# Consideration of Icing in the Design of Wind Turbine Blade Sections

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*Abstract*—**Ice accretion on a 2D section of wind turbine blades is simulated and considered in the design methodology with the aim to determine blade shapes with reduced aerodynamic performance degradation due to icing. The ice accretion model simulates the air flow around the blade, determines the trajectories of water droplets, and calculates the ratio of droplets that freeze on the blade surface. The shape is designed by applying an inverse design process that provides the blade shape from a prescribed pressure or velocity distribution. The aerodynamic coefficients of the bare blade and the iced blade are calculated, and thus, the aerodynamic performance of the iced blade is compared to that of the bare blade. The aerodynamic performance degradation may be reduced by involving a correction factor in the process. This correction factor modifies the prescribed velocity distribution so that the inverse design process results in a blade shape that will be applicable under some icing conditions. These conditions are considered according to the prevailing meteorological conditions of the location where the wind turbine is installed. Simulations also reveal the modification of the ice shape on the blade surface during the icing event, and subsequently, the influence of the length of icing event on the aerodynamics of the blade. The consideration of icing of the blade in the design process contributes to finding blade shapes that can enable wind turbines to operate under a wide range of ambient conditions satisfactorily.**

Keywords— ***blade shape, ice accretion, inverse design, numerical simulation, wind turbine***

## I. INTRODUCTION

The aerodynamic properties of wind turbine blades have a substantial effect on the entire system of the wind turbine. A challenging problem that the designer faces is finding the relationship between the blade shape and its aerodynamic properties. Since many favourable sites for wind farms are located in cold, wet regions, the effects of ice formation can usually not be neglected in the design of blade shapes. Ice accretion on wind turbine blades reduces lift generation and enhances drag, leading to power loss, which may go up to 30-50% at sites with particularly high risk of icing [1], [2]. Furthermore, ice accumulation also affects safety and lifetime of the wind turbine systems.

These problems justified the great research efforts that had been made to study the effects of icing on wind turbine blades. The ice accretion process and its effects on wind turbine performance have been studied numerically and experimentally. Reference [3] observed ice formation on horizontal axis wind turbine blades, and reported icing profiles that were formed in natural glaze icing events. Reference [4] modelled the rime-ice accretion process numerically using the commercial CFD code Fluent. They simulated the cloud as a two-phase flow composed by cold air and water. Then, they determined the thickness of the accreted ice layer on the blade surface of a horizontal axis wind turbine. Reference [5] carried out numerical investigation to predict power loss due to ice accretion. Reference [6] relied on experimental observations to determine the loss of annual energy production due to ice accretion. Reference [7] studied icing on a small horizontal axis wind turbine numerically and experimentally. They determined the distribution of ice accretion along the blade length, and revealed the effects of ice accretion on the aerodynamics of the wind turbine blade, and consequently, on the energy production. Some recent studies also considered the effects of blade geometry on the ice accretion, and involved ice accretion in the design process. Reference [8] investigated the effects of airfoil shape and airfoils thickness on the quantity of ice accumulated on the blade, and they also discussed the effects of ice accretion on the aerodynamic performance of the wind turbine. Reference [9] proposed a methodology for the design of the blade shape, which took into account the effects of icing conditions in choosing the blade design parameters.

The traditional rotor design process is based on given target performance criteria, which is tested either experimentally or computationally. Test results are then used to modify the geometry and the design loop is repeated until an adequate blade design is found. Inverse design methods differ from traditional methods in that geometry is generated automatically for a pre-defined required aerodynamic performance. Nonetheless, ice accretion changes the operational geometry, and thereby, it modifies the aerodynamic properties. Therefore, the prevailing icing conditions of the location where the wind farm is installed as well as the effects of icing under those conditions on the aerodynamics of the blade were involved in the design methodology proposed in [9]. They concluded, however, that the method could be improved by considering several further factors that influence the icing process. The present study will apply a different numerical approach to simulate the icing process. This approach is applicable to simulate the growth of ice in time; thus, it permits to observe how the growing ice shape worsens gradually the aerodynamic performance of the blade.

The procedure to design the shape of the two dimensional (2D) section of wind turbine blades is implemented in Matlab. Simulations of ice accretion and the calculation of the aerodynamic coefficients are carried out by finite element modelling. More precisely, ice accretion is simulated using Ansys Fensap-Ice [10], and the aerodynamic coefficients are determined by applying Ansys Fluent.

## II. Methodology to Design Shape of Blade Section

### A. Inverse Design Process

The process to find the shape of the 2D section of bare blade is based on the Garabedian-McFadden technique [11] that was later modified in [12]. The technique is an iterative process to find geometry of the blade according to a required pressure or velocity distribution. An initial blade shape is chosen, and then the positions of blade coordinates are modified so that they approach the positions along the surface that corresponds to the target velocity distribution. The upper and lower surfaces of the blade are divided into subdomains, and the surface ordinates are moved in each step of the iteration. The equation to be solved at each blade position is the following

$$A\Delta y + B\frac{\mathrm{d}(\Delta y)}{\mathrm{d}x} - C\frac{\mathrm{d}^2(\Delta y)}{\mathrm{d}x^2} = V_{tar}^2 - V_{pr}^2 \tag{1}$$

where $V_{pr}$ and $V_{tar}$ are the present and target velocities, respectively, and $A$, $B$ and $C$ are numerical constants. There is no analytical method to choose the values of these constants. The values were chosen so that they should be large enough to avoid the airfoil from changing too much in one step, and that the number of iterations should be the smallest when the free stream velocity is in the range of interest (i.e. up to 30 m/s, which is the range of velocity prevailing during icing events). If the derivatives in Eq. (1) are written in discrete form, then the equation to be solved may be organized in the form

$$\begin{bmatrix} k_2 & k_3 & & & 0 \\ k_1 & k_2 & k_3 & & \\ & k_1 & k_2 & \ddots & \\ & & \ddots & \ddots & k_3 \\ 0 & & & k_1 & k_2 \end{bmatrix} \begin{bmatrix} \Delta y_2 \\ \Delta y_3 \\ \Delta y_4 \\ \vdots \\ \Delta y_{n-1} \end{bmatrix} = \begin{bmatrix} V_{tar,2}^2 - V_{pr,2}^2 \\ V_{tar,3}^2 - V_{pr,3}^2 \\ V_{tar,4}^2 - V_{pr,4}^2 \\ \vdots \\ V_{tar,n-1}^2 - V_{pr,n-1}^2 \end{bmatrix} \tag{2}$$

where the parameters $k_1$, $k_2$ and $k_3$ include the numerical constants $A$, $B$ and $C$, and $n$ denotes the number of points along the upper and lower blade surfaces. The first and last points along the blade do not change the position, i.e. $\Delta y_1 = \Delta y_n = 0$. The coefficient matrix is a tridiagonal matrix; thus, Eq. (2) can be solved to obtain $\Delta y_2, \ldots, \Delta y_{n-1}$. Further details are provided in [9].

### B. Application of Correction Factor

The process described in Section II.A does not consider the possibility that ice may accrete on the blade, which changes the aerodynamics of the blade, and consequently, the performance of the wind turbine. If the ratio of power outputs with and without ice accretion on the blade are estimated, then a correction factor may be applied in the inverse design process. This factor modifies the target velocity distribution according to the severity and frequency of icing events in the location where the wind turbine is installed. Consequently, the inverse design process provides a modified blade shape, which results in improved performance under icing conditions.

The power coefficient, and consequently, the power output of the wind turbine is related to the lift-to-drag ratio. Thus, the reduction in the power output due to ice accretion can be estimated from the reduction in the lift-to-drag ratio. Once the iced shape is known, and the lift and drag coefficients are calculated, then one can also estimate the ratio of power coefficients for the bare and iced blades $r_{CP}$. The frequency of icing events at a given location may be considered via the number of icing days per year divided by the number of total days when the wind turbine operates in a year $r_{ice}$. Reference [9] defined a formula using these two parameters in order to determine the correction factor

$$r = 1 + r_{CP} r_{ice} \tag{3}$$

This correction factor is used to increase the difference between velocities near the upper and lower surfaces of the blade. Increasing this velocity difference requires a more asymmetric blade shape that provides greater lift. It was found in [9] that the reduction in the lift-to-drag ratio due to ice accretion is relatively smaller for such shapes.

## III. Simulation of Ice Accretion

Simulation of ice accretion on the wind turbine blade involves several steps. First, the airflow around the turbine blade should be determined; then the droplet trajectories are simulated, which provides the local ratio of droplets that hit the blade surface; and finally, the local ratio of droplets that freeze to the blade surface is calculated from the heat balance. These steps were implemented in Matlab in the preceding research [9], [13]. That approach is suitable for distinguishing ice shapes obtained on different blade shapes under different icing conditions. However, the commercial software Ansys Fensap-Ice [10] is also applicable for simulating icing events during given time intervals. Therefore, this software was applied in the present project in order to scrutinize how the length of icing event influences the ice shape obtained in former studies.

### A. Icing Conditions and Blade Shapes

The shape of ice accretion and the aerodynamics of the iced blade are influenced essentially by the icing conditions and by the blade shapes. Therefore, the methodology to design blade shape was applied for different icing conditions and for various target velocity distributions that can be produced by different blade shapes.

Two icing conditions, namely in-cloud icing and freezing drizzle, were considered. The thermodynamic parameters describing a typical case under each of these conditions [14] are listed in Table 1. Only zero angle of attack was considered in the present simulations.

TABLE I. Thermodynamic parameters considered for in-cloud icing and freezing drizzle conditions

| Parameter | In-cloud icing | Freezing drizzle |
|---|---|---|
| Wind speed (m/s) | 20 | 10 |
| Air temperature (°C) | – 10 | – 5 |
| Liquid water content (g/m$^3$) | 0.3 | 1.5 |
| Median volume diameter (μm) | 27 | 62 |

The NACA 4-digit airfoils were considered as the 2D section of blades. In particular, ice accretion on four airfoils were simulated and studied in this project, which are the NACA2412, NACA4412, NACA6412 and NACA8412 airfoils. The first digit in these airfoils was varied, which means that the position of the maximum camber and the thickness of the airfoil were kept constant, but the maximum camber was changed. Increasing the maximum camber means a greater curvature of the camber line leading to a more asymmetric shape and greater lift.

### *B. Computational Model*

Ice accretion on the blade shapes listed in Section III.A was simulated using Ansys Fensap-Ice. Three dimensional (3D) geometries are considered in these simulations, with constant cross sections defined by the airfoils listed in Section III.A and a width of 1 m. The computation involves three solvers that provide the flow field solution, the droplet solution, and the icing solution. In order to simulate the time dependent process of ice accretion, a quasi-steady multishot approach is applied. Multishot ice accretion with automatic mesh displacement is available in Fensap-Ice [10]. It means that the total time of ice accretion is divided into smaller steady-state intervals (shots) where the airflow, droplet trajectories and icing are computed on a fixed grid. At the end of each shot, a mesh is produced to account for the additional ice deposition obtained during this shot and is used in the next shot. This new mesh includes the same number of nodes; thus, the size and aspect ratio of the elements near the ice change compared to the mesh of the previous shot. The time intervals of icing simulations were chosen 60 min, 90 min and 120 min. Two longer simulations that lasted 240 min were also carried out with the NACA4412 airfoil under the two icing conditions defined in Section III.A. The flowchart of this computation can be seen in Fig. 1.

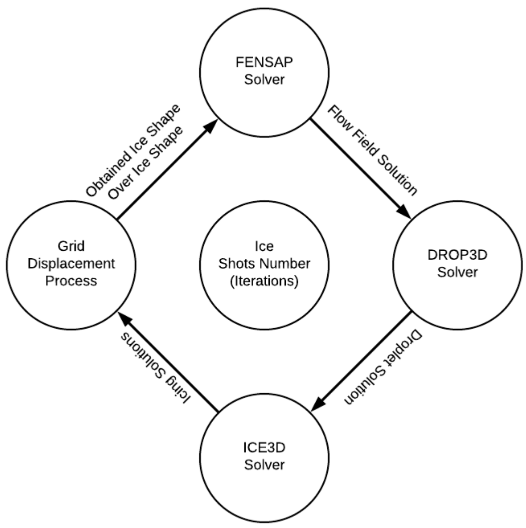


Fig. 1 Flowchart of multishot calculation in Fensap-Ice

The aerodynamic coefficients of the iced blade shapes were calculated using Ansys Fluent. In these simulations, 2D sections of the iced shapes were considered. The geometry of the iced shape was determined by the coordinates of the mid-section of the 3D iced blade obtained in the icing simulation using Fensap-Ice. The computational domain was chosen so that it extended four times the chord length before the leading edge, fifteen times the chord length after the trailing edge, and twice the chord length above and below the chord line that connects the leading edge and the trailing edge. Automatic mesh was applied with face sizes of 0.05 mm. Turbulence was modelled by the $k$-$\varepsilon$ model with standard wall functions. Velocity at the inlet of the computational domain was prescribed according to the free stream velocity as boundary condition. Settings of spatial discretization included Green-Gauss node-based gradient evaluation, standard scheme for the pressure equation, and second order upwind scheme for the momentum and energy equations. Solution was initialized from the inlet, and calculation ran for 500 iterations.

## IV. Simulation Results

### *A. Shape of Iced Blades*

Icing on the 3D geometry of the airfoils under the icing conditions is obtained from the Fensap-Ice simulations. Typical ice shapes are shown in Fig. 2 where icing on the NACA4412 airfoil was simulated under freezing drizzle and in-cloud icing conditions, and simulation time was 240 min.

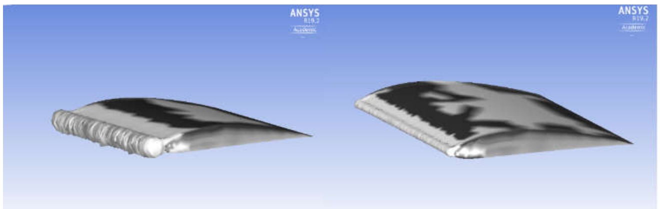

Fig. 2 Icing on the NACA4412 airfoil after 240 min under freezing drizzle (left) and in-cloud icing (right) conditions

The aerodynamic coefficients were calculated using Ansys Fluent on the 2D sections that were taken from the middle of the 3D iced blade. The sections obtained from the iced blade shown in Fig. 2 are drawn in Fig. 3. These shapes served as the basis of comparison and as input for the flow simulations in Ansys Fluent.

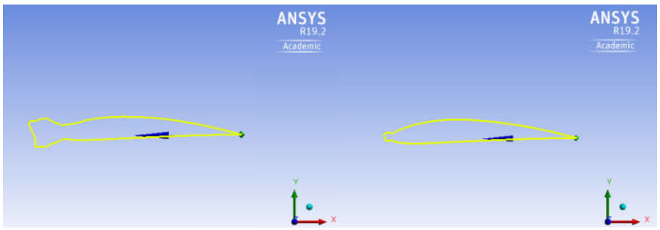


Fig. 3 Cross sections of iced shapes of NACA4412 airfoils after 240 min under freezing drizzle (left) and in-cloud icing (right) conditions

Fig. 3 shows clearly that significantly more ice accumulates on the blade under freezing drizzle condition that under in-cloud icing condition. This result corresponds to formerly published observations [9, 15, 16]. Simulation results at different time instances also show how the ice shape changes in time under the conditions considered. These results can be seen in Fig. 4 for the four airfoils and for the two icing conditions considered. Ice accretion is not only greater in size under freezing drizzle condition, but it also appears on a greater surface of the blade. It can also be observed in Fig. 4 that more ice accretes on the upper surface and less ice occurs on the lower surface of the blade when the maximum camber (i.e. the first digit in the airfoil code) increases. This finding follows from the fact that the curvature of the camber line increases when the maximum camber is greater, and thus, a greater part of the upper surface is exposed to the flow in case of the same angle of attack.

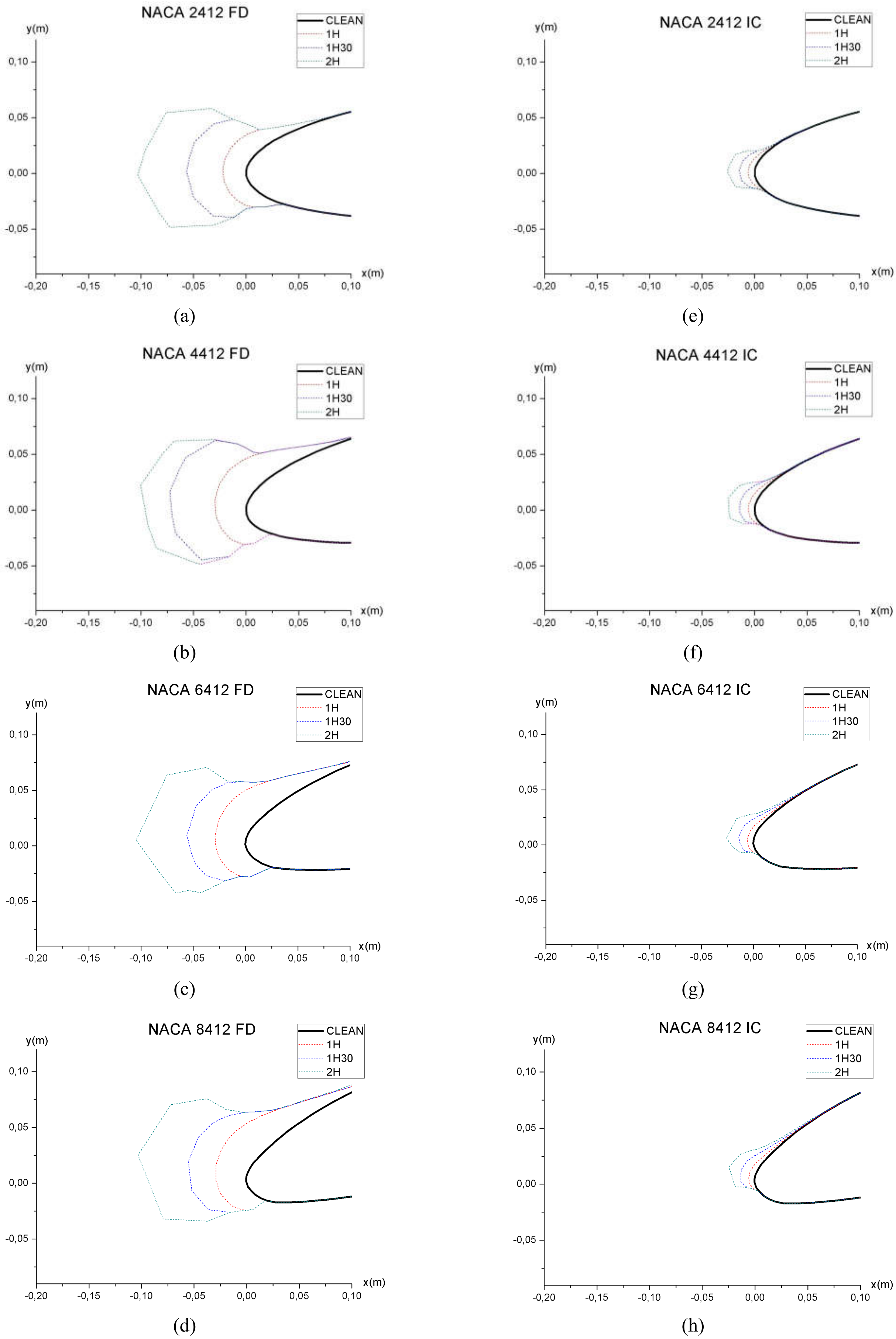


Fig. 4 Variation of iced shapes in time on the four airfoils considered under freezing drizzle (a-d) and in-cloud icing (e-h) conditions

*B. Aerodynamic Coefficients of the Iced Shapes*

The ice accretion on the blade has a significant influence on the aerodynamic coefficients. In particular, the drag increases and the lift decreases; thus, the aerodynamic performance degradation due to ice can be expressed by the lift-to-drag ratio. The reduction of this parameter due to ice accretion during freezing drizzle is shown in Fig. 5. The lift-to-drag ratio after 60, 90 and 120 min of icing reduces to about 70-80%, 40-70% and 25-35%, respectively, of its value obtained for the bare blade. Thus, freezing drizzle has a severe effect on the aerodynamics after a relatively short time. It was found in [9] that the lift-to-drag ratio due to ice accretion under freezing drizzle condition reduces to below 50% of the value obtained for the bare blade. This reduction was observed after 120 min of icing event in the present simulations.

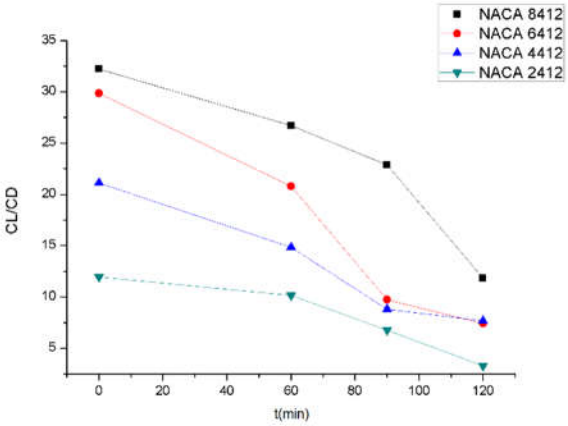


Fig. 5 Variation of lift-to-drag ratio ($C_L/C_D$) with duration of icing event ($t$) under freezing drizzle condition

The reduction of the lift-to-drag ratio due to ice accretion during in-cloud icing is shown in Fig. 6. The reduction of the lift-to-drag ratio is significantly smaller than under freezing drizzle condition. Its value after 120 min of icing is still close to 90% of its value obtained for the bare blade. The reduction of the lift-to-drag ratio obtained in [9] was around 70-75%, or even more in some cases. This aerodynamic performance degradation may be only caused by longer icing events. A further reason of the discrepancy between the results is that Fensap-Ice estimates less ice on the lower surface of the blade; therefore, the reduction of the lift-to-drag ratio is underestimated.

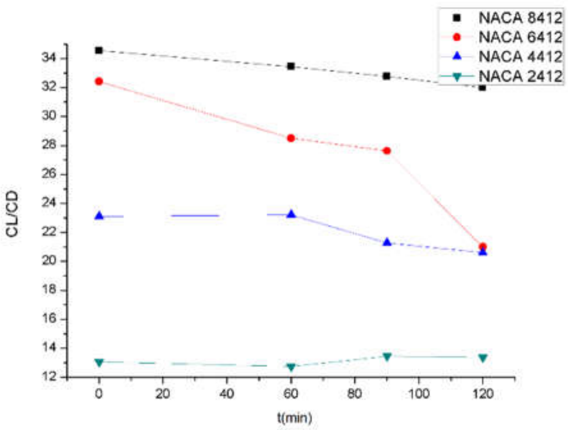


Fig. 6 Variation of lift-to-drag ratio ($C_L/C_D$) with duration of icing event ($t$) under in-cloud icing condition

*C. Discussion on Involving the Duration of Icing Event in the Correction factor*

Reference [9] concluded that the formula (3) recommended for calculating the correction factor does not consider several factors that influence the icing process or the aerodynamic performance of the wind turbine. The results above suggest that the duration of icing event is one of the important factors to be considered. This factor may be involved in different ways. One possibility is to take the average duration of the icing event into consideration, which may be based on statistics of meteorological data for the geographical location where the wind turbine is installed. Alternatively, the same formula (i.e. Eq. (3)) is applied to determine the correction factor, but a time limit is also defined so that if the duration of icing event exceeds this time limit then the wind turbine should be shut down. The reason for this decision is that the aerodynamic performance degradation, and consequently, the reduction in the power output becomes so severe that it will be disadvantageous to use the wind turbine until the end of the icing event.

## V. Conclusions

The present research investigated the influence of the duration of icing event on the aerodynamic performance degradation of wind turbines. The commercial software Ansys Fensap-Ice was applied to simulate icing on four airfoils with different shapes and for two essentially different icing conditions. The results revealed the reduction in the lift-to-drag ratio with the duration of icing event in all of the cases considered. The lift-to-drag ratio was about 90% of its value obtained for bare blade even after 2h of icing under in-cloud icing condition. However, this reduction was much more severe under freezing drizzle condition. The lift-to-drag ratio reduced to about the half of its value for the bare blade after 1h 30min, and to about one third of its value for the bare blade after 2h. Thus, it is recommended to consider the duration of icing event in the correction factor that was formerly proposed to be involved in the design process. The consideration of the duration of icing event may happen in different ways, which is the subject of further study.

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