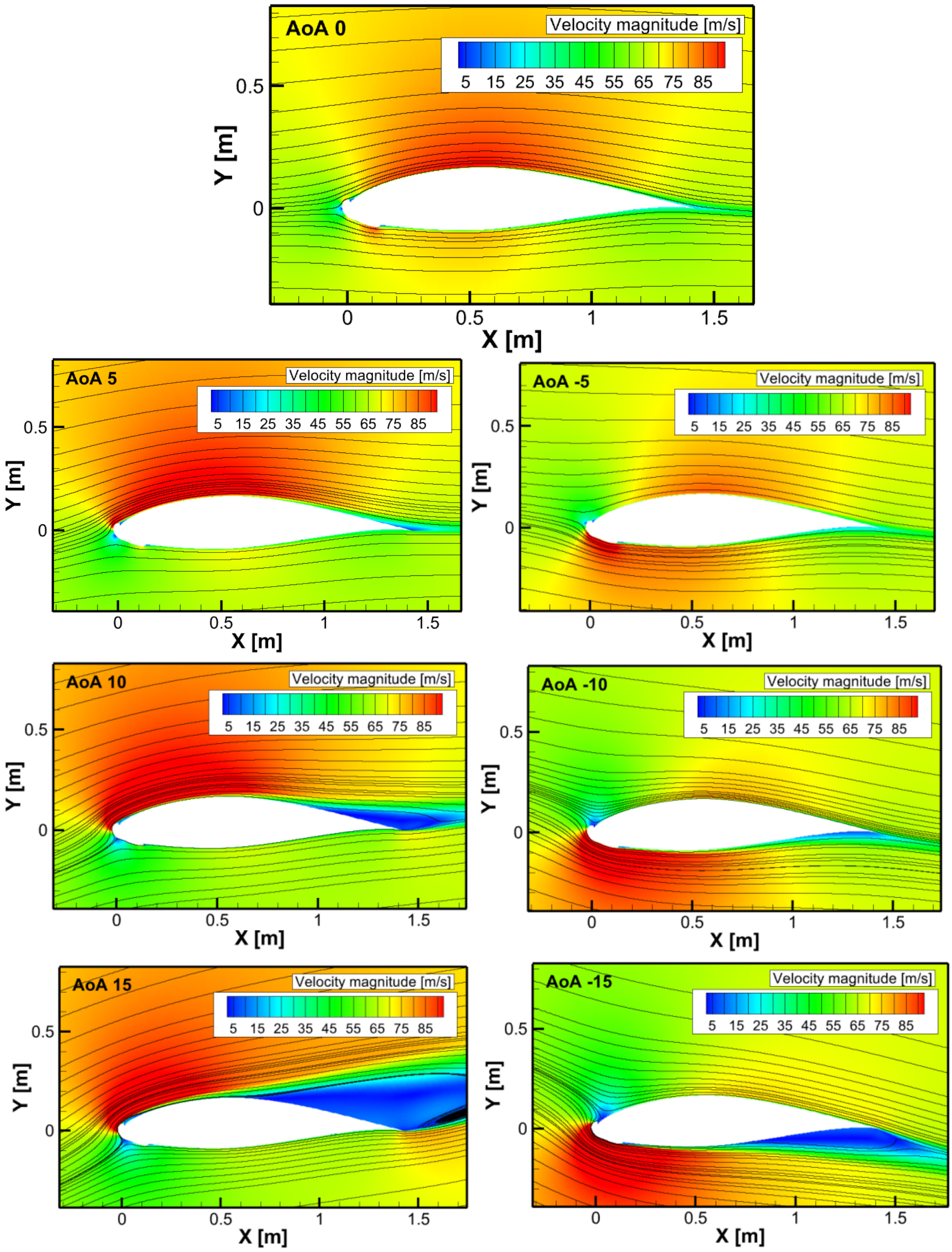

Figure 5. Flow velocity fields for the NACA 64-618 iced airfoil.

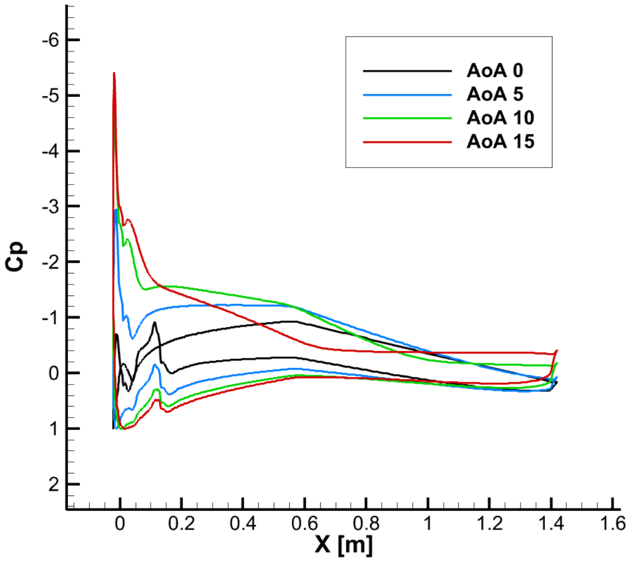

Figure 6. Pressure coefficient distribution along the NACA 64-618 iced airfoil.

4. Conclusion

In this paper, the ice accretion effect on the aerodynamic characteristics of the wind turbine blade tip airfoil after a short icing event was investigated. As a result of CFD numerical simulation of the flow at different angles of attack, the aerodynamic coefficients were calculated. The lift coefficient is negative at negative angles of attack. The maximum lift coefficient value of 1.177 was obtained at the angle of attack of 10°. The lowest drag coefficient values are observed at angles of attack from -10° to 5°. The result of calculating the aerodynamic coefficients showed that the AoA 5° case has the highest C_L/C_D ratio, indicating the best performance for the iced airfoil at the AoA 5°. The pressure coefficient distribution is disturbed compared to the clean airfoil. At the AoA 0°, the lowest pressure difference is observed due to the changed shape of the profile. The analysis of the flow velocity fields and pressure coefficient distributions showed that the flow stall occurs at the AoA 15°.

Acknowledgments

This research was supported by the Russian Science Foundation Grant [grant number 22-29-20294], https://rscf.ru/project/22-29-20294/.

References

[1] Global Energy Review 2021. The International Energy Agency

[2] Global Wind Report 2021. Global Wind Energy Council

[3] Ma X, Li Y and Li Z 2022 The projection of canadian wind energy potential in future scenarios using a convection-permitting regional climate model. *Energy Reports* **8** 87-7176

[4] Solbakken K, Birkelund Y and Samuelsen E M 2021 Evaluation of surface wind using WRF in complex terrain: Atmospheric input data and grid spacing. *Environmental Modelling & Software* **145** 105182

[5] Abbey C, Katiraei F, Brothers C, Dignard-Bailey L and Joos G 2006 Integration of distributed generation and wind energy in Canada *2006. IEEE Power Engineering Society General Meeting (IEEE)* 1–7

[6] Gao L, Tao T, Liu Y and Hu H 2021 A field study of ice accretion and its effects on the power production of utility-scale wind turbines. *Renew Energy* **167** 28-917

[7] Ibrahim G M, Pope K and Muzychka Y S 2018 Effects of blade design on ice accretion for horizontal axis wind turbines. *Journal of Wind Engineering and Industrial Aerodynamics* **173** 39–52

[8] Barber S, Wang Y, Jafari S, Chokani N and Abhari R S 2011 The Impact of Ice Formation on

Wind Turbine Performance and Aerodynamics. *J Sol Energy Eng* **133** 1–9
[9] Homola M C, Virk M S, Nicklasson P J and Sundsbø P A 2012 Performance losses due to ice accretion for a 5 MW wind turbine. *Wind Energy* **15** 379–89
[10] Roberge P, Lemay J, Ruel J and Bégin-Drolet A 2022 Evaluation of meteorological measurements made on the nacelle of wind turbines in cold climate. *Cold Reg Sci Technol* **203** 103658
[11] Parent O and Ilinca A 2011 Anti-icing and de-icing techniques for wind turbines: Critical review. *Cold Reg Sci Technol* **65** 88–96
[12] Kangash A, Virk M S and Maryandyshev P 2022 Numerical study of icing impact on the performance of pitch-regulated large wind turbine. *Wind Engineering* 1–13
[13] Jonkman J, Butterfield S, Musial W and Scott G 2009 Definition of a 5-MW Reference Wind Turbine for Offshore System Development
[14] Sener M Z and Aksu E 2022 The numerical investigation of the rotation speed and Reynolds number variations of a NACA 0012 airfoil. *Ocean Engineering* **249** 1–10
[15] Jones R and Williams D 1936 *The effect of surface roughness of the characteristics of the airfoils NACA 0012 and RAF 34*
[16] Liu Y, Li P, He W and Jiang K 2020 Numerical study of the effect of surface grooves on the aerodynamic performance of a NACA 4415 airfoil for small wind turbines. *Journal of Wind Engineering and Industrial Aerodynamics* **206** 104263
[17] Wilcox D C 1988 Reassessment of the scale-determining equation for advanced turbulence models. *AIAA Journal* **26** 1299–310
[18] Menter F 1993 Zonal Two Equation k-w Turbulence Models For Aerodynamic Flows *23rd Fluid Dynamics, Plasmadynamics, and Lasers Conference* (Reston, Virigina: American Institute of Aeronautics and Astronautics)
[19] Menter F R 1994 Two-equation eddy-viscosity turbulence models for engineering applications. *AIAA Journal* **32** 1598–605
[20] Rocha P A C, Rocha H H B, Carneiro F O M, Vieira da Silva M E and Bueno A V 2014 k–ω SST (shear stress transport) turbulence model calibration: A case study on a small scale horizontal axis wind turbine. *Energy* **65** 8-412
[21] Moshfeghi M, Song Y J and Xie Y H 2012 Effects of near-wall grid spacing on SST-K-ω model using NREL Phase VI horizontal axis wind turbine. *Journal of Wind Engineering and Industrial Aerodynamics* **107–108** 94–105
[22] Zanon A, de Gennaro M and Kühnelt H 2018 Wind energy harnessing of the NREL 5 MW reference wind turbine in icing conditions under different operational strategies. *Renew Energy* **115** 72-760
[23] Gantasala S, Tabatabaei N, Cervantes M and Aidanpää J-O 2019 Numerical Investigation of the Aeroelastic Behavior of a Wind Turbine with Iced Blades. *Energies (Basel)* **12** 1–24