McGill

A PDE-Based 3D Approach to In-Flight Ice Accretion

Héloïse Beaugendre

Cermics, ENPC 18/02/2004

CFD Lab

What is In-flight Icing?

- The in-flight icing phenomenon results from the capturing of supercooled droplets (still in liquid form at a lower temperature than freezing point) present in a cloud

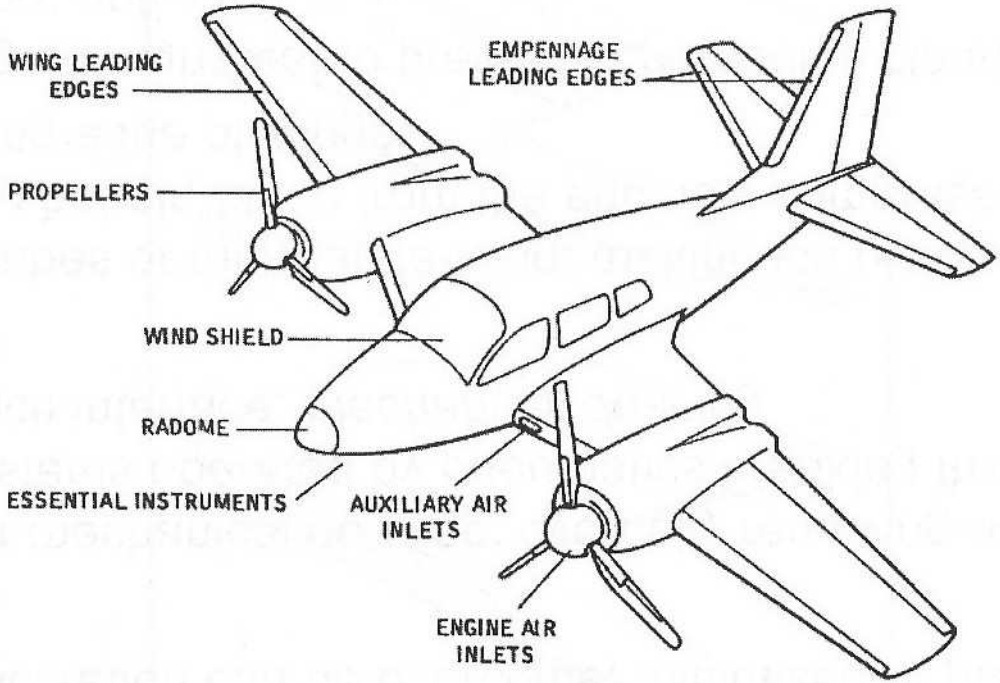
- When an aircraft enters an icing cloud, these droplets keep hitting the frontal area surfaces, forming an ice layer whose roughness and form can lead to substantial distortions in the aerodynamic profiles of wings, propellers, etc.

The in-flight icing phenomenon

- Contamination by icing is still a major cause of aircraft incidents and accidents (R.J. Kind)

- Small aircrafts and turboprops:
  - → Spend more time in clouds
  - → Fly at lower altitudes

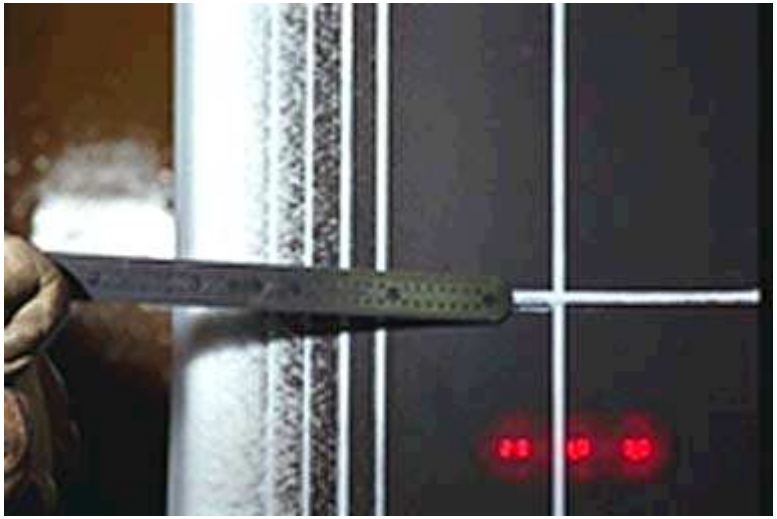
Area of the aircraft that may require ice protection



source: FAA, Technical Report ADS-4, December 1963.

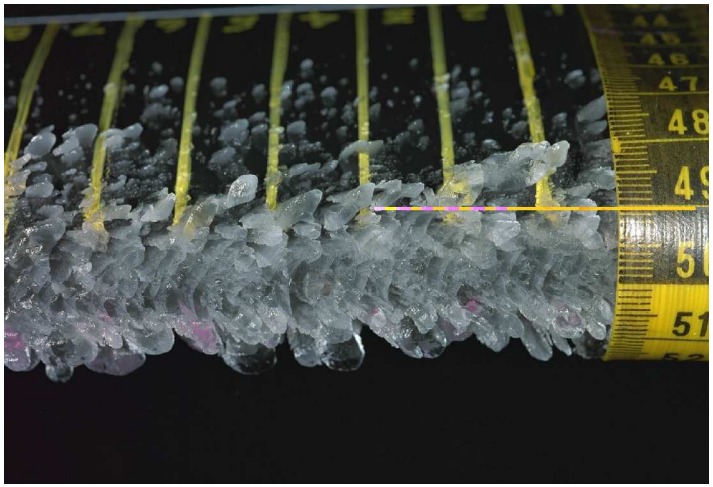
In-flight icing, rime ice

- Rime ice:
  - At low air temperatures
  - Low airspeeds, low LWC
  - Water freezes on impact
  - Ice shape remains reasonably aerodynamic
  - Surface is rough



In-flight icing, glaze ice

- Glaze ice:
  - At higher air temperatures
  - At high airspeeds, and high LWC
  - Only a fraction of water freezes on impact
  - The remainder runs back
  - Has non-aerodynamic ice shapes (horn-like)
  - Substantial performance degradation



The status of CFD for IFI

- National + proprietary ice accretion simulation codes (LEWICE, ONERA, ICECREMO, CANICE) are based on:
  - Panel methods or V/I interaction for flow
  - Lagrangian tracking for droplet impingement
  - CV analysis of mass and H-T for ice accretion

- Limited ability to:
  - Handle 3D or complex geometries
  - Account for compressibility effects
  - Detect flow recirculation and/or separation

Classical approaches for 3D computations

- 3D panel method for the flow calculation

- 3D Lagrangian tracking techniques for impingement
  - Difficulty in determining launching areas
  - Costly calculations
  - Difficulty in determining shadow zones

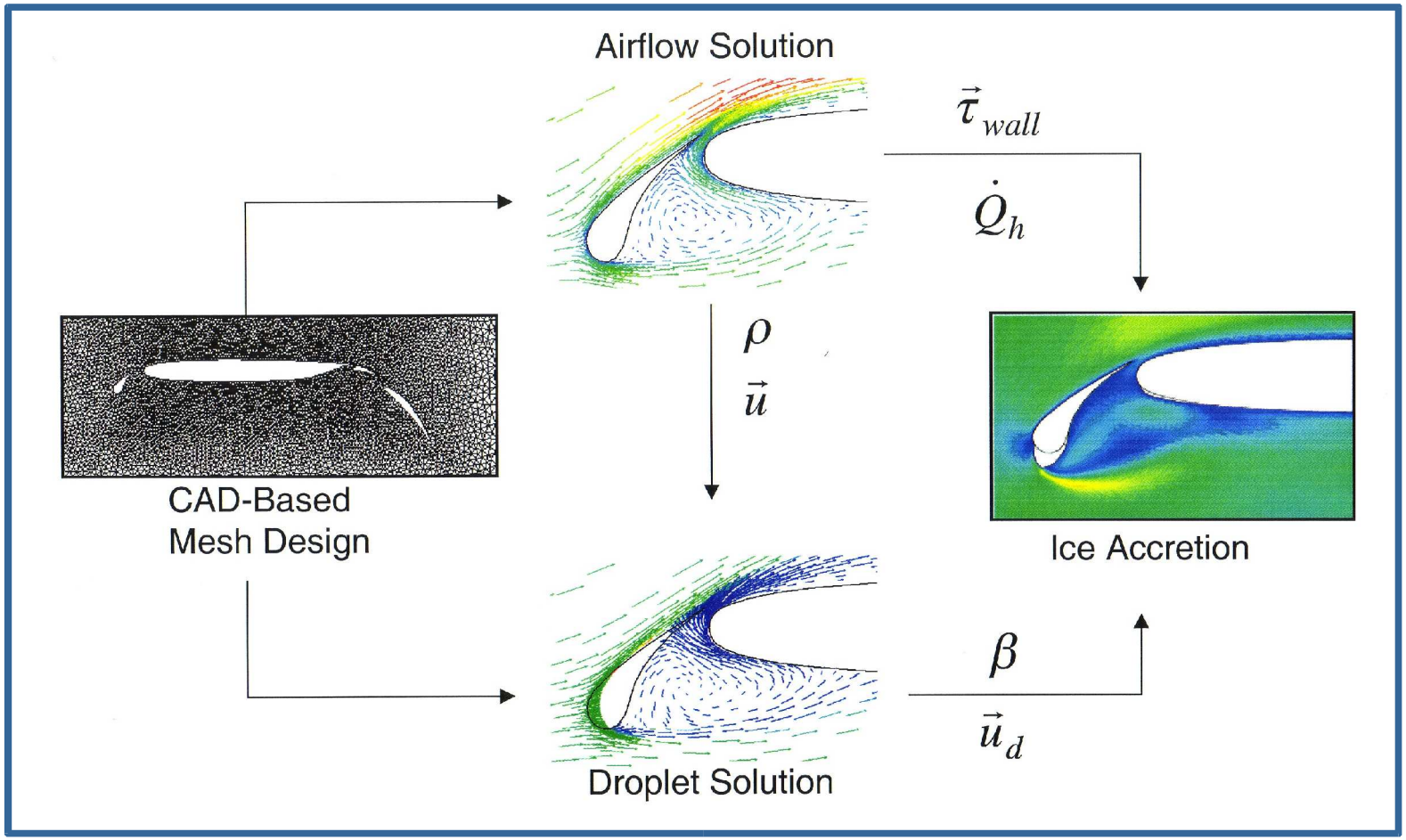
- Ice accretion
  - Determination of the stagnation line + streamlines of interest
  - 2D BL calculations along the streamlines
  - 2D ice accretion along the streamlines
    - No runback across the streamlines

Our modular approach

An approach, more compatible with current Aero methods, has been sorely needed for in-flight icing to be integrated as part of CFD studies:

- Increased mathematical fidelity (new PDEs)
- Increased geometric fidelity (3D + CAD)
- Increased flow fidelity (N-S + turbulence)
- Increased code modularity (interchangeability, same mesh for each step of the icing process)

Proposed CFD-based system: the "interchangeable" modules



The airflow

- The airflow solution is computed by 3D N-S:
  - Determine pressure, temperature, density and velocity, as well as convective heat fluxes and shear stress on all solid surfaces

- The turbulent convective heat flux along the surface strongly influences ice shape:
  - Appropriate turbulence modeling is needed
  - Appropriate roughness modeling is needed

Spalart-Allmaras 1-equation model

$$\frac{\partial \tilde{\nu}}{\partial t} + u_j \frac{\partial \tilde{\nu}}{\partial x_j} \quad ¿ \quad \frac{1}{\sigma \mathrm{Re}_\infty} \frac{\partial}{\partial x_k}\left[\left(\nu + \tilde{\nu}\right)\frac{\partial \tilde{\nu}}{\partial x_k}\right] + c_{b1}\left(1 - f_{t2}\right)\tilde{S}\tilde{\nu}$$

$$- \left[c_{w1} f_w - \frac{c_{b1}}{\kappa^2} f_{t2}\right]\frac{1}{\mathrm{Re}_\infty}\left(\frac{\tilde{\nu}}{d}\right)^2 + \frac{c_{b2}}{\sigma \mathrm{Re}_\infty}\frac{\partial \tilde{\nu}}{\partial x_k}\frac{\partial \tilde{\nu}}{\partial x_k} + \mathrm{Re}_\infty\left(f_{t1}\Delta U^2\right)$$

- Tripping functions to impose transition
- Simple implementation of roughness
- Spatial discretization by FEM
- Newton linearization of equations
- Implicit time-stepping scheme
- GMRES procedure to solve the matrix

Impact of roughness in icing

- Convective heat transfer
  - Is strongly related to surface roughness
  - influences the growth rate, shape and type of ice

- It is proposed to account for roughness of iced surfaces via an equivalent sandgrain roughness

- When the sandgrain roughness:
  - Is increased, the convective heat transfer will increase, producing rime ice
  - Is decreased, the convective heat transfer will decrease and only a fraction of the droplets freezes on impact, producing glaze ice

Rough-wall treatment with S-A

- The distance from the wall, d, is increased:

$$d = d_{\min} + 0.03\, k_s$$

- A mixed (Robin) BC is applied on the walls

$$\frac{\partial \tilde{\nu}}{\partial n} = \frac{\tilde{\nu}}{d}$$

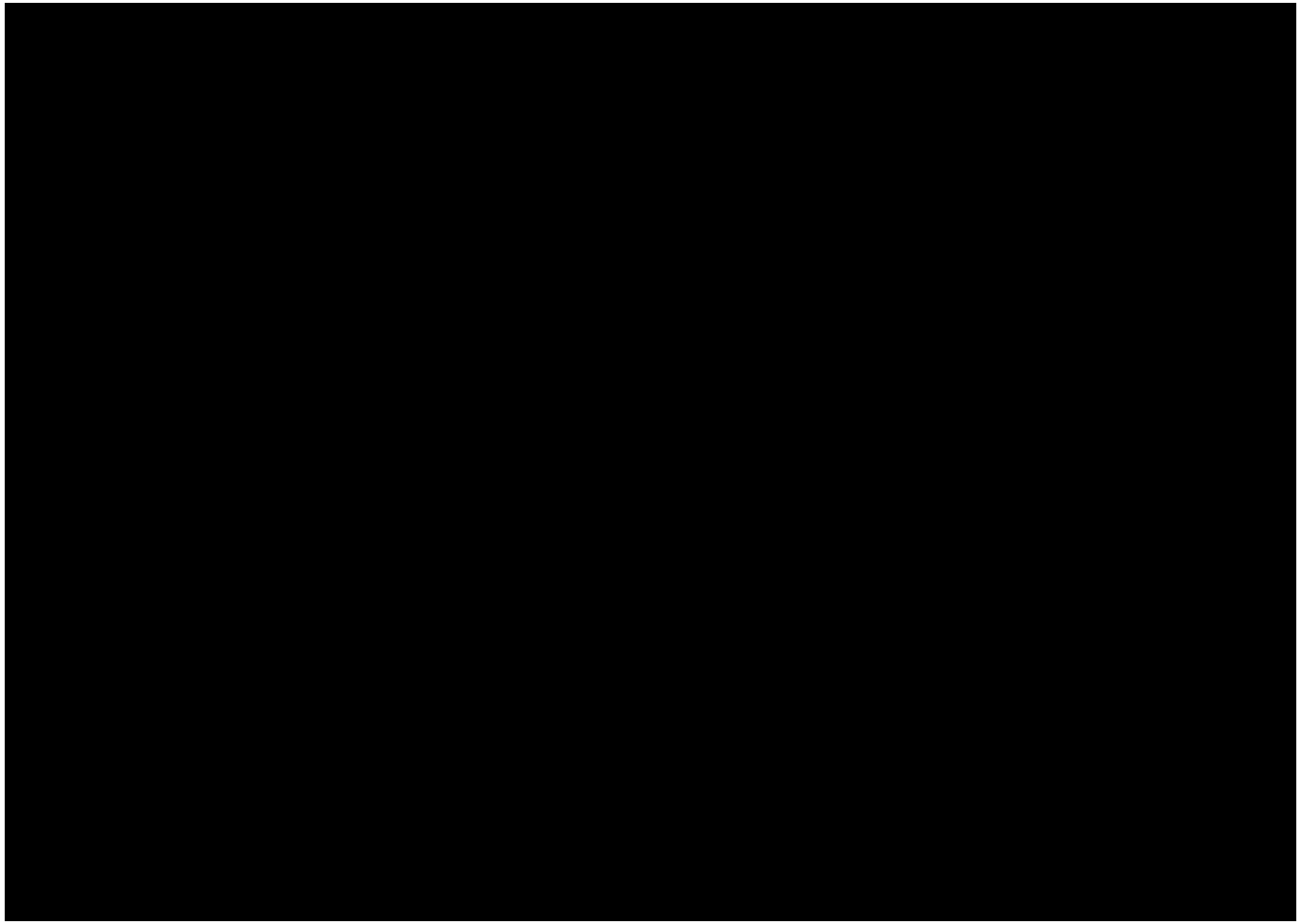
Validation of roughness-model

For different sandgrain roughness the velocity profiles agree well with Nikuradse's universal profile:

$$u^+ = \frac{1}{\kappa} \ln \frac{y}{k_s} + 8.5$$

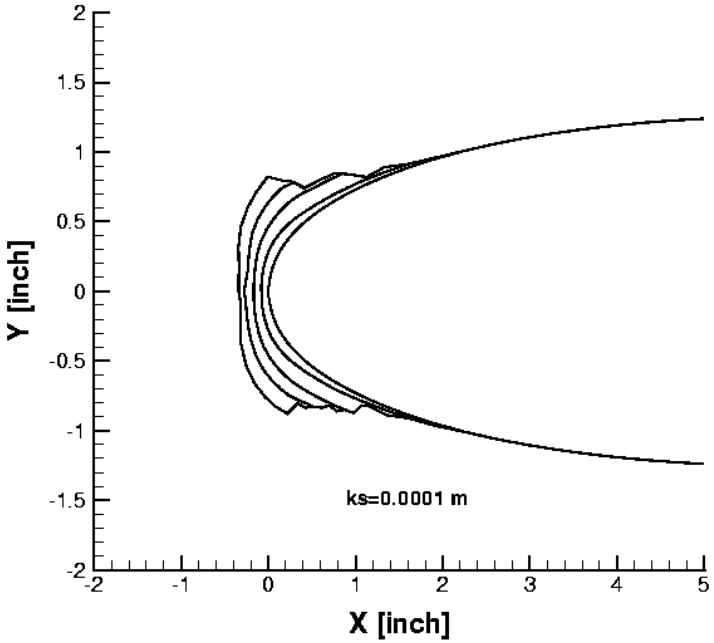
Skin friction on rough surface

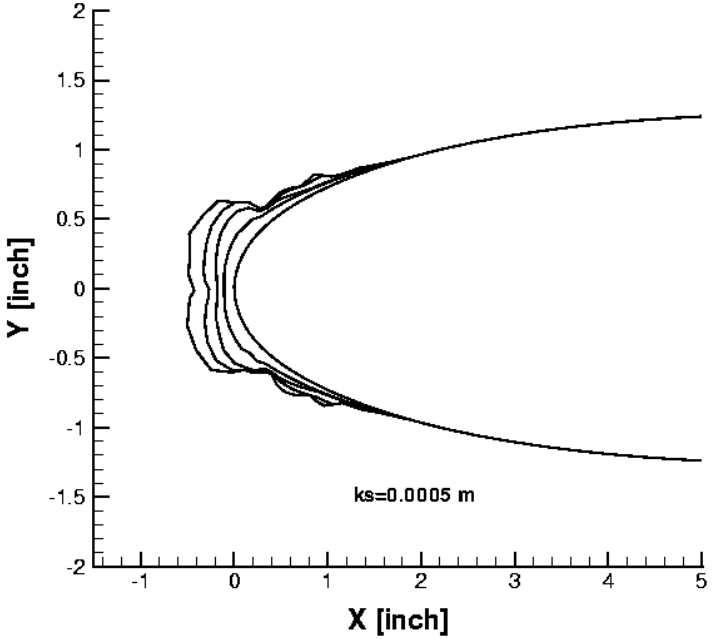
Velocity profiles in rough pipes

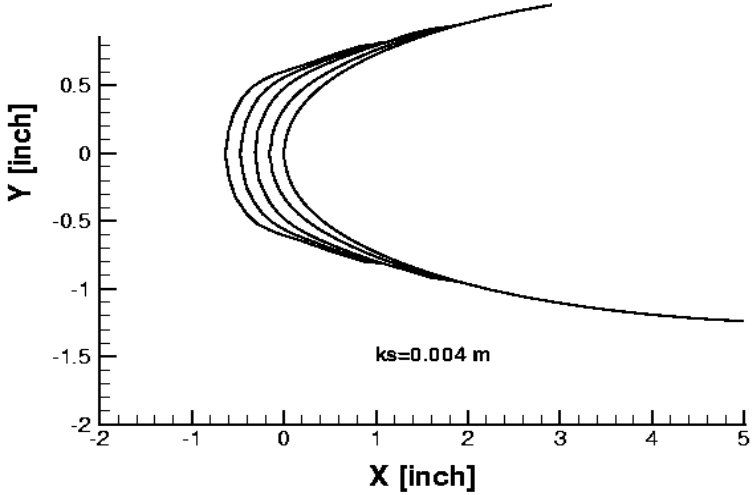


Stanton number on rough surfaces

Effects of roughness NACA 0012







Impingement module

The following assumptions are made:

- Continuous medium
- The particles are too small and their concentration too disperse to affect the flow
- Spherical droplets without any deformation or breaking
- No droplets collision, coalescence or splashing
- No heat and mass exchange between the droplets and the surrounding air
- The only forces acting on droplets are drag, gravity and buoyancy

Impingement module

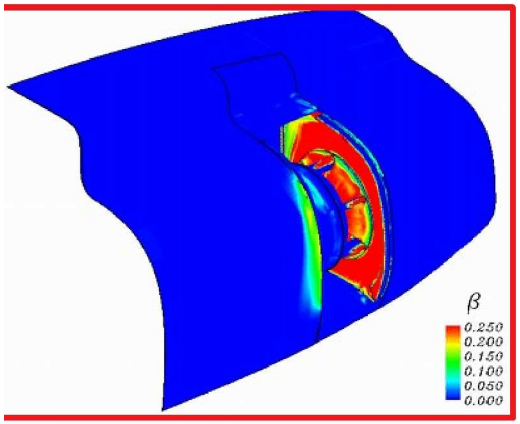
- Continuity equation

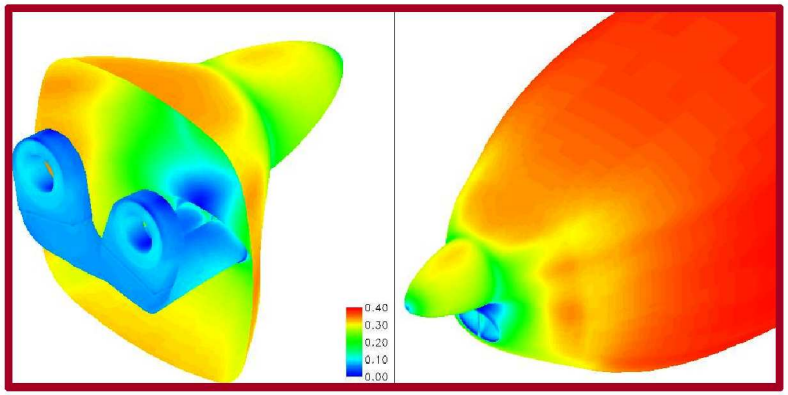
$$\frac{\partial \alpha}{\partial t} + \nabla \cdot \left(\alpha \vec{u}_d \right) = 0$$

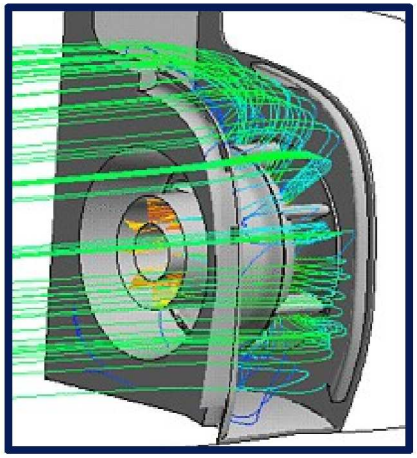
- Momentum equation

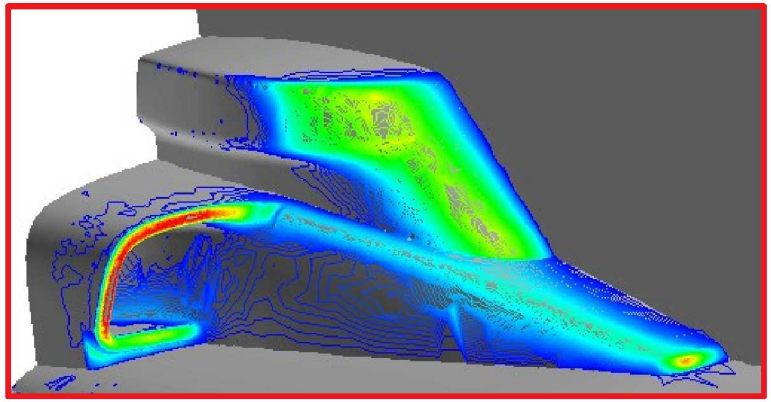
$$\frac{\partial \vec{u}_d}{\partial t} + \vec{u}_d \cdot \nabla \vec{u}_d = \frac{C_D \mathrm{Re}_d}{24 K} \left(\vec{u}_a - \vec{u}_d \right) + \left(1 - \frac{\rho_a}{\rho} \right) \frac{1}{Fr^2} \vec{g} + \frac{\rho_a}{\rho} \left(\frac{\partial \vec{u}_a}{\partial t} + \vec{u}_a \cdot \nabla \vec{u}_a \right)$$

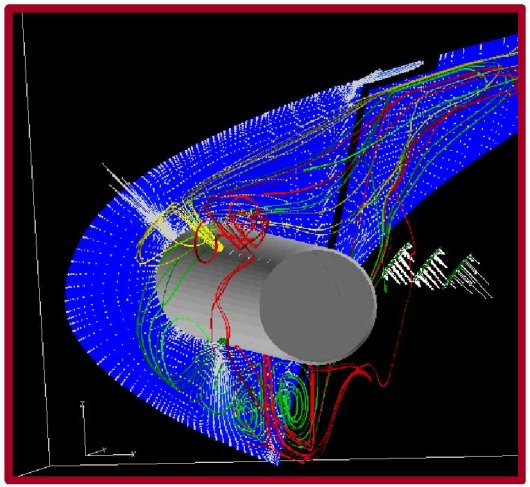
3D Geometries

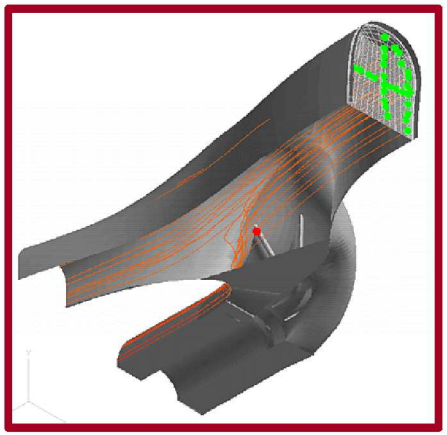


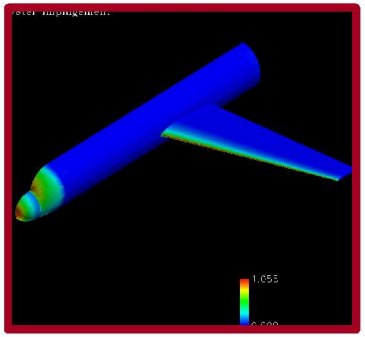












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The ice accretion module

Physical model

Governing equations

Discretization method

3D ice accretion model

- The velocity of the water film is a function of the coordinates
- The problem can be simplified by introducing a linear velocity profile for the film:

$$\vec{u}_f = \frac{y}{\mu_w} \vec{\tau}_{wall}\left(\vec{x}, y\right)$$

- By averaging along the film thickness we obtain:

$$\bar{u}_f = \frac{h_f}{2\mu_w} \vec{\tau}_{wall}\left(\vec{x}, y\right)$$

Mass conservation equation

Mass transfer by evaporation

$$\rho_w \left[\frac{\partial h_f}{\partial t} + div\left(\bar{u}_f h_f \right) \right] \quad ¿ \quad U_\infty LWC\,\beta - \dot{m}_{evap} - \dot{m}_{ice}$$

Mass transfer by water droplet impingement

Mass transfer by ice accretion

Energy conservation equation

Heat transfer by supercooled water droplets impingement

Heat transfer by radiation

$$\rho_w \left[\frac{\partial h_f c_{p,w} \tilde{T}}{\partial t} + div\left(\bar{u}_f h_f c_{p,w} \tilde{T} \right) \right] \text{¿} \left[c_{p,w} \tilde{T}_{d,\infty} + \frac{\| \vec{u}_d \|^2}{2} \right] \times U_\infty LWC\, \beta + \sigma\varepsilon \left(T_\infty^4 - T^4 \right)$$

$$- 0.5 \left(L_{evap} + L_{sub} \right) \dot{m}_{evap} + \left(L_{fus} - c_{p,ice} \tilde{T} \right) \dot{m}_{ice} + \dot{Q}_h$$

Heat transfer by evaporation

Heat transfer by Ice accretion

Heat transfer by convection

A parametric model for evaporation

- MacArthur gives a relation to calculate the mass flux that evaporates or sublimates as:

$$\dot{m}_{evap} = \frac{0.7 h_c}{c_{p,air}} \left[\frac{P_{v,p}(T) - H_{r,\infty} P_{v,\infty}}{P_{wall}} \right]$$

- Where:
  - $P_{v,p}$ Saturation vapor pressure at the surface
  - $P_{v,\infty}$ Saturation vapor pressure of water in ambient air
  - P_{wall} Absolute pressure above the control volume outside the BL
  - h_c Convective heat transfer coefficient given by the airflow solution
  - $c_{p,air}$ Specific heat capacity of air
  - $H_{r,\infty}$ Relative humidity

Closure of the problem

- Flow solver provides local shear stress $\vec{\tau}_{wall}$ + convective heat fluxes $\dot{Q}_h$
- Eulerian droplet module provides collection efficiency β + droplet impact velocity $\vec{u}_d$
- Compatibility relations are needed to close the system, ensuring that no liquid water is predicted below the freezing point, and that no ice forms at a temperature above the freezing point

$$\boxed{h_f \geq 0 \quad \dot{m}_{ice} \geq 0 \quad h_f \tilde{T} \geq 0 \quad \dot{m}_{ice} \tilde{T} \leq 0}$$

A “non obvious” system

- Hyperbolic system, non linear, with stiff source terms

- 4 inequalities to close the system: can be seen as nonlinear complementarity constraints

- The PDE’s degenerate in 2 cases:
  - » In rime ice conditions because $h_f = 0$
  - » In glaze ice conditions because $\tilde{T} = 0$

Computational approach

- The equation system is formulated for curvilinear 2D surfaces embedded in 3D geometries

- An explicit scheme is used to capture the water phase changes:
  - → From liquid to solid
  - → From solid to liquid
  - → From solid-liquid to gas

- A FVM is applied to discretize the equations

- On hexahedral, tetrahedral or prismatic meshes

Dual meshes
hexahedral/tetrahedral grids

Skin mesh: boundary of the 3D mesh at (air-structure)/(ice shape) interface

Dual mesh: dashed lines, mesh of the discretization

Spatial discretization
Roe scheme

Residual equation for mass conservation:

$$\boxed{vol(C_i)\left(\rho_w \frac{\partial h_i}{\partial t} - S_i^h\right) + \sum_{j\ neighbor\ of\ i} R_{ij}^h = 0}$$

Residual equation for energy conservation:

$$\boxed{vol(C_i)\left(\rho_w \frac{\partial c_w h_i \tilde{T}_i}{\partial t} - S_i^{\tilde{T}}\right) + \sum_{j\ neighbor\ of\ i} R_{ij}^{\tilde{T}} = 0}$$

With

$$R_{ij}^h = \frac{1}{2}\rho_w\left[h_i^2 + h_j^2\right]\vec{u}_{ij}\cdot\vec{n}_{ij} - \rho_w\left|\vec{u}_{ij}\cdot\vec{n}_{ij}\right| h_{ij}\left[h_j - h_i\right]$$

$$R_{ij}^{\tilde{T}} = \frac{1}{2}\rho_w c_{p,w}\left[h_i^2\tilde{T}_i + h_j^2\tilde{T}_j\right]\vec{u}_{ij}\cdot\vec{n}_{ij} - \rho_w\left|\vec{u}_{ij}\cdot\vec{n}_{ij}\right| h_{ij}\left[c_{p,w}\left(h_j - h_i\right)\tilde{T}_{ij} + c_{p,w}\left(h_j\tilde{T}_j - h_i\tilde{T}_i\right)\right]$$

Geometry update

- Convert ice accretion rate to a surface displacement for a given time

- Could be done within the flow solver:

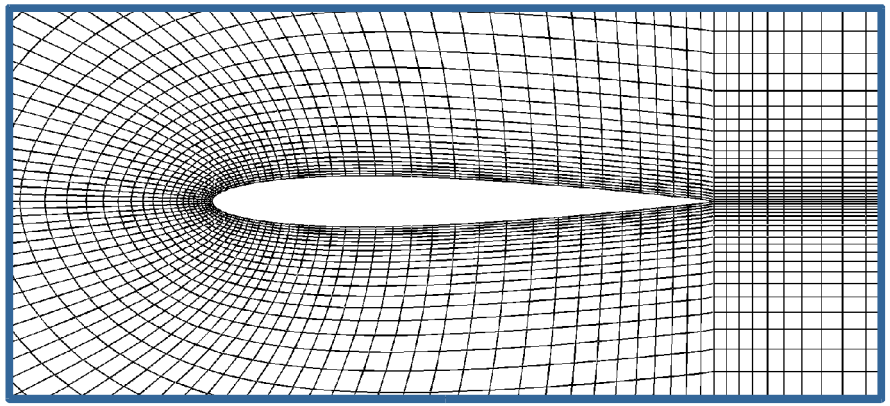
  - ALE method enables node movement during airflow solution

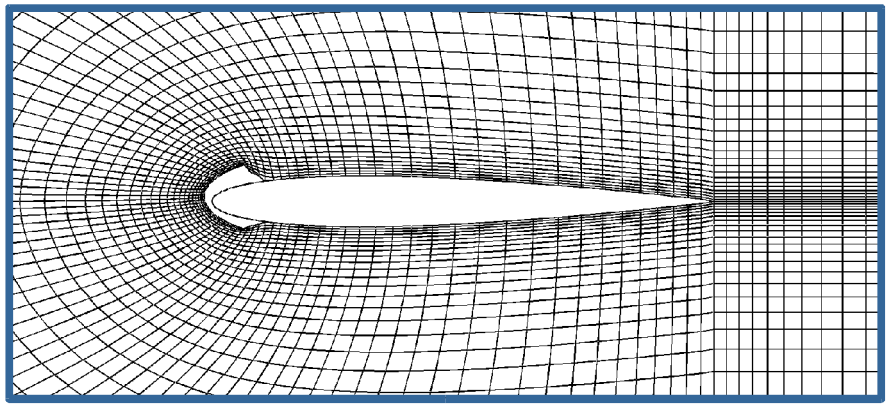
  - Limitations: large displacement may lead to distorted elements (what to do: mesh adaptation or remeshing?)

ALE displacement of grids

Grids move with ice growth

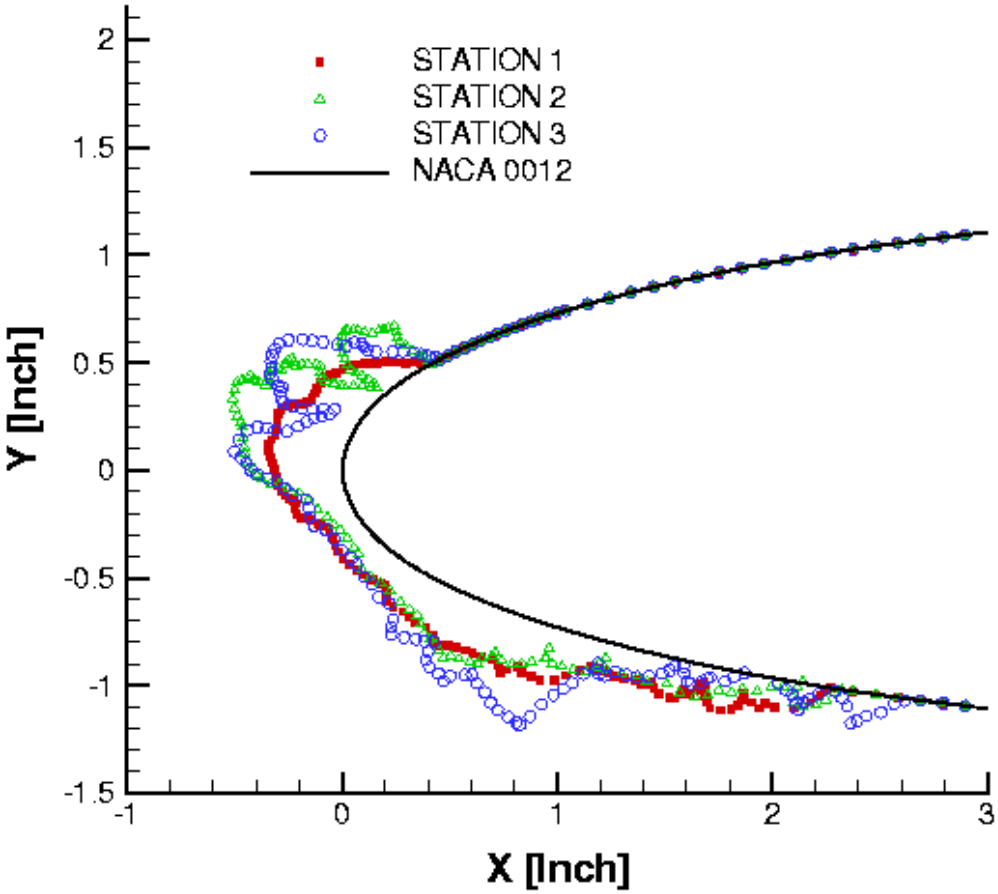
No remeshing needed



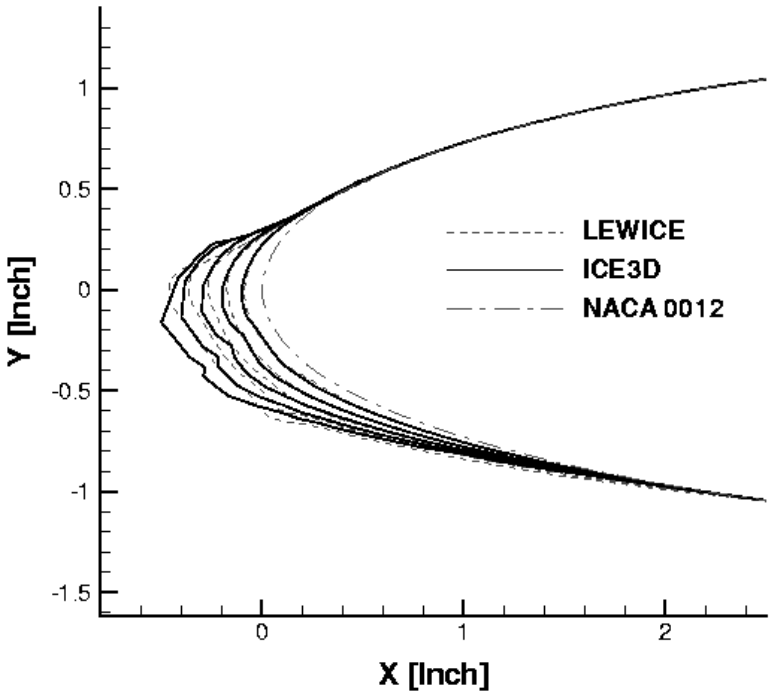


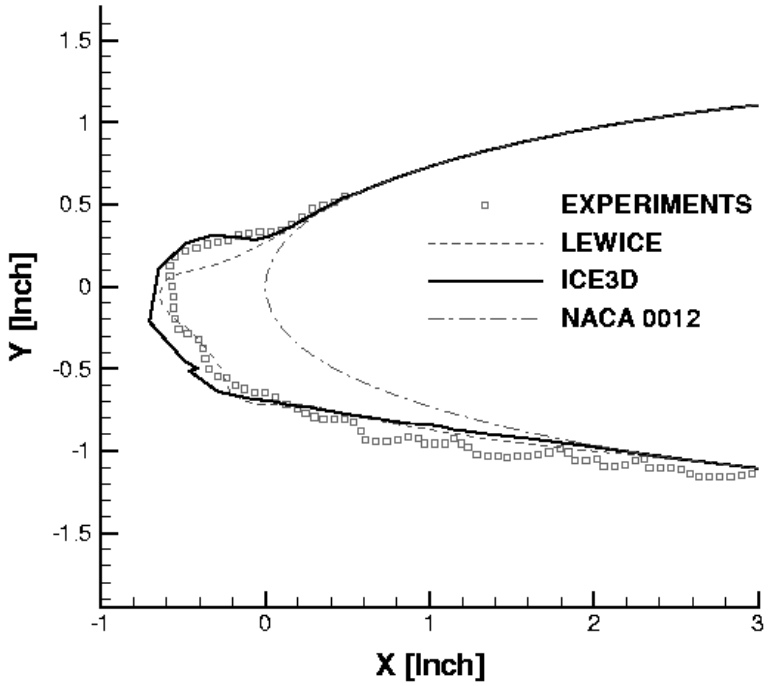
2D Validations

Experimental inherent variability



Rime ice NACA 0012 airfoil
Run 404

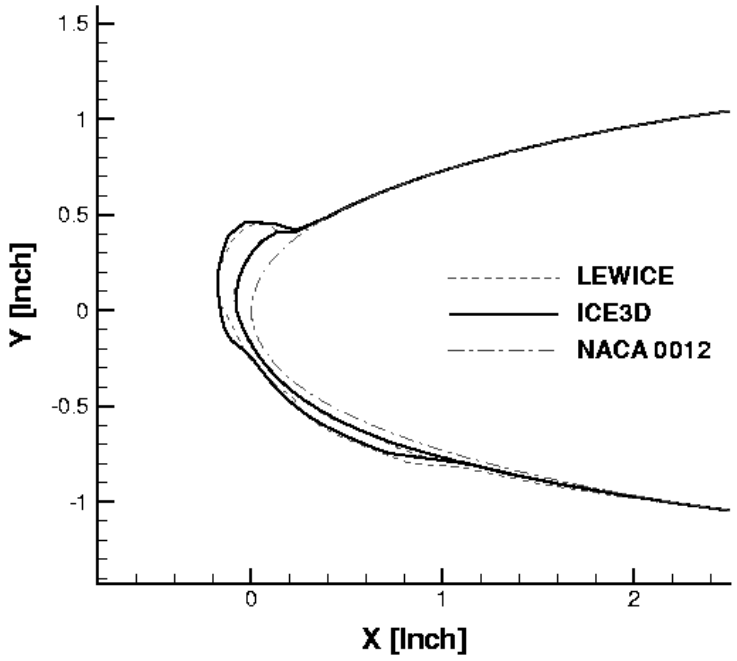


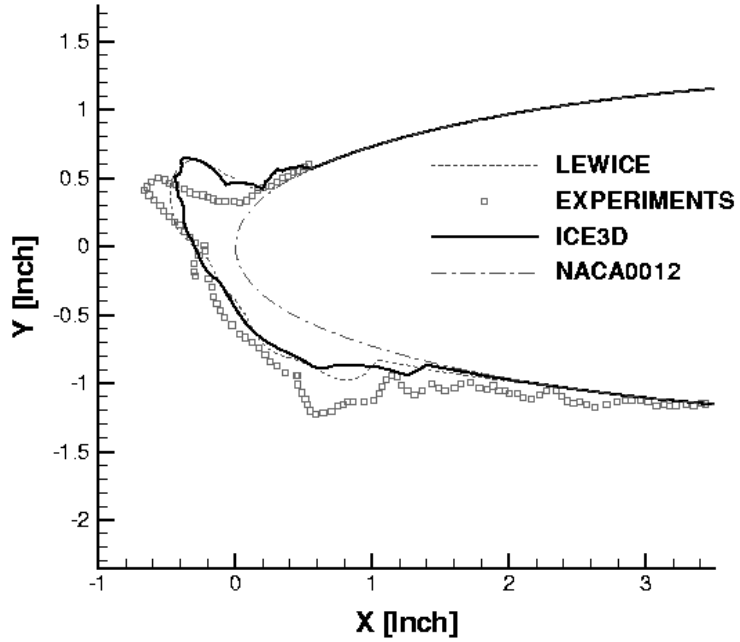


$$U_\infty = 102.8\ m/s \qquad AOA = 4^o \qquad T_\infty = 256.49\ K$$

$$LWC = 0.55\ g/m^3 \qquad MVD = 20\ \mu m \qquad t = 7\ \text{min}$$

Glaze ice NACA 0012 airfoil
Run 308





$$U_\infty = 102.8\ m/s \qquad AOA = 4^o \qquad T_\infty = 262.04\ K$$

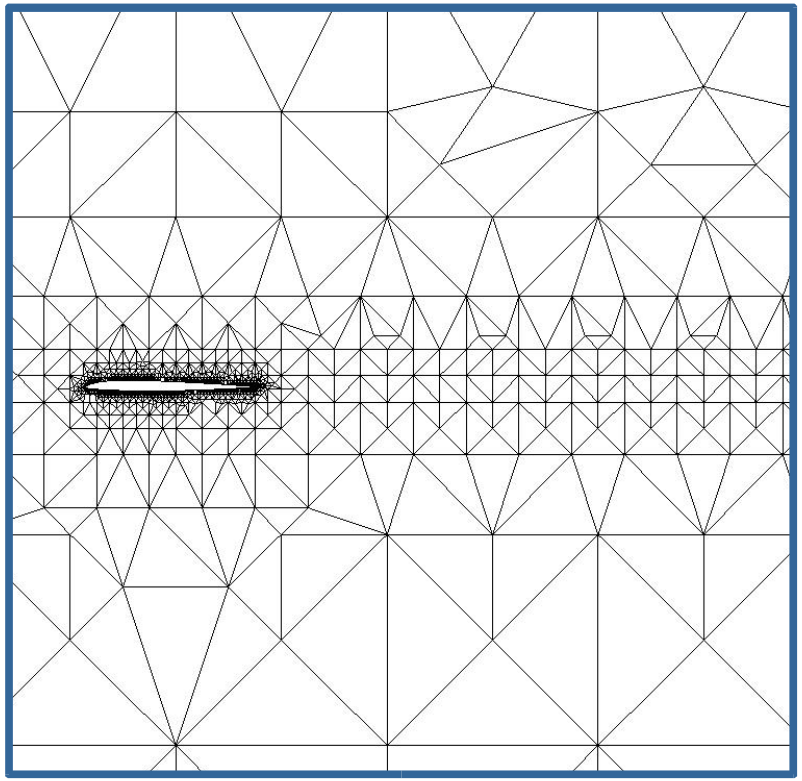
$$MVD = 20\ \mu m \qquad LWC = 1\ g/m^3 \qquad t = 231\ s$$

3D Results

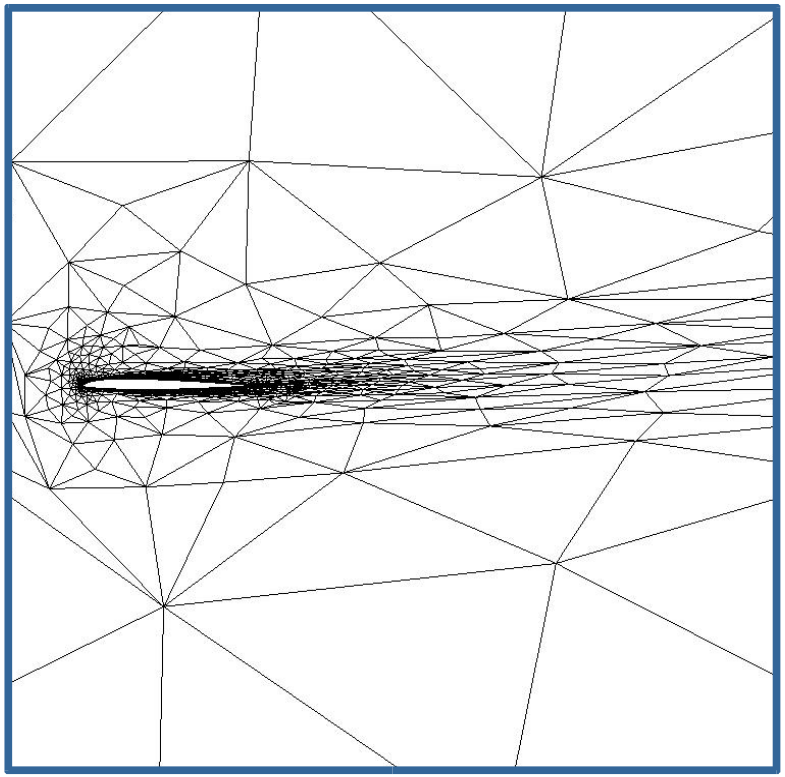
3D Helicopter Rotor Blade Tip

Boeing 737-300 inlet nacelle

3D Rotor blade tip, Mesh adaptation



Original Mesh: 221,800 nodes
1,118,131 elements

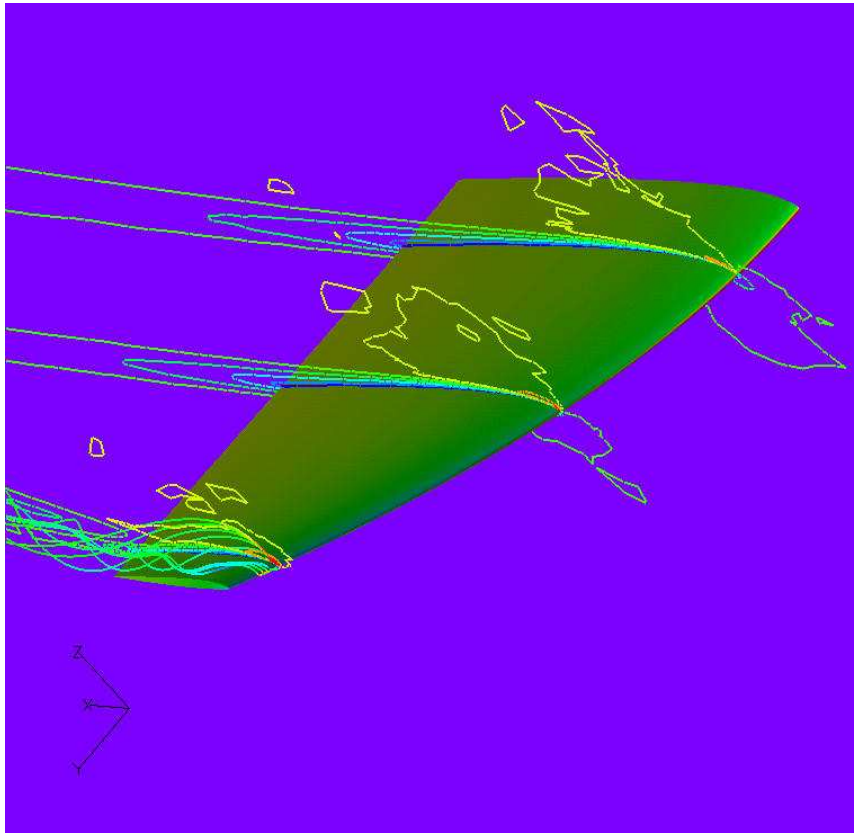


Adaptation 3: 467,705 nodes
2,546,857 elements

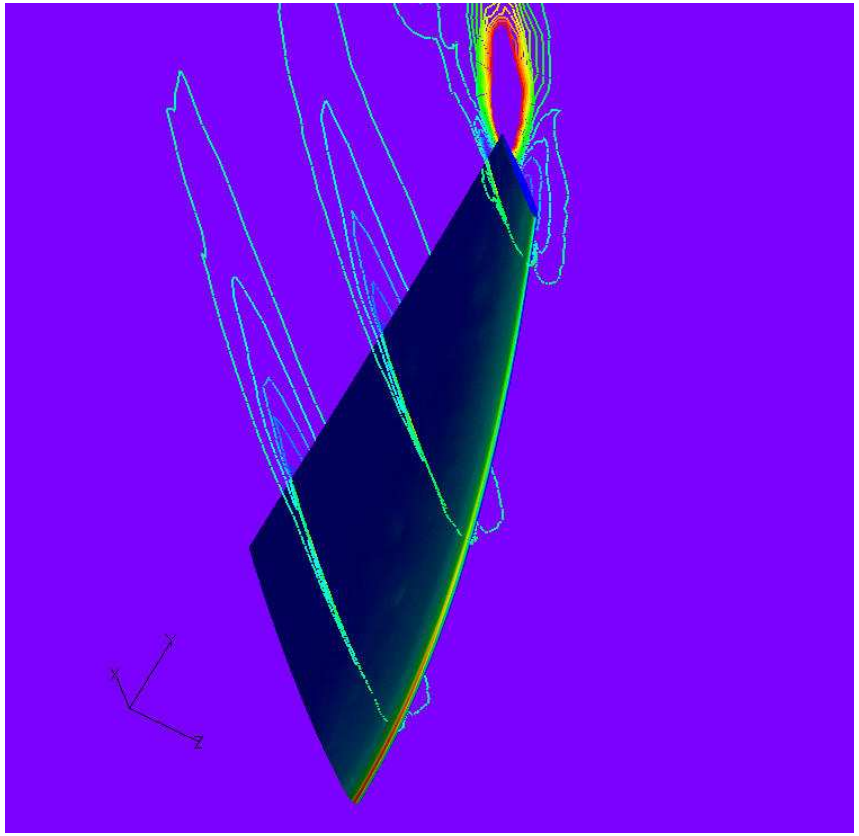
3D rotor blade tip: airflow solution

- N-S turbulent solution
  - One equation S-A model
  - Equivalent sandgrain roughness
- Ambient conditions:

$$T_\infty = -30.5^o C$$
$$P_\infty = 45.6\ kPa$$
$$Mach = 0.52$$
$$AoA = 9.5^o$$
$$MVD = 20\ \mu m$$
$$LWC = 1g/m^3$$
$$t = 91\ s$$

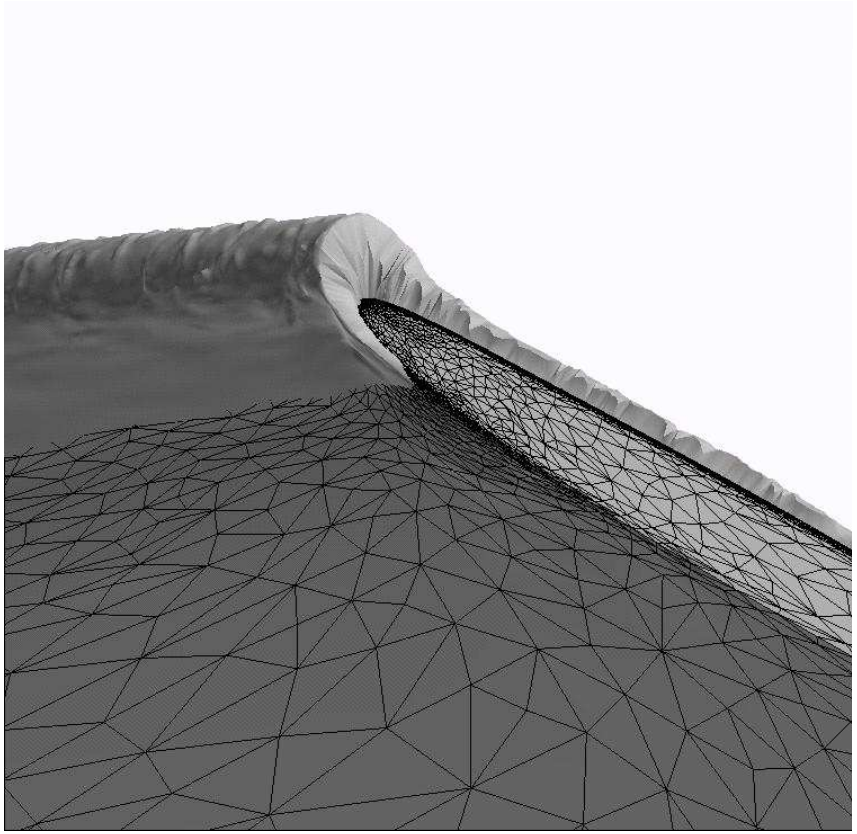


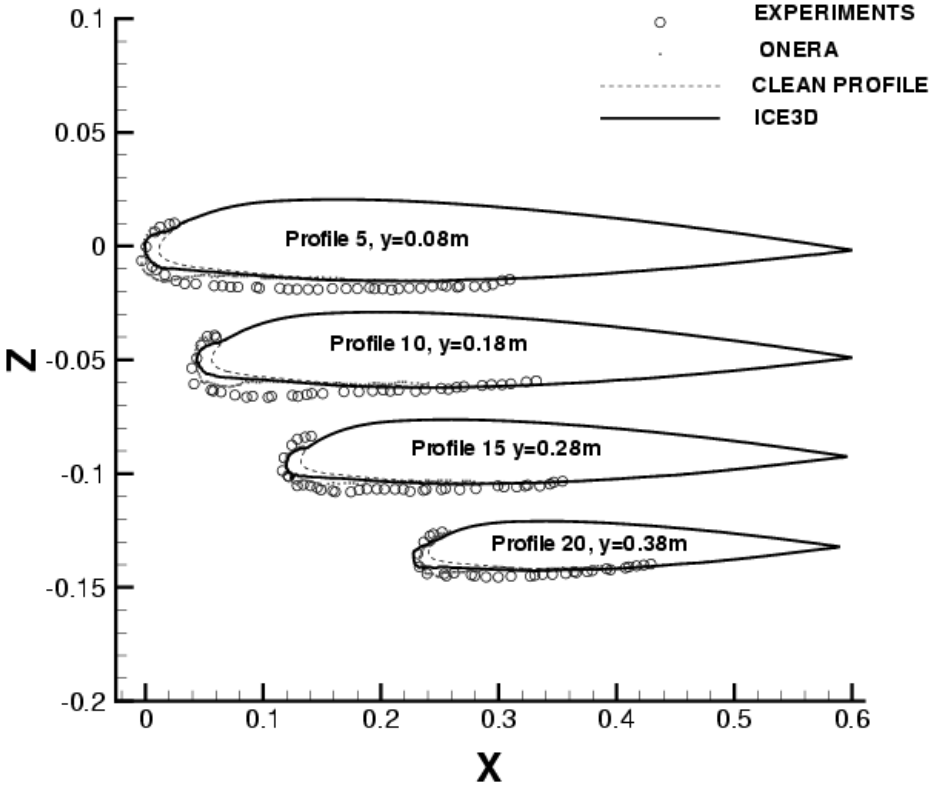
Impingement solution



Collection efficiency distribution on wing and LWC contours
at 3 stations

3D rotor blade tip, ice accretion

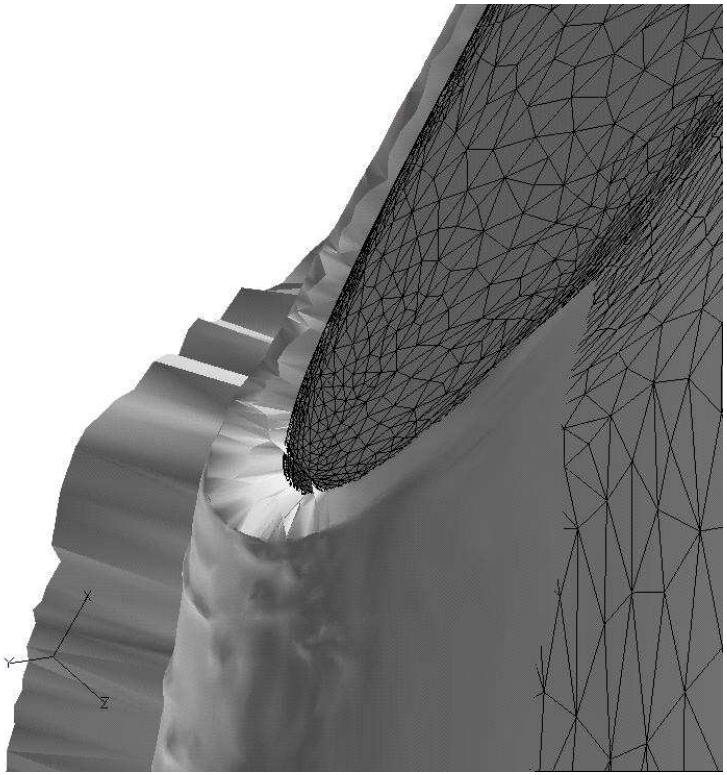




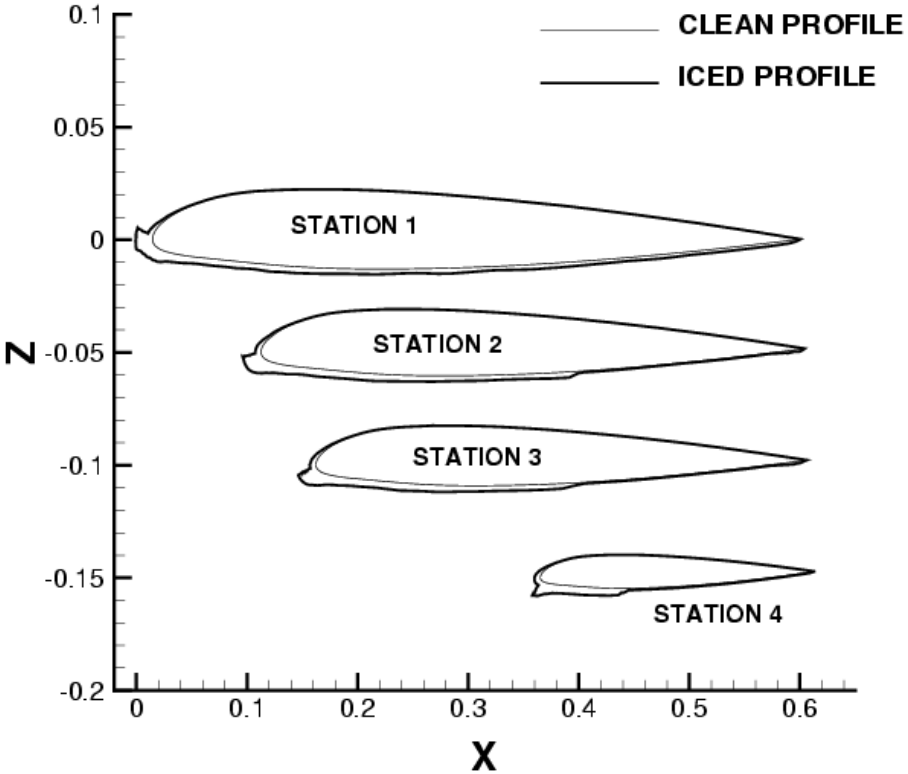
Zoom at blade tip

2D cuts at 4 stations

Highlighting the 3D capabilities for icing



Zoom at blade tip

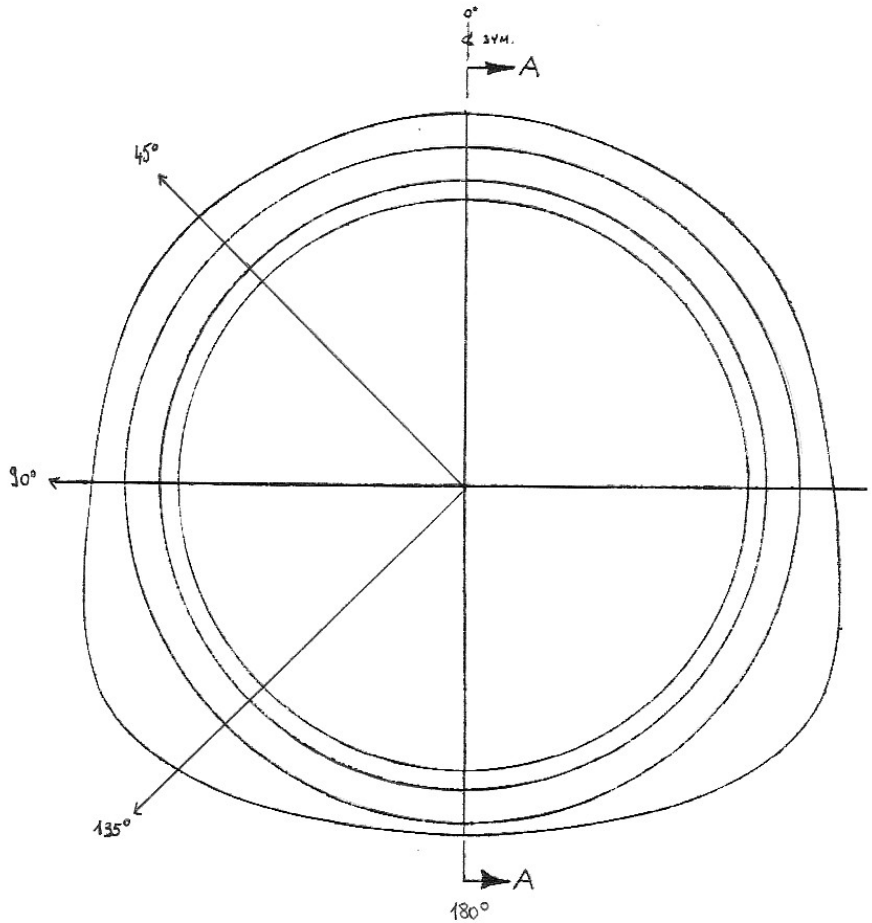


2D cuts at 4 stations

3D Boeing 737-300 inlet nacelle

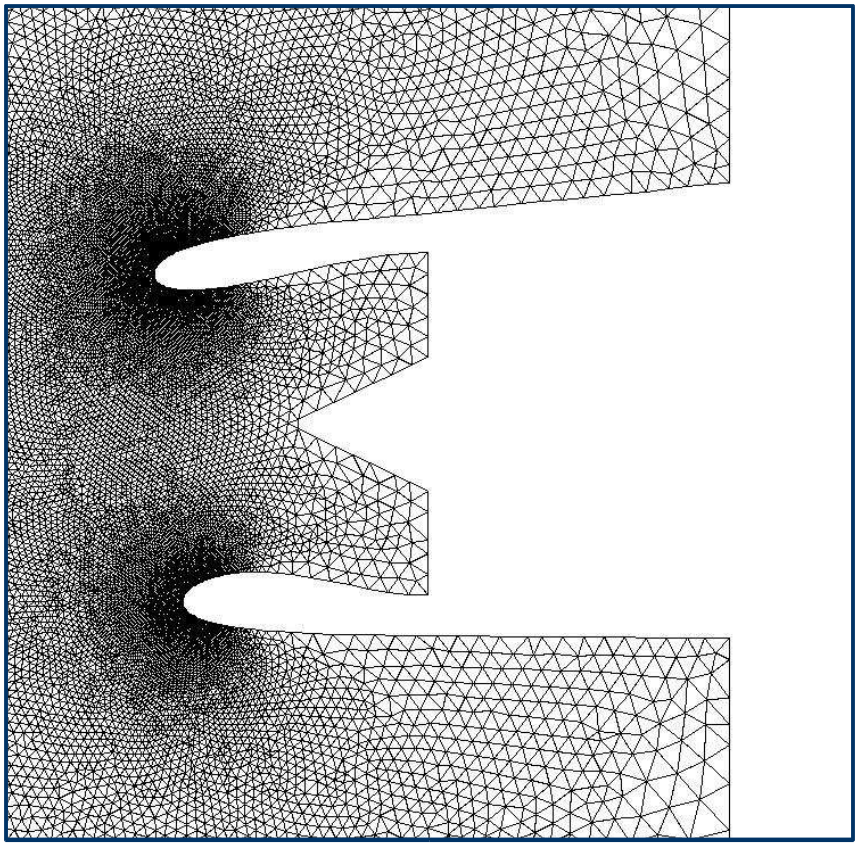
- Two cases were analyzed:
  - → 0° nacelle incidence
  - → 15° nacelle incidence

- Ambient conditions:
  - → Airspeed of 75 m/s
  - → Inlet mass flow 10.4 kg/s
  - → Static temperature 7°C
  - → Static pressure 95840 Pa

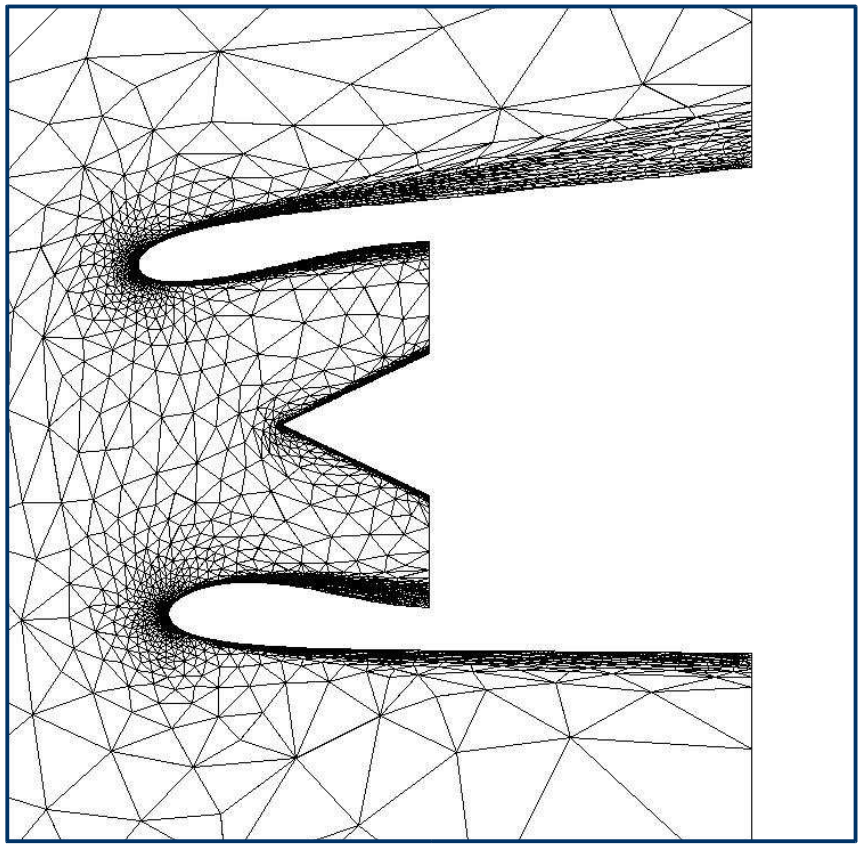


Experimental blotter strip locations

Nacelle inlet, mesh adaptation



Original mesh, symmetry plane

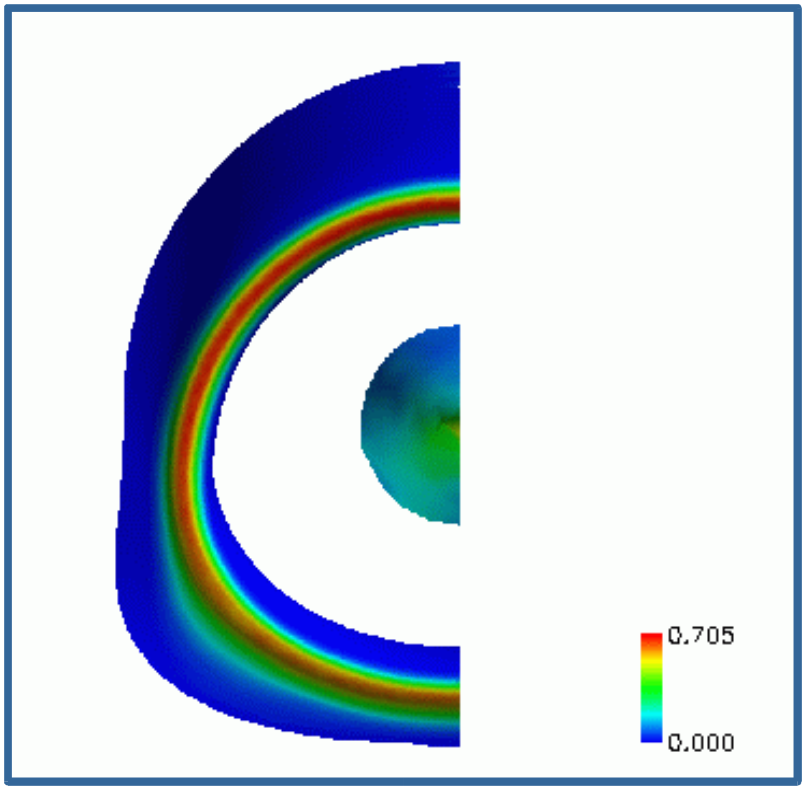


Adapted mesh (15° incidence), Symmetry plane

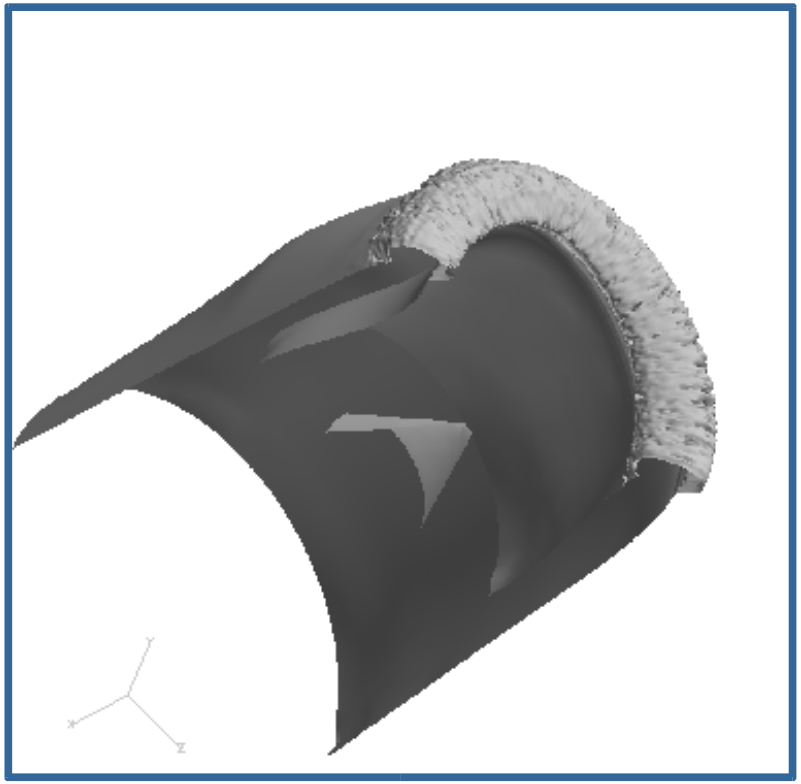
Nacelle inlet, ice accretion

- Two icing conditions for each incidence:
  - Rime conditions
    - » LWC of 0.2 g/m^3
    - » Static temperature -29.9^{o}C
    - » Accretion time 30 minutes
  - Glaze conditions
    - » LWC of 0.695 g/m^3
    - » Static temperature -9.3^{o}C
    - » Accretion time 30 minutes

Nacelle inlet, 3D impingement solution and ice shape

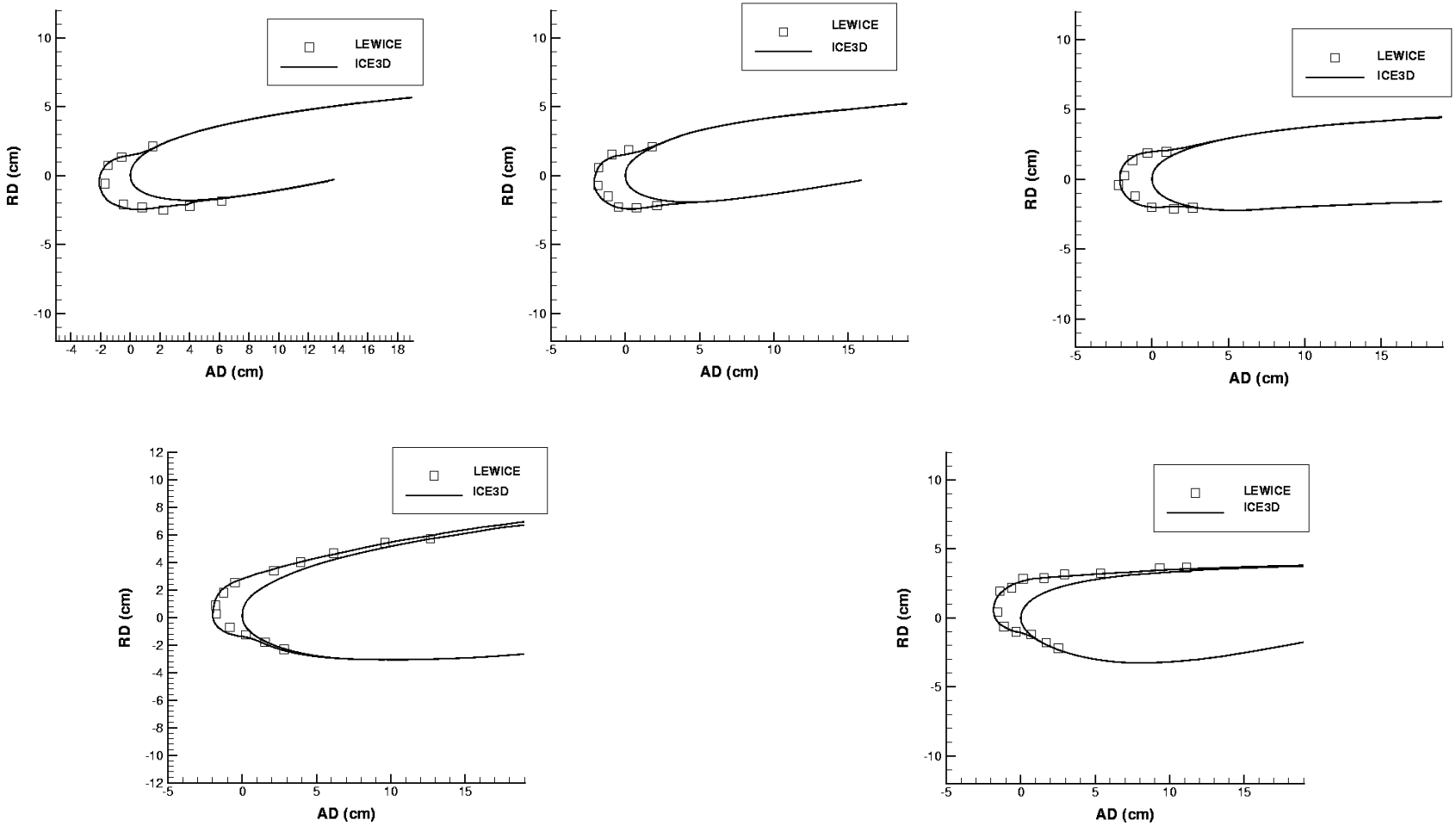


Collection efficiency on the nacelle
Langmuir-D distribution: MVD=20.36µm

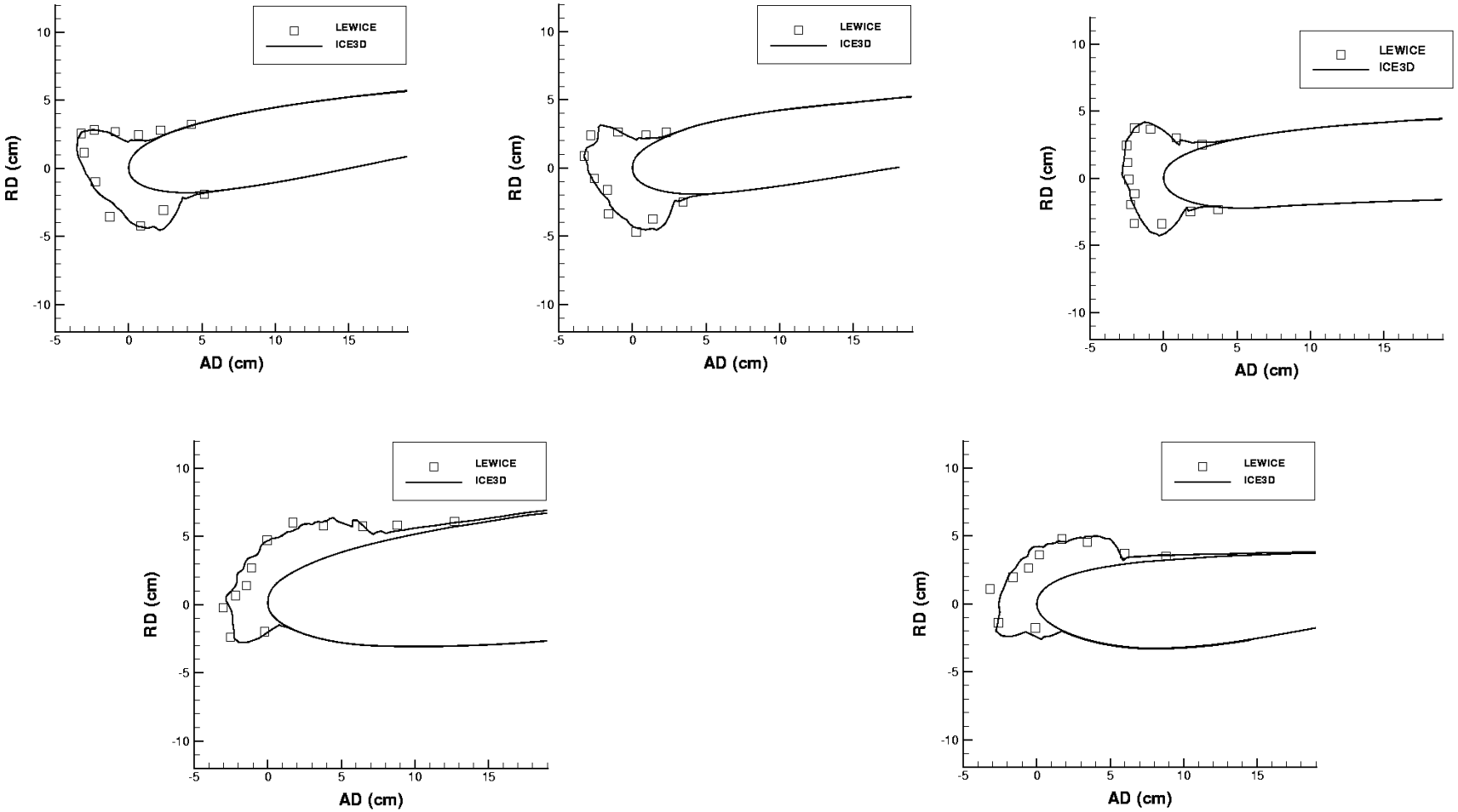


3D ice shape on the nacelle
Rime ice

Rime ice, 15° nacelle incidence



Glaze ice, 15° nacelle incidence



Conclusions

- A modern 3D in-flight ice simulation tool has been developed:
  - Modular in its approach
  - Based on current CFD technologies
  - Compatible with aero methods
- The S-A model has been implemented and calibrated
- Roughness effects on ice shape have been shown through test cases

Conclusions

- A new icing model has been derived:
  - Based on 2 PDEs (mass and energy)
  - With 4 inequalities to close the system
  - An explicit FVM is used to solve the system
- Validation of the in-flight icing accretion method
  - Success to predict ice shapes on 2D symmetrical and lifting airfoils
- 3D results
  - The objective is reached, the proposed ice accretion module yields fully 3D ice shapes

Future work

The current code can be used as a platform to:

- Study the effects of the unsteady terms
- Attempt the simulation of scallop ice
  - » Seems to be partially due to 3D flow patterns
- Improve the physics of the model (rivulets)
- Addition of anti- or de-icing capabilities to the thermodynamic ice accretion module