A Lagrangean Interactive Interface to Evaluate Ice Accretion Modeling on a Cylinder – A test case for icing modeling on wind turbine airfoils

A multiphase CFX based approach into ice accretion modeling on a cylinder

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INTRODUCTION

The impact of icing on wind turbines

State of art of icing simulation (problematic and particularity of ice.)

Literature reviews, context and objectives

Methodology and plan of study

1st Paper: Lagrangian interactive interface to evaluate ice accretion modeling on a cylinder
  ▪ Trajectory calculations
  ▪ Scenarios and results

2nd Paper: Multiphase CFX based approach into ice accretion modeling on a cylinder
  ▪ Eulerian approach for calculations of water collection efficiency
  ▪ Validation of results

Conclusion & References
INTRODUCTION

Wind velocity plays important role in wind power resources.

Power available in the wind:

\[ P_a = \frac{1}{2} \rho_a \cdot S \cdot V_a^3 \]

Very significant wind resources are available in cold regions where icing effects are also significant.
THE IMPACT OF ICING ON WIND TURBINES

The problem of icing on wind turbines is related to:

- **Performance:** Loss of annual power production.
- **Loads:** Increase of dynamic loads and fatigue.
- **Safety:** Formation of large chunks of ice on blades.

All that coincides with the most abundant days of wind in the year.
Power loss due to the aerodynamic performance degradation depends on the type and the shape of the ice accreted.

Roughness and profile deformation decreases the lift-to-drag ratio $C_L/C_D$ which leads to the degradation of wind turbine performance and loss of annual power production.
STATE OF ART OF ICING SIMULATION

- Theory of icing on structures:
  - complexity of physical phenomenon: many branches of sciences interferes
  - complexity of icing simulation; CFD Aerodynamics (Finite Volume Method)
    - Navier-Stokes equations solution of air flow velocities
      (time and cost of computations)
    - Panel Method; Calculations of potential flow according to object’s profile (simplicity vs. errors)

- Lack of knowledge for wind turbines’ icing: Most codes, researches or anti-icing/de-icing systems were developed for aircrafts where security has priority over rentability.

- High capabilities of advanced CFD commercial software: Multi-phase and thermal modeling, powerful turbulence 3D simulation and coupling capability with user’s defined code.

- Icing on a cylinder is the fundamental of icing researches.

- In Canada, the phenomenon is underestimated.
PARTICULARITY OF ICE*

At temperatures lower than freezing point down to -40°C water is still liquid until the collision of a solid object.

Fog-type humidity is composed of super-cooled water droplets which is a meta-stable state. This will create problems of immediate phase change (Fluid, Liquid, Solid, vapor) resulting in different types of icing: Rime, Glaze, wet snow,...etc.

Water droplets in air will be treated as multi-phase fluid composed of air as continuous fluid and water as dispersed fluid.
PARAMETERS TO EVALUATE ICE ACCRETION*

• **Liquid Water Content LWC**
  The quantity of water contained in the air expressed as g/m³.

• **Median Volumetric Diameter MVD**
  A representative value of the water droplet distribution expressed as µm

• **Water Volume Fraction**
  Water volume exists in a control volume.

• **Collection Efficiency**
  The Capacity of an object to capture water droplets in a flow.
COLLECTION EFFICIENCY*

 Represents the ratio of the mass-flux of the impinging droplets to the mass flux in the free stream.
 It is the ability of an object to capture water droplets presented in the flow.
 Local collection efficiency $\beta$ is a differential form.

 $\beta \uparrow$ quand:

 $\alpha \uparrow$, $V_a \uparrow$, $MVD \uparrow$

 $C \downarrow$
Collection over a cylinder*

According to the studies of Lozowski et al. on fixed and rotating cylinder, calculations of the local collection for a cylinder can be used as a first approximation of ice accretion on other objects.

\[ D = 0.03 \, C \]

To simplify the calculations of ice accretion on an airfoil, a cylinder with a diameter of 0.03 of the profile’s chord may be representative of the airfoil.
OBJECTIVES

This project addresses the issues of icing effects on wind turbines in cold climates.

- **General objectives**
  - To evaluate the long-term impact of icing on the performance of wind turbines.
  - To develop effective techniques for defrosting.

- **Specific objectives**
  
  To develop numerical tools to simulate geometry deformation of objects and wind turbine profiles due to ice accretion using commercial CFD programs which will enable us to switch to a three-dimensional simulation of ice accretion around rotating blades of wind turbine needed to assess in total the impact of icing on a wind energy site.
Methodology of ice accretion simulation - physical models*

Four modules have to be adapted to calculate the geometric deformation based on the local ice accretion rate on surface element for every time step:

- **Aerodynamics simulation**
  Turbulence modeling, Profile of velocity.

- **Estimation of collection efficiency**
  Based on aerodynamics simulation using Eulerian approach (Water Volume Fraction) or Lagrangian approach (Droplets’ trajectory).

- **Thermodynamics**
  Calculation of ice accretion based on mass conservation and heat Transfer.

- **Geometric deformation**
  Based on the local ice accretion rate on surface element for every time step.

These modules are adapted using mutli-phase models available in ANSYS-CFX software to calculate the geometric deformation based on the local ice accretion rate on surface element for every time step.
The plan of study will consider the above modules to validate ice accretion simulation over a cylinder then to apply the method for wind turbine blades.
A Lagrangian Interactive Interface to Evaluate Ice Accretion Modeling on a Cylinder
An Interactive interface for tracking a water droplet in air flow intercepting a cylinder has been developed using MS-Excel supported with VBA - Visual Basic for Applications.

This interface provides much efficiency and flexibility to demonstrate various scenarios that can help to validate subsequent results.
TRAJECTORY CALCULATIONS

The Lagrangean approach models the movement of a super-cooled water droplets in an airstream. Therefore, we need to define the different forces acting on the droplet.

Forces acting on snow flake

- Gravity force, $F_g$
- Buoyancy force, $F_A$
- Lift force, $F_L$
- Drag force, $F_D$
- Pitch moment, $M_T$

We should, also, model the different equations of motion, the effect of the cylinder on the droplet speed, the constraints due to boundary conditions and the application of the fourth order Runge Kutta resolution scheme.
Assumptions

- Water particle is assumed to be spherical, rigid and having a radius R<500 Microns.
- Water droplets do not interact between them.
- Air flow disturbance through water droplets is negligible.
- Furthermore, we consider that the spherical water droplet cannot rotate and is subjected to no pitching effects. The motion of the particle is analyzed as a point mass which reacts with the potential flow without affecting it.

Those assumptions are essential; otherwise, the modelling would have been highly complex.
The relative velocity of a particle in air:

- $V_d$ represents the velocity of the water particle and $V_a$ the velocity of the air flow.

- We define $V_{dx}$ as the horizontal component of the water droplet velocity and $V_{dy}$ as the vertical component.

- Similarly, $V_{ax}$ and $V_{ay}$ stand for the horizontal and vertical velocity components of the airstream velocity respectively.

- We define $\gamma$ as the angle subtended by the relative velocity $V_r$ and the horizontal axis.

Vector diagram of velocities
Equations of movement

\[ \sum F_x = m_d \cdot a_{dx} + F_D \cdot \cos \gamma + F_L \cdot \sin \gamma = 0 \]
\[ \sum F_y = m_d \cdot a_{dy} + F_D \cdot \sin \gamma - F_L \cdot \cos \gamma + F_g - F_A = 0 \]

\[
F_A = \rho_a \cdot V_d \cdot g \quad F_g = \rho_d \cdot V_d \cdot g \quad V_d = \frac{v}{\delta} \cdot \pi \cdot d_d^3
\]
\[
F_L = \frac{1}{2} \cdot \rho_a \cdot A_T \cdot C_L \cdot |\bar{v}_r| \cdot \bar{v}_r \quad d_d = 0.05816 \cdot d_f^{0.817}
\]
\[
F_D = \frac{1}{2} \cdot \rho_a \cdot A_T \cdot C_D \cdot |\bar{v}_r| \cdot \bar{v}_r \quad A_T = \frac{1}{4} \cdot \pi \cdot d_d^2
\]

\[
\frac{dv_{dx}}{dt} = \frac{3}{4} \cdot \frac{\rho_a \cdot C_D}{\rho_d \cdot d_d} \cdot \sqrt{(v_{dx} - v_{a_x})^2 + (v_{dy} - v_{a_y})^2} \cdot (v_{dx} - v_{a_x})
\]

\[
\frac{dv_{dy}}{dt} = \frac{3}{4} \cdot \frac{\rho_a \cdot C_D}{\rho_d \cdot d_d} \cdot \sqrt{(v_{dx} - v_{a_x})^2 + (v_{dy} - v_{a_y})^2} \cdot (v_{dy} - v_{a_y}) + \left( \frac{\rho_a}{\rho_d} - 1 \right) g
\]

\[
\frac{dv_{d_d}}{dt} = \frac{C_D \cdot Re_d}{24 \cdot K_d} \left( \frac{v}{\nu_a} - \bar{v}_d \right) + \left( 1 - \frac{\rho_a}{\rho_d} \right) \bar{g} \quad K_d = \frac{1}{18 \cdot \mu_a} D_d^2
\]

\[
Re_d = \frac{d_d \cdot |\bar{v}_r|}{\nu_a} = \frac{d_d}{\nu_a} \sqrt{(v_{dx} - v_{a_x})^2 + (v_{dy} - v_{a_y})^2} \quad \nu = \frac{\mu}{\rho}
\]

\[
C_D = \frac{C_D}{f_c} \quad \text{si } d_d \leq 10 \text{ \(\mu m\)}
\]
Effect of the cylinder on air velocity $V_a^*$

$$\psi = V_\infty \sin \theta \left( r - \frac{R^2}{r} \right)$$

$$r = \sqrt{x^2 + y^2}, \quad \theta = \tan^{-1} \frac{y}{x}$$

$$\psi = V_\infty y \left( 1 - \frac{R^2}{x^2 + y^2} \right)$$

$$\frac{\partial \psi}{\partial x} = -V_{ay}, \quad \frac{\partial \psi}{\partial y} = V_{ax}$$

$$V_{ax} = V_\infty \left[ 1 + \left( \frac{R^2}{x^2 + y^2} \right) \right]$$

$$V_{ay} = -2V_\infty R^2 \frac{y \cdot x}{(x^2 + y^2)^2}$$
Solution of ODE with RK4*

Fourth Order Runge-Kutta

\[
\begin{align*}
y(t + \Delta t) &= y(t) + \frac{1}{6}(k_1 + 2k_2 + 2k_3 + k_4)\Delta t \\
k_1 &= f(y(t), t) \quad \text{Value at beginning of interval} \\
k_2 &= f(y(t) + k_1 \frac{\Delta t}{2}, t + \frac{\Delta t}{2}) \quad \text{Two estimates of value at mid-point} \\
k_3 &= f(y(t) + k_2 \frac{\Delta t}{2}, t + \frac{\Delta t}{2}) \\
k_4 &= f(y(t) + k_3 \Delta t, t + \Delta t) \quad \text{Estimate of value at end of interval}
\end{align*}
\]

\[
\frac{dy}{dt} = f(y, t)
\]

\[
y(t + \frac{\Delta t}{2}) = y(t) + f(y(t), t)\frac{\Delta t}{2}
\]

\[
y(t + \Delta t) = y(t) + f(y(t + \frac{\Delta t}{2}), t + \frac{\Delta t}{2})\Delta t
\]
Combination of variables

\[
\begin{align*}
\text{k1} &= \text{dx}(t, x, \text{vdx}) \\
\text{k2} &= \text{dx}(t + h/2, x + \text{k1} h/2, \text{vdx} + \text{m1} h/2) \\
\text{k3} &= \text{dx}(t + h/2, x + \text{k2} h/2, \text{vdx} + \text{m2} h/2) \\
\text{k4} &= \text{dx}(t + h, x + \text{k3} h, \text{vdx} + \text{m3} h) \\
\text{l1} &= \text{dy}(t, y, \text{vdy}) \\
\text{l2} &= \text{dy}(t + h/2, y + \text{l1} h/2, \text{vdy} + \text{n1} h/2) \\
\text{l3} &= \text{dy}(t + h/2, y + \text{l2} h/2, \text{vdy} + \text{n2} h/2) \\
\text{l4} &= \text{dy}(t + h, y + \text{l3} h, \text{vdy} + \text{n3} h)
\end{align*}
\]

\[
\begin{align*}
x_{n+1} &= x_n + \frac{1}{6}(k_1 + 2k_2 + 2k_3 + k_4) \\
z_{n+1} &= z_n + \frac{1}{6}(l_1 + 2l_2 + 2l_3 + l_4)
\end{align*}
\]

\[
\begin{align*}
k_1 &= \Delta t \cdot f(x_n, z_n, t_n) \\
k_2 &= \Delta t \cdot f(x_n + \frac{k_1}{2}, z_n + \frac{l_1}{2}, t_n + \frac{\Delta t}{2}) \\
k_3 &= \Delta t \cdot f(x_n + \frac{k_2}{2}, z_n + \frac{l_2}{2}, t_n + \frac{\Delta t}{2}) \\
k_4 &= \Delta t \cdot f(x_n + k_3, z_n + l_3, t_n + \Delta t)
\end{align*}
\]

\[
\begin{align*}
l_1 &= \Delta t \cdot g(x_n, z_n, t_n) \\
l_2 &= \Delta t \cdot g(x_n + \frac{k_1}{2}, z_n + \frac{l_1}{2}, t_n + \frac{\Delta t}{2}) \\
l_3 &= \Delta t \cdot g(x_n + \frac{k_2}{2}, z_n + \frac{l_2}{2}, t_n + \frac{\Delta t}{2}) \\
l_4 &= \Delta t \cdot g(x_n + k_3, z_n + l_3, t_n + \Delta t)
\end{align*}
\]
### Parameters and conditions of simulation

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atmospheric pressure</td>
<td>1.01325 e³ Pa</td>
</tr>
<tr>
<td>Ambient temperature</td>
<td>288.16 K</td>
</tr>
<tr>
<td>Heat coefficient at constant pressure, c_p</td>
<td>1005 J/kgK</td>
</tr>
<tr>
<td>Heat coefficient at constant volume, c_v</td>
<td>717.98 J/kgK</td>
</tr>
<tr>
<td>Precipitation</td>
<td>2.8 mm/hr</td>
</tr>
<tr>
<td>Liquid water content, LWC *¹</td>
<td>8 g/m³</td>
</tr>
<tr>
<td>Diameter of water droplet MVD *²</td>
<td>3.13779x 10⁻³ m</td>
</tr>
<tr>
<td>μ of air (the dynamic viscosity)</td>
<td>1.8 x 10⁻⁵ kg/m.s</td>
</tr>
<tr>
<td>Diameter of the cylinder</td>
<td>0.02 m</td>
</tr>
<tr>
<td>Density of water</td>
<td>1000 kg/m³</td>
</tr>
<tr>
<td>μ of air (the dynamic viscosity)</td>
<td>1.69 x 10⁻⁵</td>
</tr>
<tr>
<td>Unperturbed velocity</td>
<td>10 m/s</td>
</tr>
</tbody>
</table>

*¹ LWC: Liquid water Content: calculated as $\frac{1000\rho \times \text{precipitation}}{36000000 \times \nu_t}$ [2]

*² MVD: Median Volumetric Diameter of water droplet

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>V_∞</td>
<td>10 m/s</td>
</tr>
<tr>
<td>d_C</td>
<td>0.02 m</td>
</tr>
<tr>
<td>X₀</td>
<td>-0.2 m</td>
</tr>
<tr>
<td>Y₀</td>
<td>-0.01 m</td>
</tr>
</tbody>
</table>
RESULTS

Some graphical results of the scenarios taken for each droplet initial vertical position $Y_0$

$x = -10d_c, y = +d_c/2$
$V_{infini} = 10m/s, dt = d_c/V_{infini}/10$
$ti=0, tf=.032$ (Pas variable)

$x = -10d_c, y = -d_c/2$
$V_{infini} = 10m/s, dt = d_c/V_{infini}/10$
$ti=0, tf=.032$ (Pas variable)
The interception with the cylinder

The whole trajectory of the water droplet in the third scenario till interception with the cylinder

The trajectory of water droplet zoomed in the vicinity of the cylinder
2nd article

A multiphase CFX based approach into ice accretion modeling on a cylinder
Eulerian approach based on multiphase models in ANSYS-CFX is used to simulate water volume fractions in order to estimate the collection efficiency due to ice accretion over a cylinder.

The k- Epsilon turbulence model has been used for the continuous phase.

Flow specifications:
Buoyant, non homogeneous, stationary, inviscid, incompressible, turbulent flow and steady state analysis

The results have been validated to be applied for wind turbine blades geometric deformation
MESH AND DOMAIN

Computational domain of the half-disc input have been used, which reduces the deformation of the velocity profile at the entrance. ANSYS CFX solver can not solve problems in 2D, for that three-dimensional geometry was built with two identical symmetries, one is extruded from the other with an amplitude equal to the length of a mesh element.

A hybrid mesh made from different size elements has been generated using trapezoids near the wall for the boundary layer and triangles for the rest of domain.

Sufficient mesh resolution is used near the stagnation region to capture accurately the local impingement characteristics.
VELOCITY PROFILE

Results of the simulation based on multiphase models in ANSYS CFX. (air as continuous fluid, water as dispersed fluid).

Air and water velocity vectors around the cylinder

It is obvious that air velocity vectors near the stagnation point deviate from the wall while water ones go over it. Those vectors are the impingement velocities required for the calculation of ice accretion.
WATER VOLUME FRACTIONS

The resulting contours of normalized water volume fraction define the accretion zone around the cylinder. In the shadowed area, water volume fraction is almost zero, no water droplets exist. It starts from the separation zone where water droplets deviates from the cylinder.

In order to determine the efficiency of ice accretion, it will be more comprehensive to use the superficial water velocity which is relates to the velocity at which the flow would have travelled if the porosity of water volume fractions was 100 %.
Water and air streamlines

Streamlines far from the cylinder pass straight without showing any interaction with it. The closer the streamlines are with the cylinder, the more affected they are by the presence of the cylinder. We note separation zones near the cylinder and impingement regions very close to the solid.

In the wake of the cylinder, we can see recirculation zones that can significantly affect the trajectory of water droplet near the cylinder zone.

We can see that the color of the streamlines define the velocity of the airstream at different locations. In the vicinity of the cylinder that the color lightens then darkens again. This shows that the airstream is initially retarded and then accelerated again as it passes along, very close to the cylinder.
Local collection efficiency for a cylinder has been estimated using an Eulerian approach in CFX. The results are shown in the figure are illustrated with respect to the circumferential distance on the cylinder.

**Simulation Conditions:**

- Cylinder radius 0.0508 m
- Free stream velocity 80 m/s
- Median Volumic Diameter of droplets MVD=16μm
- Liquid Water Content LWC=0.55 g/m³
- Ambient temperature 285.15 K
- Ambient Pressure 89867 Pa
- Density of air at inlet 1.097 kg/m³

Local collection efficiency is plotted as a function of the wraparound-distance over the cylinder.

The peak value ($\beta_{\text{max at stagnation point}}$) = 0.47
The impingement limits = [-0.04 m to +0.04 m]
VERIFICATION & VALIDATION

Results of local collection efficiency estimated using Eulerian approach in CFX

Though we see that qualitatively the model correctly shows the regions of ice accumulation, we need to validate the results quantitatively. The results are compared with data produced by Ruff et al. [1] using a Lagrangean and Eulerian approach which have been in turn validated with the results of FENSAP-ICE(DROP3D) [7]. This figure shows the superposition of those three results.
The results of local collection efficiency estimated using Eulerian approach in ANSYS-CFX are also compared with experimental results [1] & [2].
Conclusion

In both, the Excel based trajectory calculations and the CFX based simulation, we note that in the wake of the cylinder, the streamlines tend to converge to reproduce the initial stream. Thus a point of inflexion is found soon after the centre of the cylinder, whereby the speed is accelerated in the wake and the y value decreases (or increase) as the x displacement increases until the streamline becomes parallel to the initial flow. We can, therefore, notice that the qualitative trajectory is in line with simulated streamlines and forces acting on the droplet.

In the first study we emphasized on the different equations that are required to model the particle tracking in an airstream. Furthermore, we defined intrinsic parameters that can affect the impingement such as the Mean Volumetric Diameter of the super cooled water droplets, and the Liquid Water Content. The EXCEL based model was made as generic interface in order that parameters can be easily changed when required.

In the second study we focused on the domain, mesh, turbulence and energy model calibration. A very important part of this paper tackles the limitations of our model and explains deviations from results as such. In later studies, such limitations will be catered for. We notice that the model provides very interesting results concerning the water collection efficiency which are validated with mathematical and experimental results.

Ice accretion simulation requires very complex and multi-disciplinary modeling. Creating an EXCEL friendly interface for water droplet trajectory calculations and the validation of ANSYS-CFX based icing simulation around the cylinder which is the fundamental of icing researches, shows the efficiency of adopting commercial softwares to reducing complexity of icing simulation to be further applied for a three-dimensional simulation of ice accretion around rotating blades of wind turbine to estimate geometry deformation and subsequent aero-elastic consequences in order to assess in total the impact of icing on a wind energy site.
REFERENCES


