TFAWS Active Thermal Paper Session

Application of CFD to Simulate Water Droplet Impingement for Aircraft Icing Analysis

Nili Bachchan, Inchul Kim, Oshin Peroomian
Metacomp Technologies, Inc.
&
Daniel da Silva
Embraer Aircraft Corp.

Presented By
Nili Bachchan

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- Aircraft Icing Analysis
  - Design of ice protection systems for a wide range of aircraft flight conditions and configurations
  - Numerical approaches are employed to support experimental testing in the prediction of the amount, shape and location of the accreted ice that may influence airframe handling characteristics

- Presentation Overview
  - CFD simulation strategy, mesh generation
  - Multiphase modeling with EDP (Eulerian Dispersed Phase) model
  - Small and large droplet impingements considered
  - Extended numerical model for Supercooled large droplets (SLD)
  - Case 1: 737-300 engine inlet simulation (small droplets only)
  - Case 2: NACA 23012 airfoil with 5 glaze ice shapes

- Collection Efficiency using EDP
  - In water collection analysis for icing, the important parameter is the collection efficiency, β

$$\beta = \left(\frac{\overline{\rho}_P \vec{u}_P \hat{n}}{\overline{\rho}_{P\infty} \left| \vec{u}_{P\infty} \right|} \right)$$

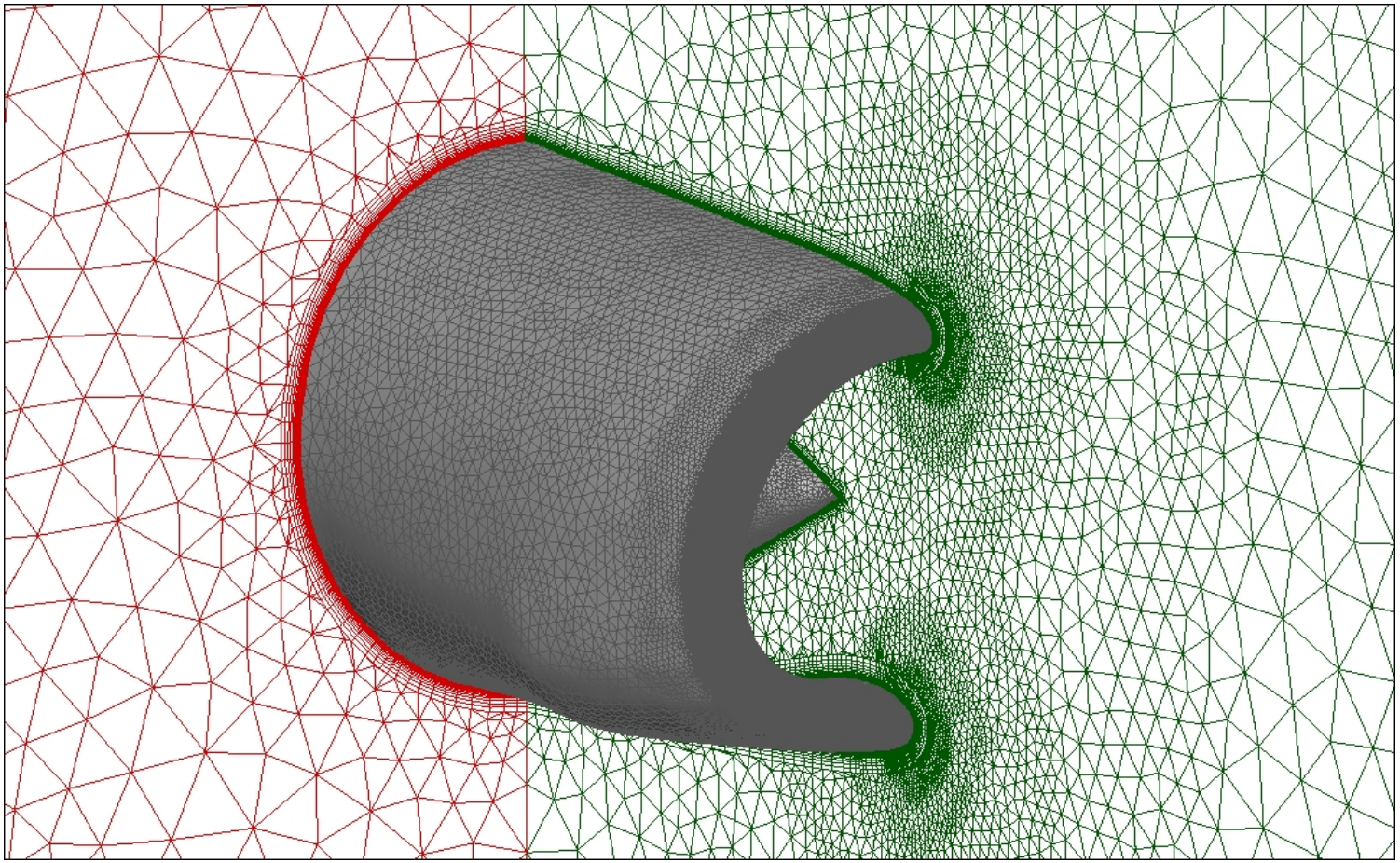
  - Ratio of MFR of the impinging droplets to the MFR of freestream
  - Lagrangian approach where droplets are tracked has also been widely used (LEWICE, ONERA)
  - Eulerian approach to compute collection efficiency:
    - Treats droplets as continuous
    - Does not require seeding of particles

- Geometry Modeling & Mesh Generation

  i. Engine inlet
  - ICEM-CFD grid generation software
  - Hybrid mesh with tetras + prism layers on walls
  - Clustering of cells at the nacelle leading edge
  - Half geometry model with symmetry condition

  ii. NACA airfoil with glaze ice shapes
  - MIME mesh generation software
  - Fine near-wall mesh with y+ ~ 1
  - Refinements near leading edge for the larger glaze ice shapes

View of the mesh: Engine inlet hybrid mesh using ICEM-CFD (tetrahedral + prism layers)



- CFD Simulation Strategy
  - CFD++ software suite by Metacomp Tech.
  - RANS equations, finite volume method
  - Compressible PG NS/Euler equations
  - Realizable k-e turbulence model
  - Some simulations with cubic k-e model
  - 1 continuous species (Air)

- Engine Inlet Case
  - Inlet mass flow rate of 10.4 kg/s
  - 0 degrees angle-of-attack
  - Adiabatic wall boundary conditions
  - Papadakis et al. 1989, IRT tunnel

- Multiphase Modeling
  - CFD++'s Eulerian Dispersed Phase (EDP) model couples the dispersed phase with the fluid dynamics
  - Additional quantities per dispersed phase tracked (EDP density, 3 velocity components of particles, temperature, number density)
  - Momentum/energy transfer between fluid and dispersed phase
  - 1 dispersed species (water droplet) Mono MVD

    MVD = Median Volumetric Diameter
    - 7 dispersed species (water droplets) MVD 20.36 microns using a Langmuir "D" droplet distribution (experimental conditions)

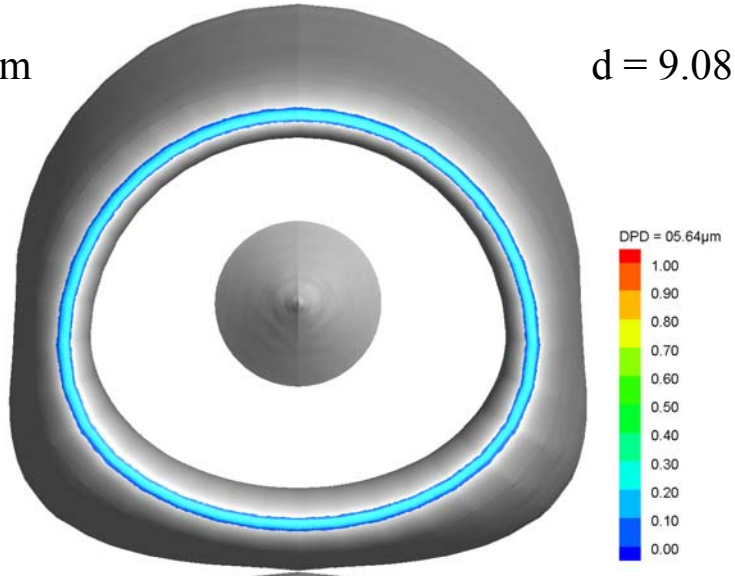
Langmuir "D" droplet distribution

LWC %	5	10	20	30	20	10	5
Droplet Diameter (μm)	5.64	9.08	13.47	20.36	32.30	46.71	66.26

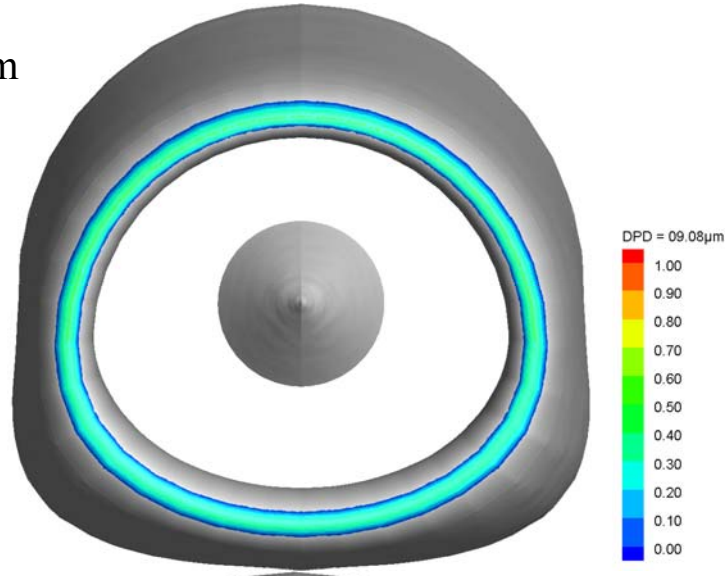
Simulation of Droplet Impingement for Aircraft Icing Analysis

CFD++ collection efficiency contours for varying droplet diameters at α=0 deg

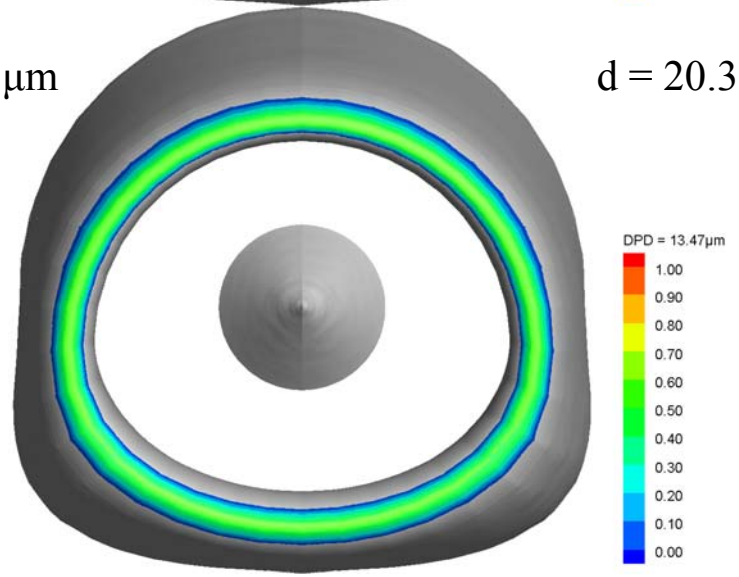
d = 5.64 μm



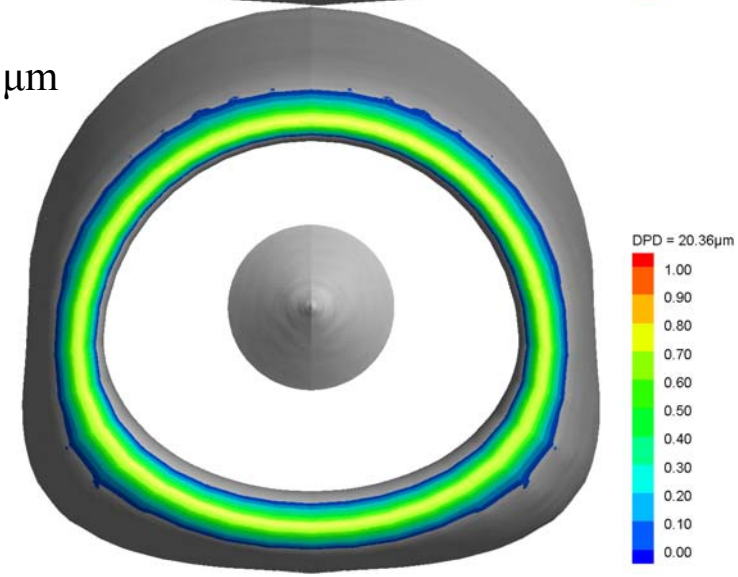
d = 9.08 μm



d = 13.47 μm



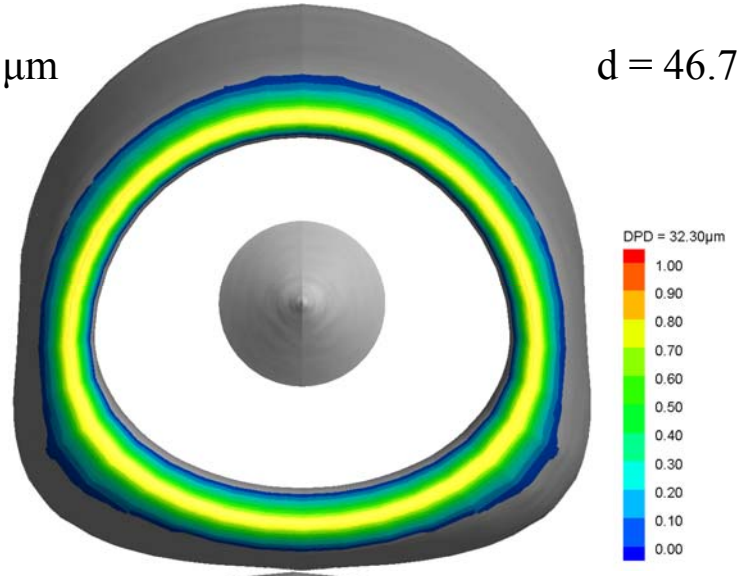
d = 20.36 μm



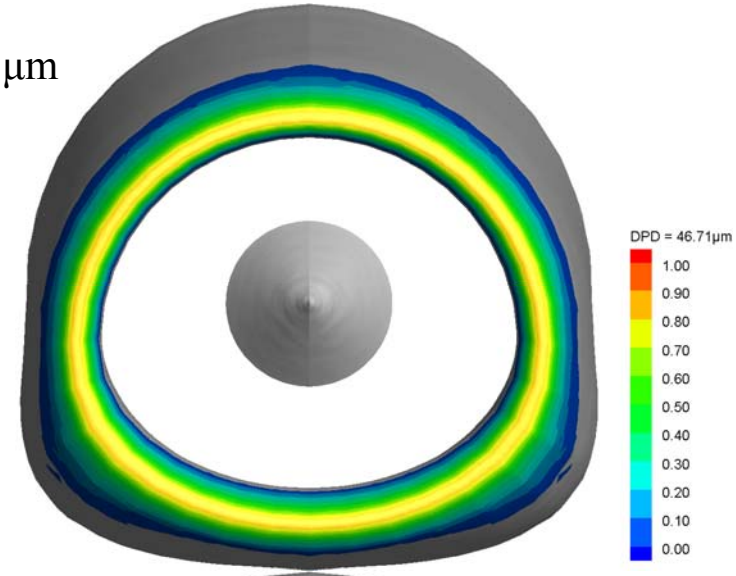
Simulation of Droplet Impingement for Aircraft Icing Analysis

CFD++ collection efficiency contours for varying droplet diameters at α=0 deg

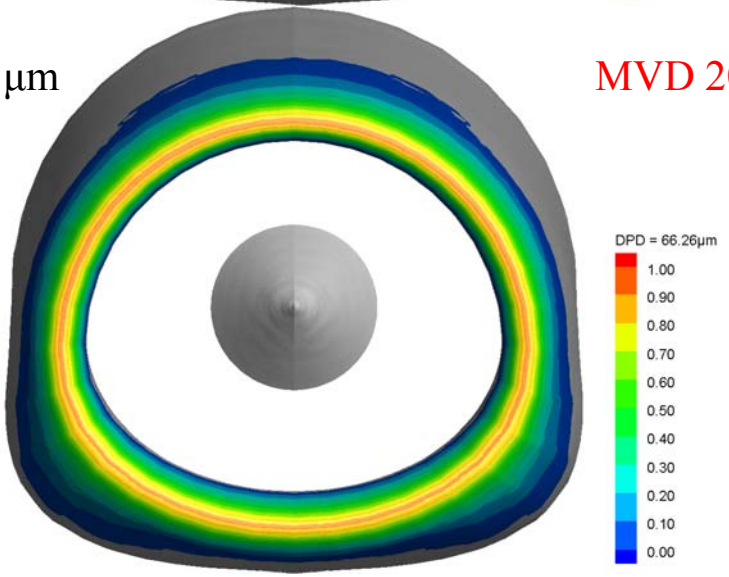
d = 32.30 μm



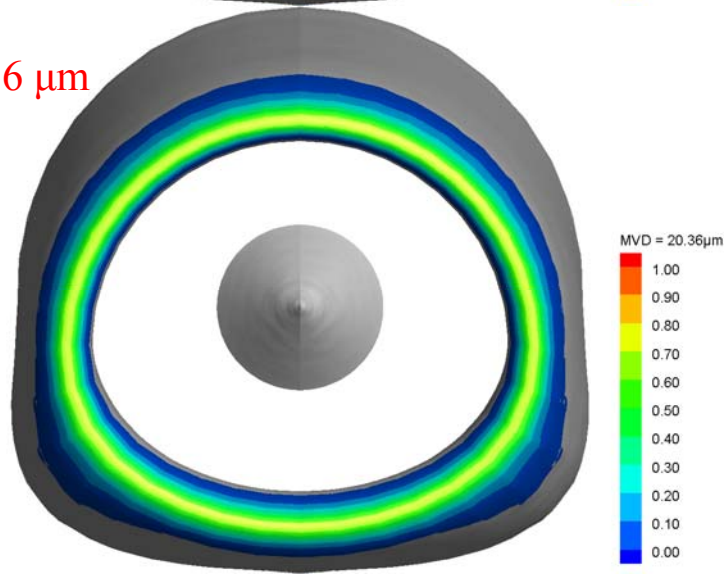
d = 46.71 μm



d = 66.26 μm

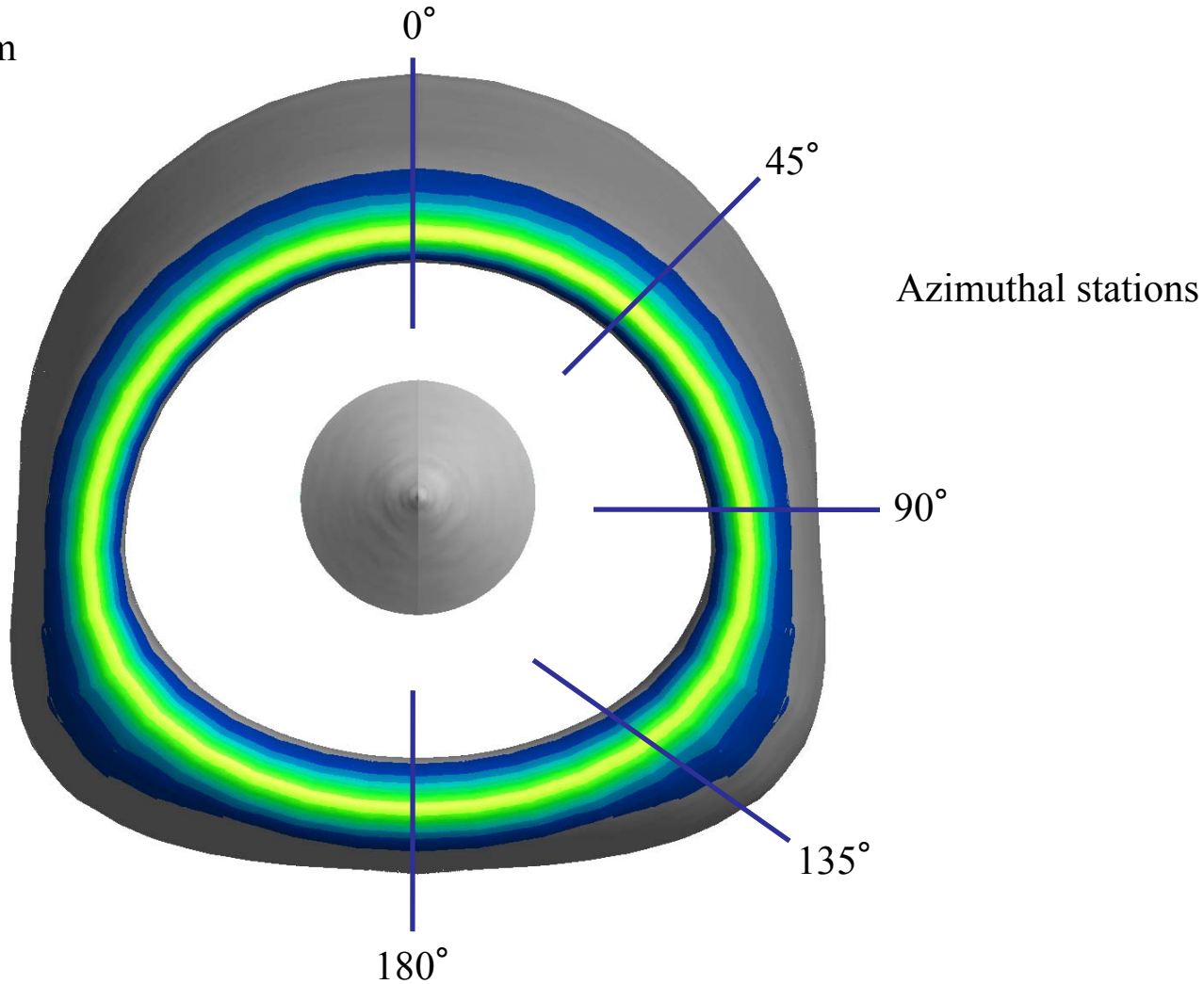


MVD 20.36 μm



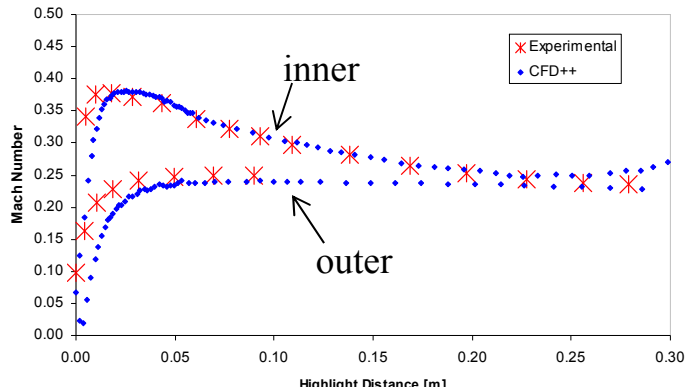
Simulation of Droplet Impingement for Aircraft Icing Analysis

MVD 7bin 20.36 μm

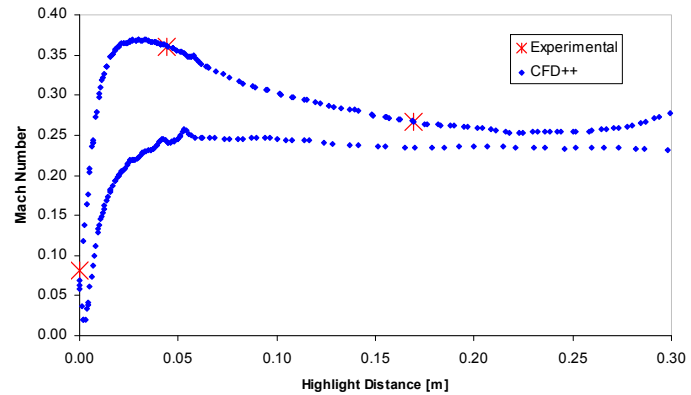


Simulation of Droplet Impingement for Aircraft Icing Analysis

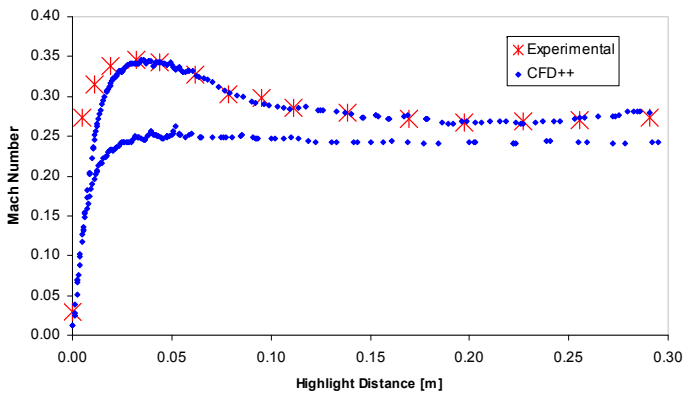
0°



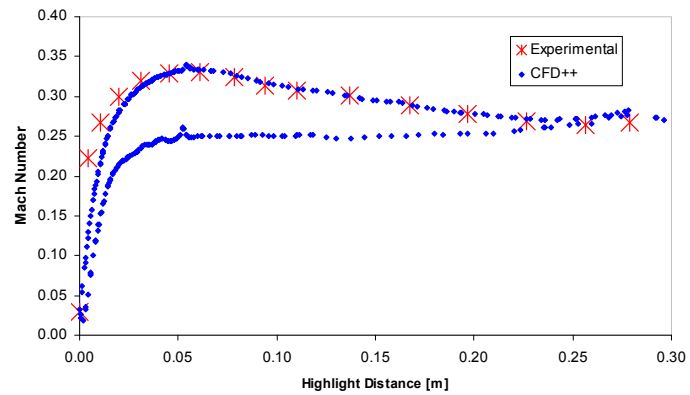
45°



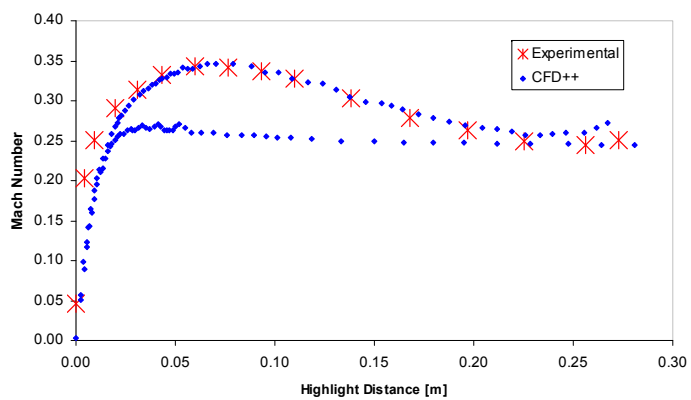
90°



135°



180°

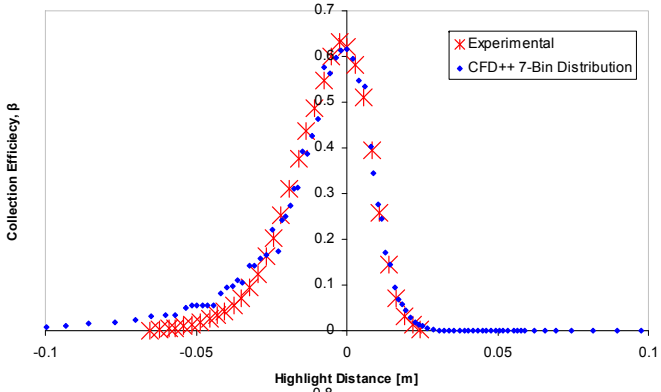


<u>MVD 7bin 20.36 µm simulation</u>
Comparison of CFD and experimental surface Mach number, experimental data from *Papadakis et al. 1989, IRT tunnel*

Mach number vs. Highlight Distance

Simulation of Droplet Impingement for Aircraft Icing Analysis

0°



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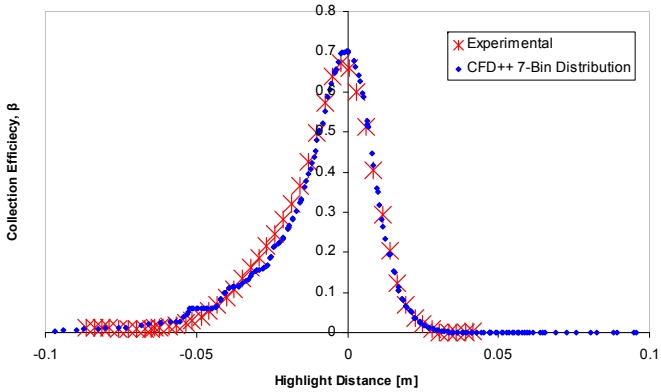

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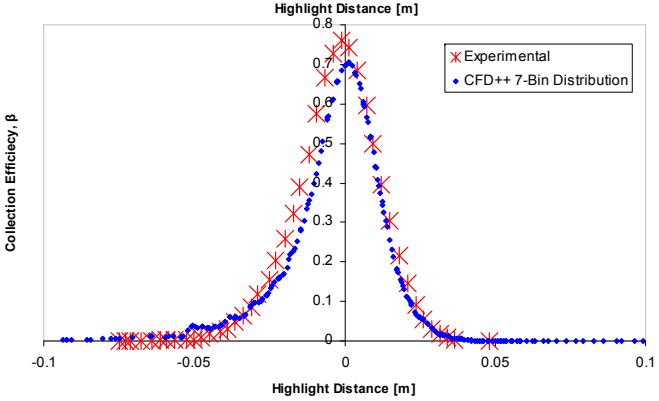

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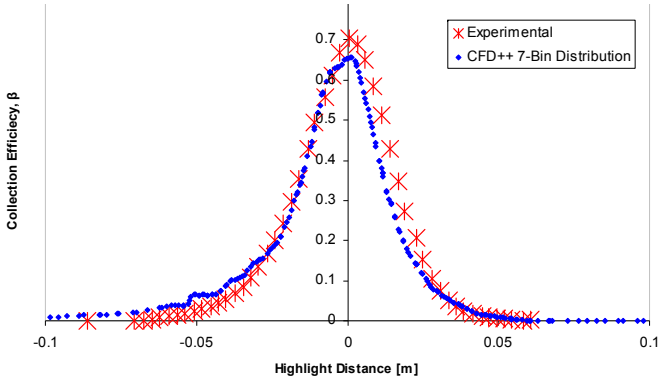
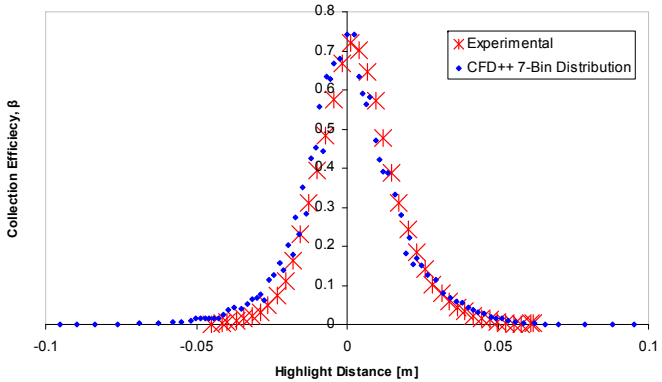


180°



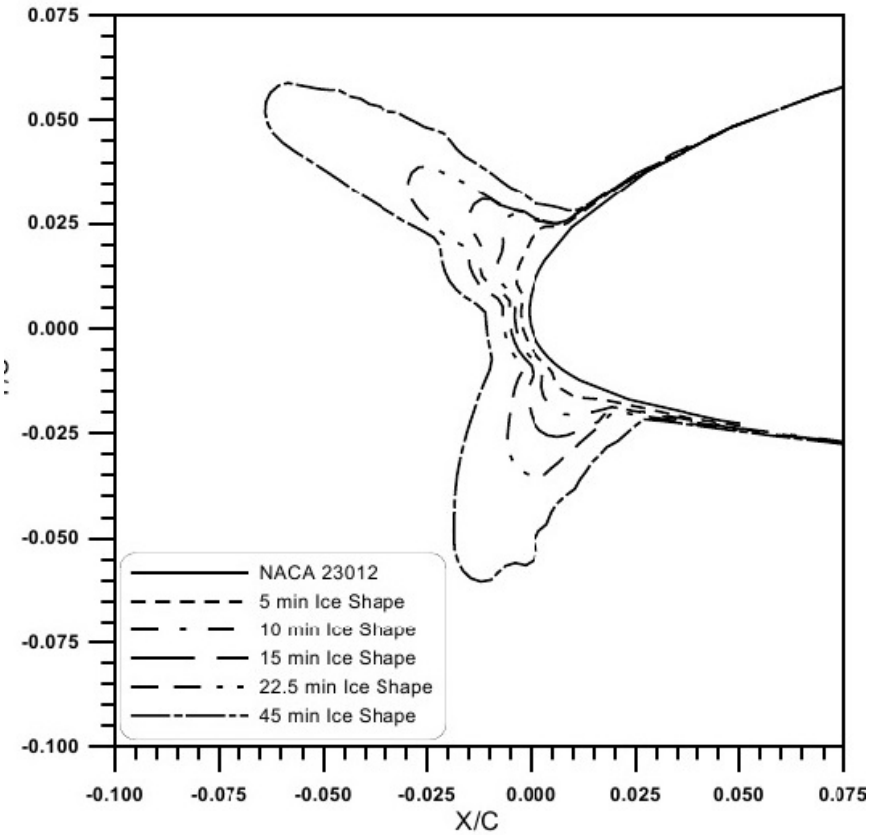
<u>MVD 7bin 20.36 µm simulation</u>
Comparison of CFD and experimental collection efficiency, experimental data from *Papadakis et al. 1989, IRT tunnel*

Collection Efficiency vs. Highlight Distance

- Engine Inlet summary
  - Highest collection efficiency values are obtained for the mono-MVD case with the largest droplet diameter of 66.26 μm.
  - Increasing collection efficiencies and impingement limits obtained with increasing droplet diameter size.
  - Good agreement between CFD++ and experimental collection efficiencies obtained at all 5 stations in terms of peak collection efficiencies and impingement limits (7-bin simulation).

NACA 23012 airfoil with 5 glaze ice shapes

- NACA 23012 airfoil, 0.9144m chord
- 5 glaze shapes generated by LEWICE icing code with progressively longer icing times: 5-min, 10-min, 15-min, 22.5-min and 45-min
- CFD simulations at Re 5.2e6, 2.5 degrees AoA, airspeed 78 m/s
- Droplet impingements with five MVDs: 20, 52, 111, 154, 236 microns
- For each MVD case, a 10-bin droplet distributions are used, taken from experimental droplet distributions
- Comparison of CFD with experiments from AIAA 2004-0565 by Papadakis et al. in the IRT tunnel at NASA.



Papadakis et al. 2004

- Supercooled Large Droplets (SLD)
  - SLD conditions ≈ icing clouds with droplet MVDs greater than 50 microns
  - Ice accretion due to SLD can cause severe performance degradation
  - New SLD modeling capability added in CFD++
  - Model by Honsek/Habashi documented in "Eulerian modeling of in-flight icing due to supercooled large droplets", Honsek, Habashi & Aube, Journal of Aircraft, Vol. 45, No. 4, pp.1290-1296, 2008, based on semi-empirical formulation of the impingement process (DROP3D)
  - Bai & Gosman model of droplet-wall interaction mechanisms:
    - ❑ Stick
    - ❑ Spread
    - ❑ Rebound
    - ❑ Splash
  - Transition between these regimes is based on the Weber number, Trujillo's parameter etc.
  - Original EDP model in CFD++ accounted for stick/spread. The new SLD model accounts for <u>rebound</u> and <u>splash</u> mechanisms

Simulation of Droplet Impingement for Aircraft Icing Analysis

The effect of droplet-wall interactions is incorporated into the dispersed phase momentum equation in non-conservative form as a body force F_S

$$\frac{\partial \mathbf{u}_p}{\partial t} + \mathbf{u}_p \cdot \nabla \mathbf{u}_p = \frac{1}{m_I}\left(\mathbf{F}_D + \mathbf{F}_B + \mathbf{F}_S\right)$$

The body force F_S is associated with the change in droplet momentum during the impingement process and can be expressed as.

$$\mathbf{F}_S = \frac{m_I \mathbf{u}_I}{\Delta T_S} f_m \left(f_{\mathbf{u}} - 1\right) = \frac{m_I f_m}{\Delta T_S}\left(\mathbf{u}_S - \mathbf{u}_I\right)$$

where ΔT_S an empirical correlation for the collision contact time, and functions f_m and f_u have been calibrated by Dr. Habashi et al. against experimental data provided by Dr. Papadakis et al. (icing impingement experiments). Note: F_S is zero throughout the domain except for cells at solid boundaries

* subscript *I* denotes pre-breakup, while subscript *S* represents post-breakup of impingement process.

When droplets impinge on a solid boundary, some of their mass is lost while they are splashing. Therefore, the dispersed mass conservation equation is modified as:

$$\frac{\partial \overline{\rho}_p}{\partial t} + \nabla \cdot (\overline{\rho}_p \mathbf{u}_p) = n\left(\frac{m_S - m_I}{\Delta T_S}\right) = \frac{\overline{\rho}_p}{\Delta T_S}\left(\frac{m_S}{m_I} - 1\right)$$

As a consequence, the number density equation is modified further, and the final number density equation is:

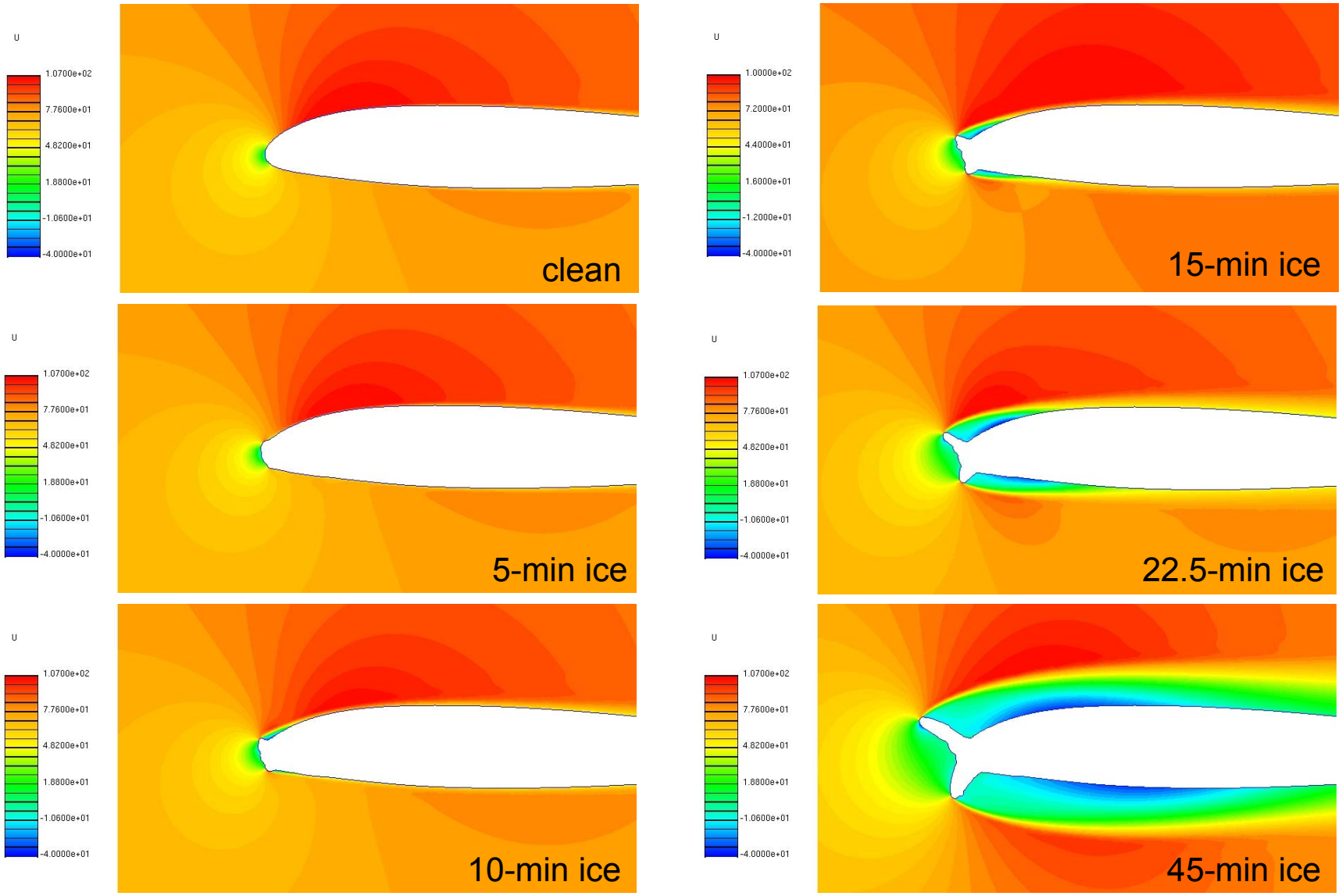
$$\frac{\partial n}{\partial t} + \nabla \cdot (n\mathbf{u}_p) = \frac{3n}{\Delta T_S}\left(1 - \frac{d_S}{d_I}\right) - \frac{n}{\Delta T_S}\left(1 - \frac{m_S}{m_I}\right)$$

$$\frac{d_S}{d_I} = \left(\frac{m_S}{m_I}\frac{1}{N_S}\right)^{1/3}$$

where N_s is the number of secondary droplet fragments and m_S/m_I are obtained from empirical relations by Stow/Stainer and Yarin/Weiss respectively.

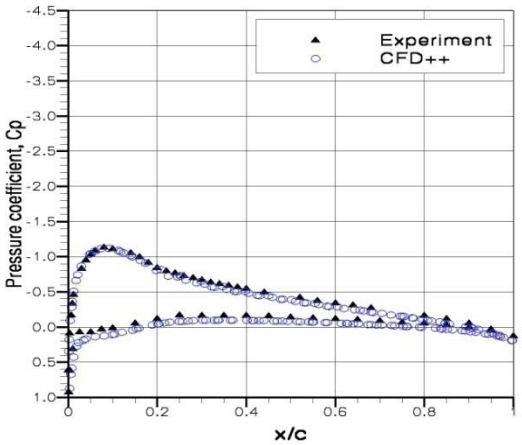
Simulation of Droplet Impingement for Aircraft Icing Analysis

CFD++ u-velocity contours

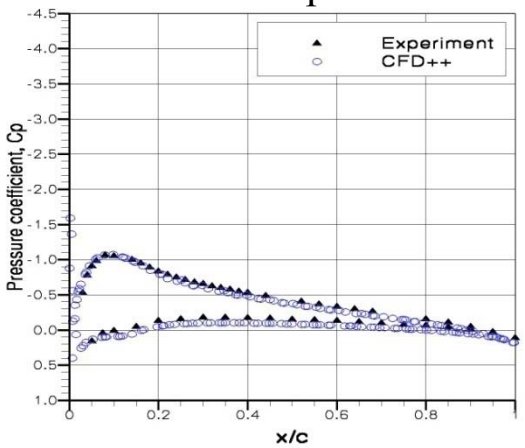


Simulation of Droplet Impingement for Aircraft Icing Analysis

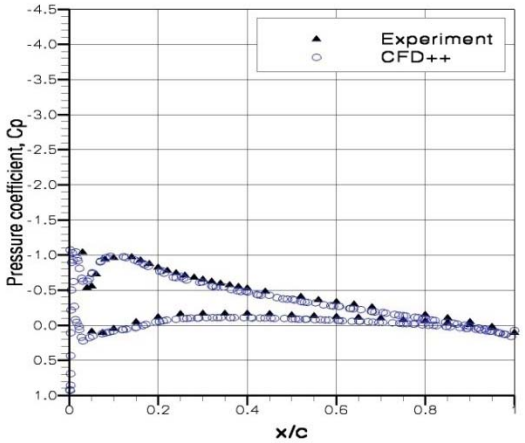
clean airfoil



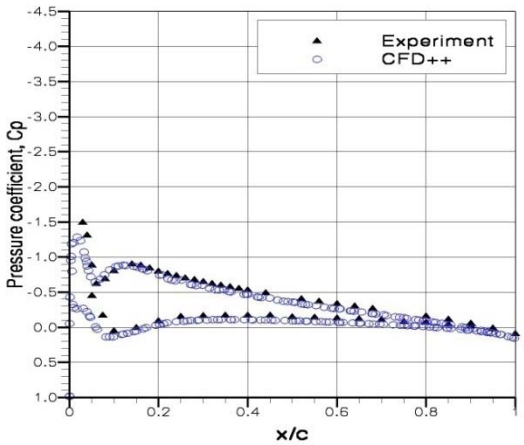
5-min ice shape



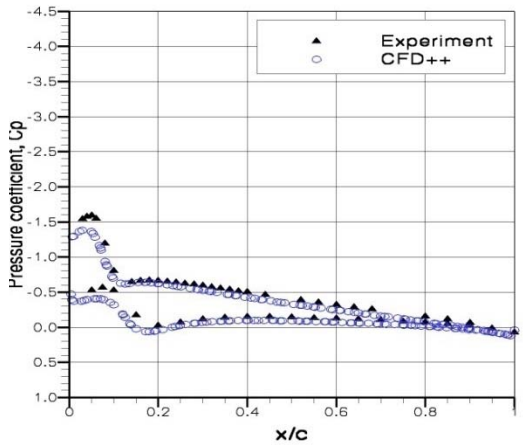
10-min ice shape



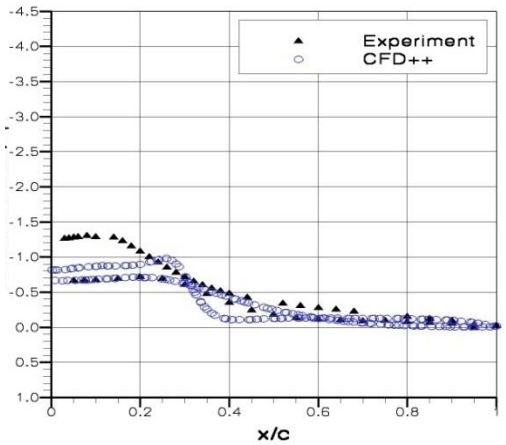
15-min ice shape



22.5-min ice shape



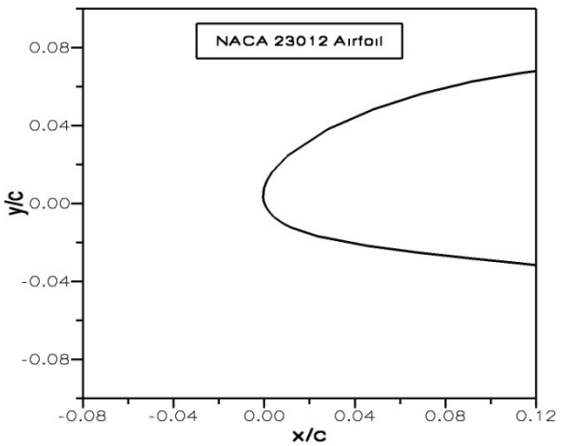
45-min ice shape



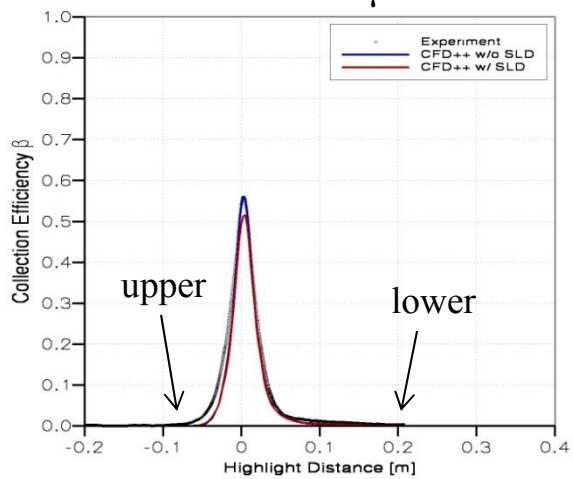
Pressure Coefficient vs. x/c: Comparison of experimental and computational pressure distributions of the NACA 23012 cases, experimental data by *Papadakis et al. 2004*

Simulation of Droplet Impingement for Aircraft Icing Analysis

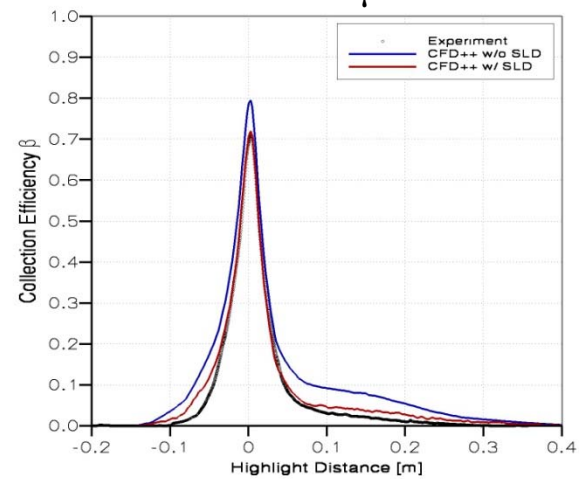
clean airfoil geometry



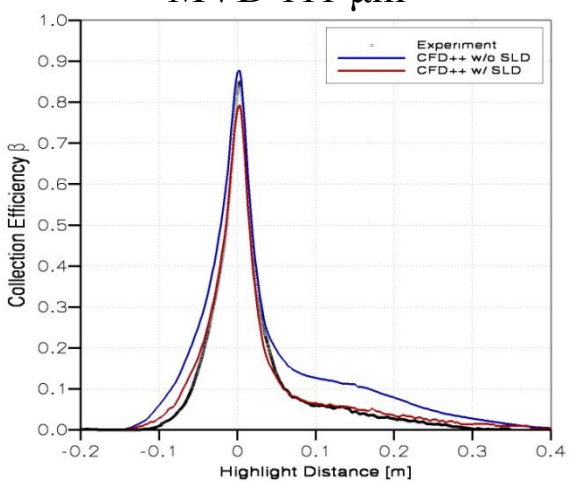
MVD 20 μm



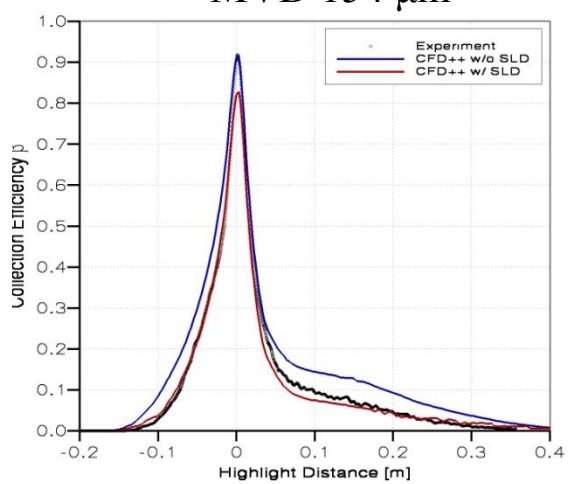
MVD 52 μm



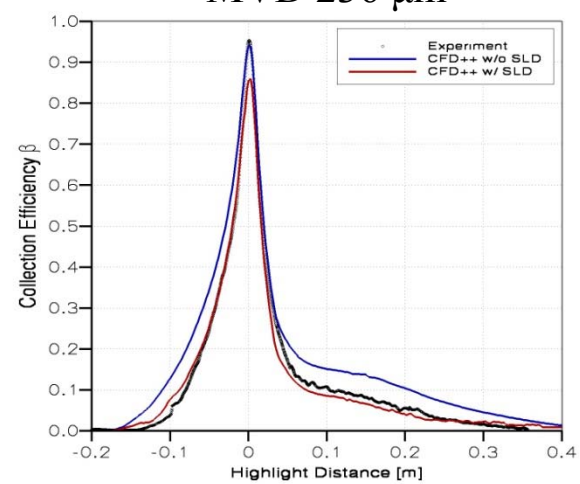
MVD 111 μm



MVD 154 μm



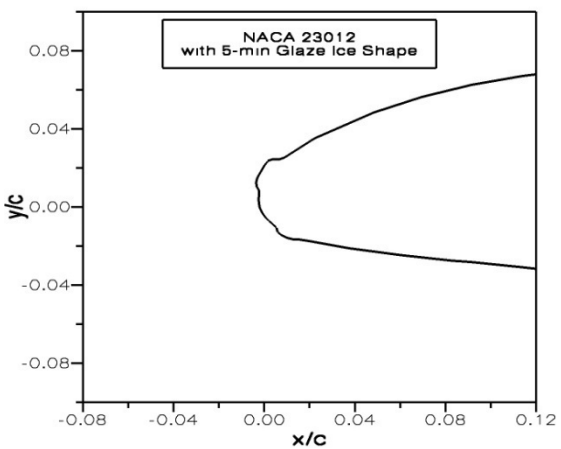
MVD 236 μm



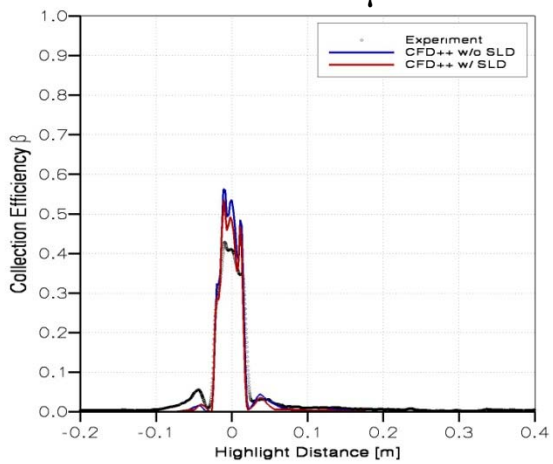
Collection Efficiency vs. Highlight Distance: CFD and experimental collection efficiency for the NACA 23012 airfoil with varying MVD, experimental data from *Papadakis et al. 2004*

Simulation of Droplet Impingement for Aircraft Icing Analysis

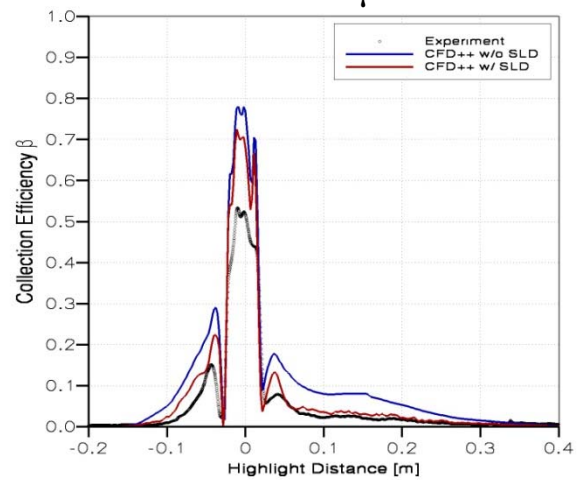
5-min ice geometry



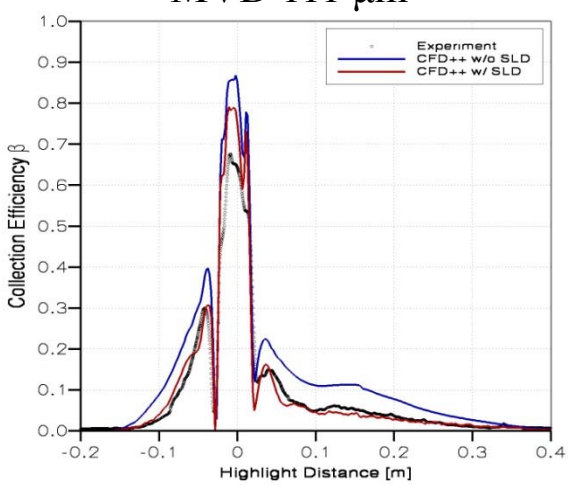
MVD 20 μm



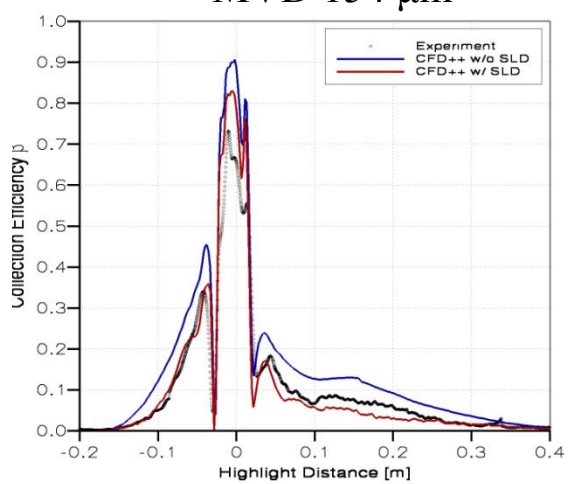
MVD 52 μm



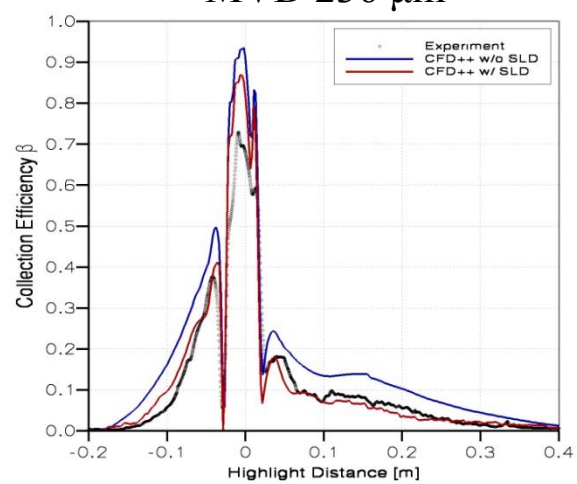
MVD 111 μm



MVD 154 μm



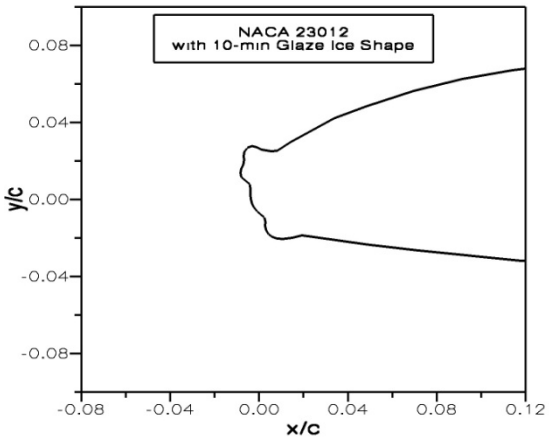
MVD 236 μm



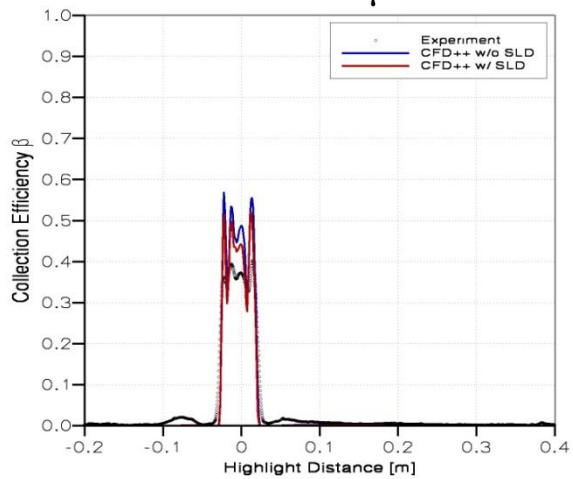
Collection Efficiency vs. Highlight Distance: CFD and experimental collection efficiency for the NACA 23012 airfoil with varying MVD, experimental data from *Papadakis et al. 2004*.

Simulation of Droplet Impingement for Aircraft Icing Analysis

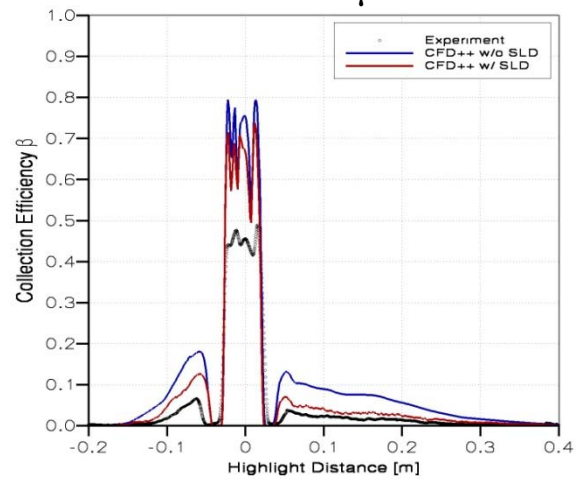
10-min ice geometry



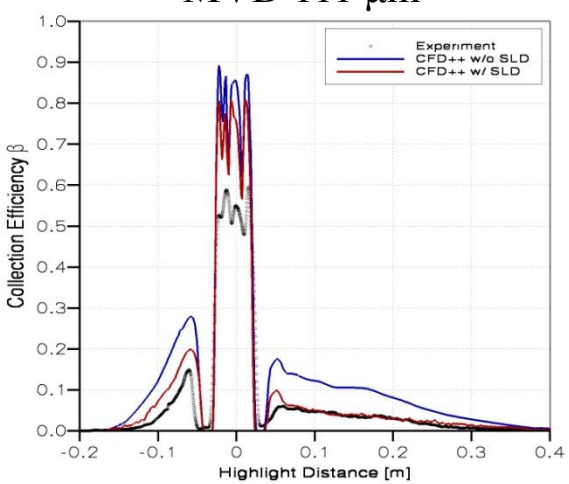
MVD 20 μm



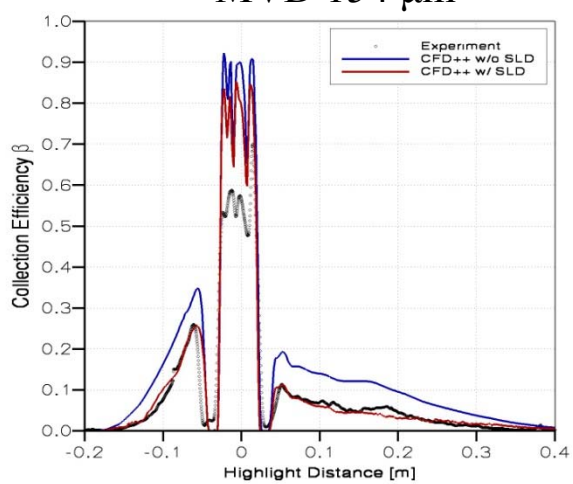
MVD 52 μm



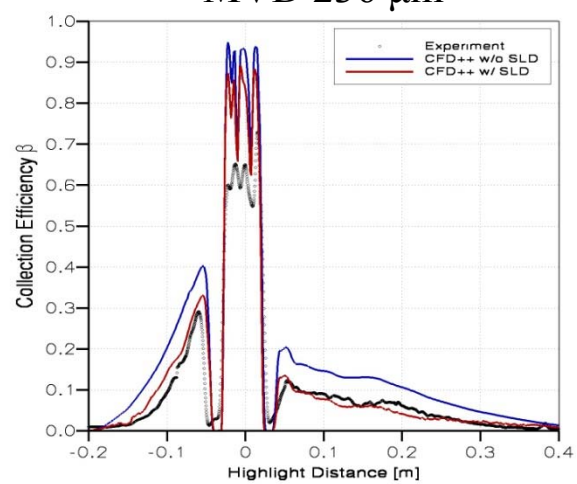
MVD 111 μm



MVD 154 μm



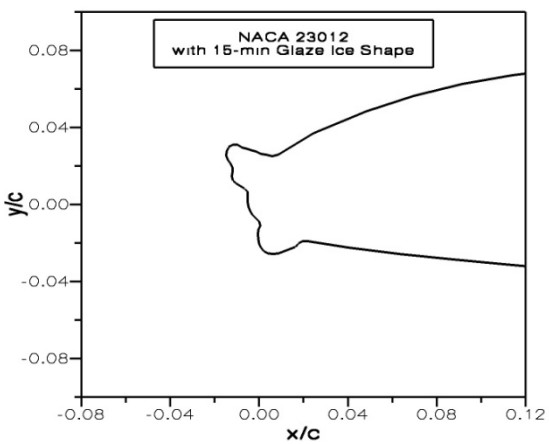
MVD 236 μm



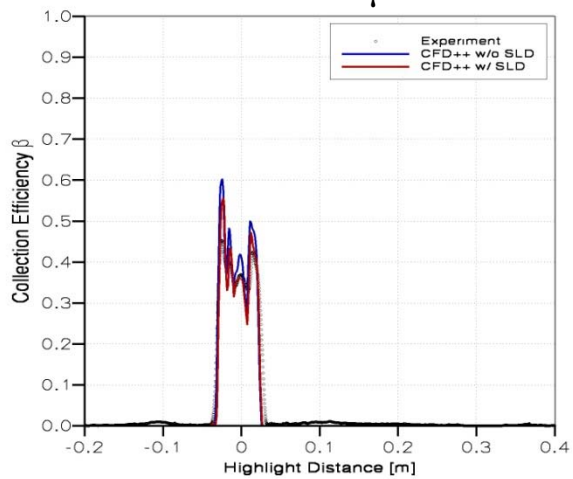
Collection Efficiency vs. Highlight Distance: CFD and experimental collection efficiency for the NACA 23012 airfoil with varying MVD, experimental data from *Papadakis et al. 2004*

Simulation of Droplet Impingement for Aircraft Icing Analysis

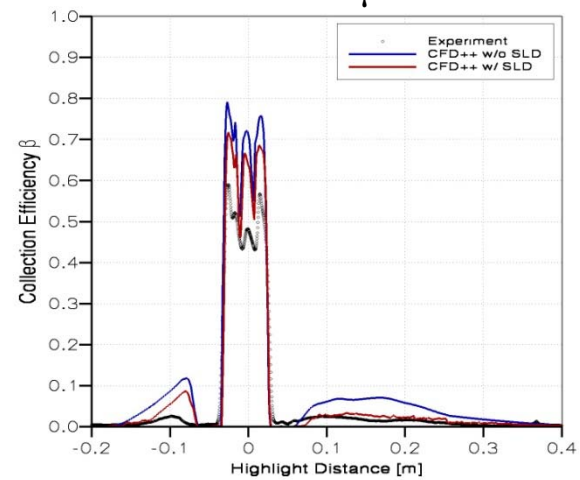
15-min ice geometry



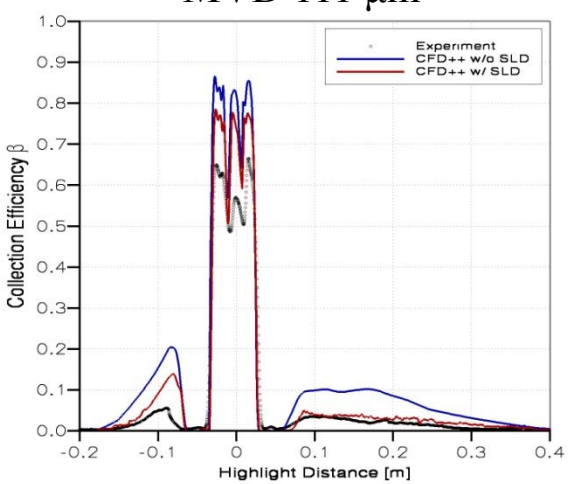
MVD 20 μm



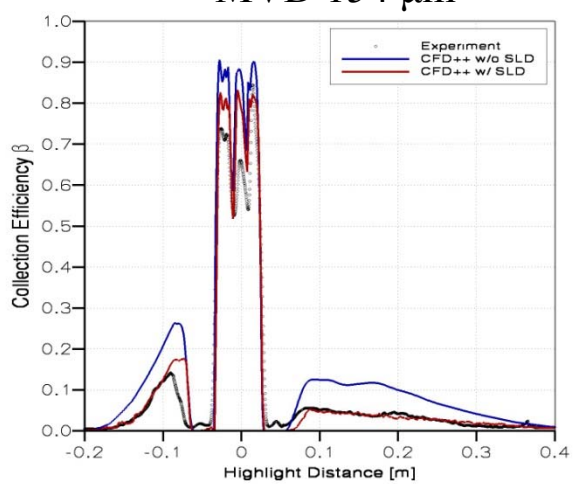
MVD 52 μm



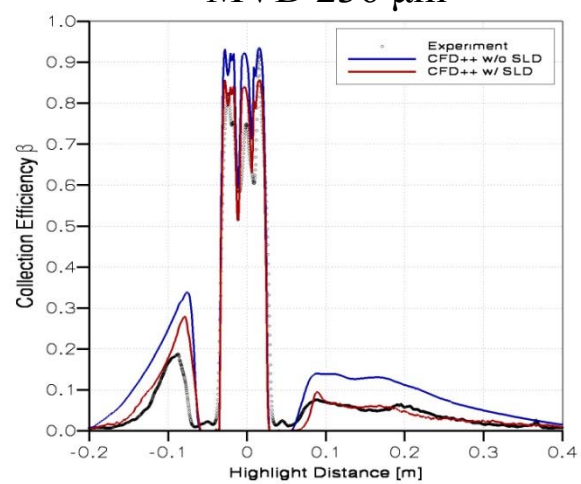
MVD 111 μm



MVD 154 μm



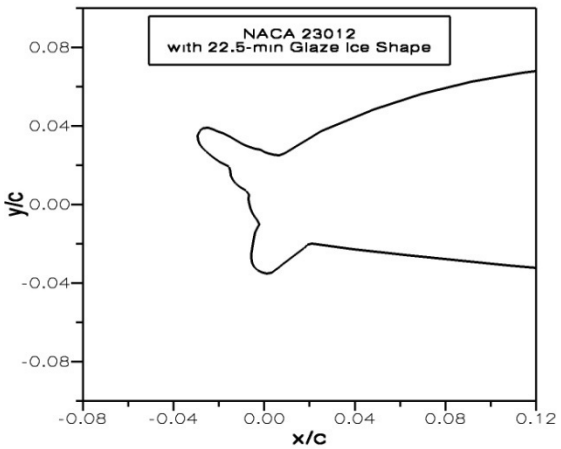
MVD 236 μm



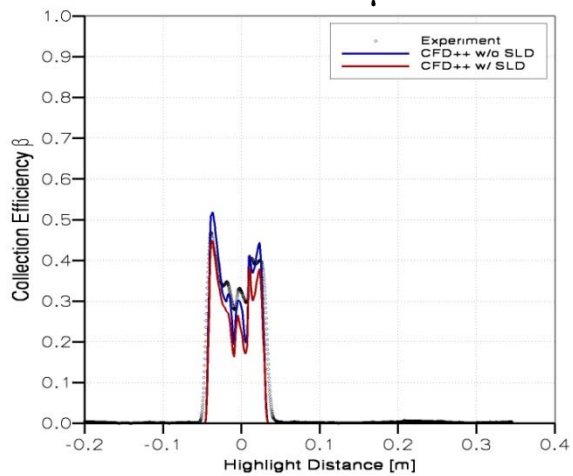
Collection Efficiency vs. Highlight Distance: CFD and experimental collection efficiency for the NACA 23012 airfoil with varying MVD, experimental data from *Papadakis et al. 2004*.

Simulation of Droplet Impingement for Aircraft Icing Analysis

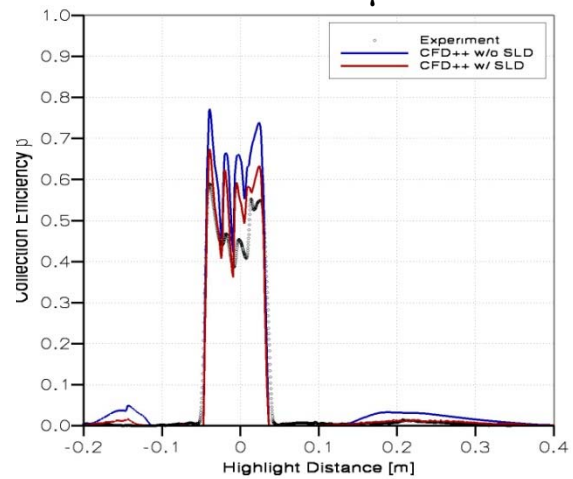
22.5-min ice geometry



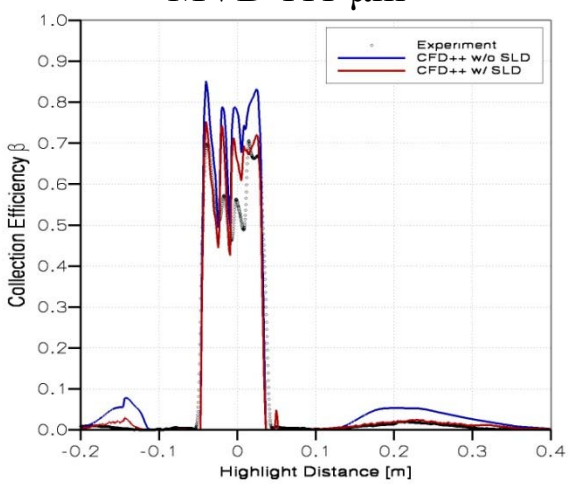
MVD 20 μm



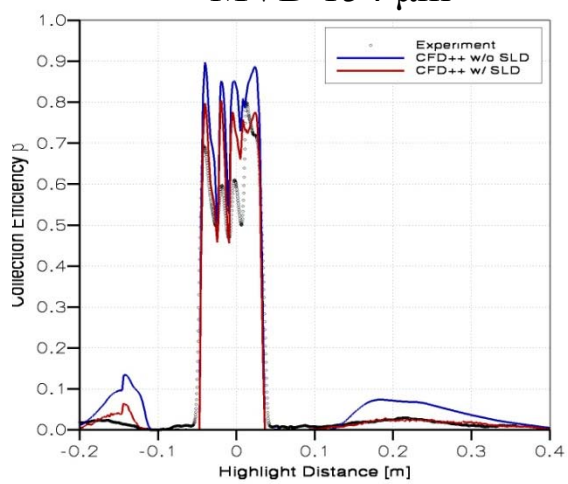
MVD 52 μm



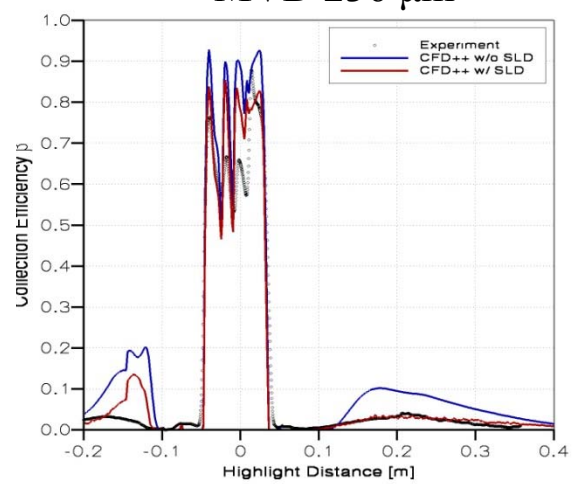
MVD 111 μm



MVD 154 μm



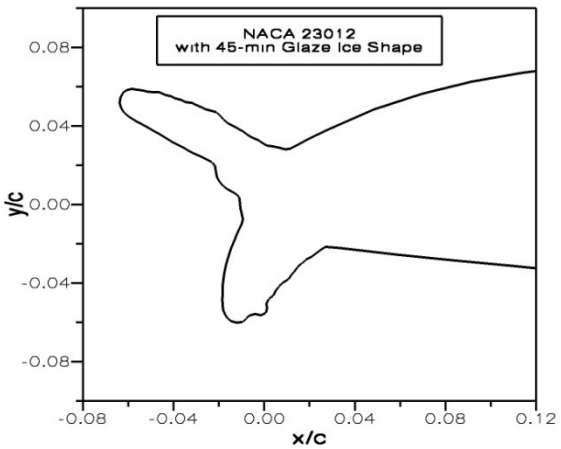
MVD 236 μm



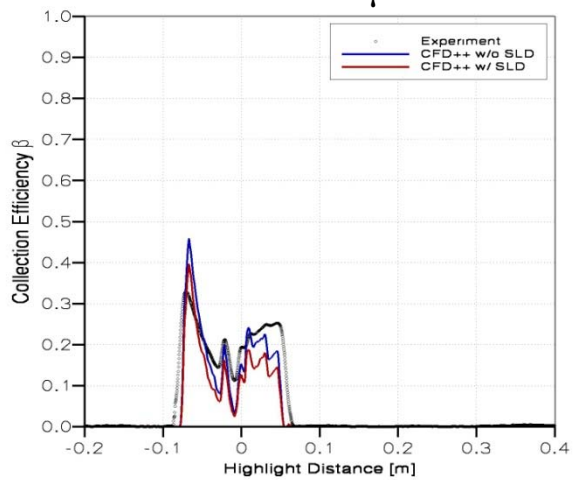
Collection Efficiency vs. Highlight Distance: CFD and experimental collection efficiency for the NACA 23012 airfoil with varying MVD, experimental data from *Papadakis et al. 2004*.

Simulation of Droplet Impingement for Aircraft Icing Analysis

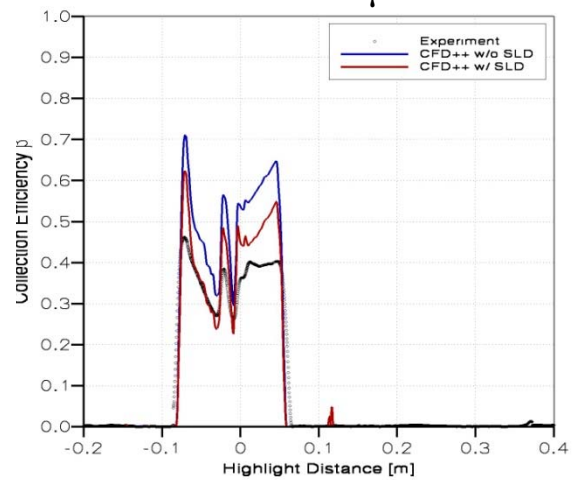
45-min ice geometry



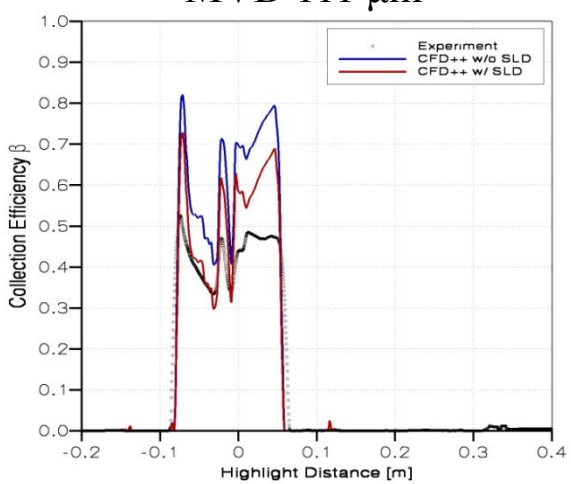
MVD 20 μm



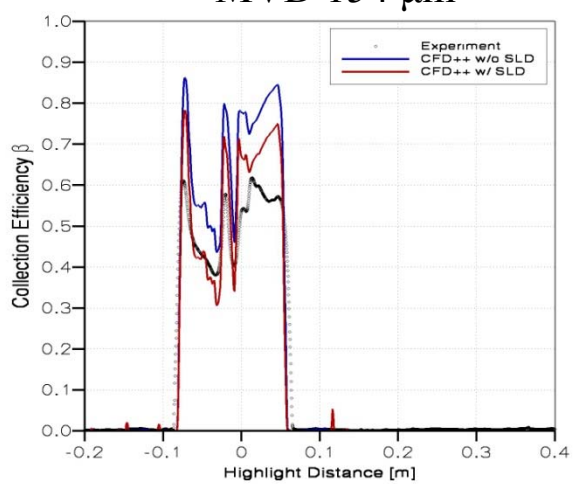
MVD 52 μm



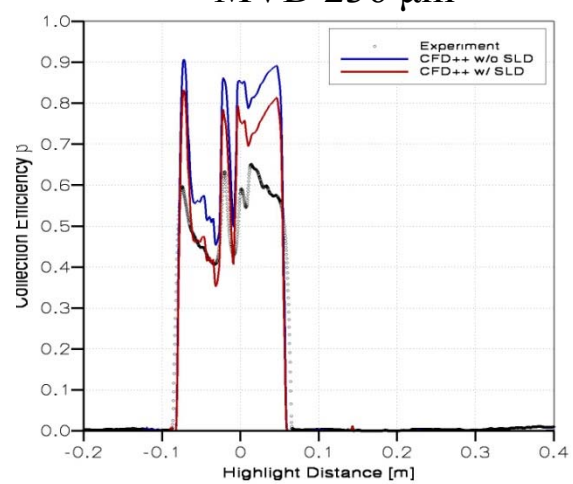
MVD 111 μm



MVD 154 μm



MVD 236 μm



Collection Efficiency vs. Highlight Distance: CFD and experimental collection efficiency for the NACA 23012 airfoil with varying MVD, experimental data from *Papadakis et al. 2004*.

- NACA 23012 ice shapes summary (without SLD)
  - For the clean airfoil cases without SLD modeling, the collection efficiency peak values are well predicted.
  - For the five glaze ice shapes without SLD modeling, fair agreement is obtained between CFD and experimental data for the smallest droplet MVD of 20μm.
  - For the larger droplet sizes, over-prediction of the collection efficiency values at the leading-edges are observed, since droplet rebound and splash are not accounted for. The discrepancies become larger with increasing droplet size.
  - As is expected, increasing droplet MVD also increases the maximum limits of impingement.

- NACA 23012 ice shapes summary (with SLD)
  - For the clean airfoil cases the close agreement with experimental data near the impingement limits was also reported by Dr. Habashi, and is attributed to the substantial mass loss from droplet bouncing
  - For the five glaze shape, the collection efficiency peak values near the leading edges are significantly reduced with SLD modeling due to the mass loss
  - The predictions show that we still obtain slightly higher peak values from CFD compared to experimental data up to the 22.5-min ice shape
  - The largest discrepancies are found in the horn region of the ice shapes, however, the trends in these regions are very similar to experiment
  - In nearly all cases away from the impingement zone, the collection efficiency drops down to nearly identical levels to those from experiment

- Concluding remarks
  - Icing collection efficiency prediction for small and large droplet impingements using CFD++ with additional SLD modeling
  - Good agreement with experiment for small droplets ~ MVD 20 microns
  - Improved predictions for large droplet impingements with SLD model up to MVD of 236 microns
  - Further work: Thin film modeling for water runback simulations, ice accretion modeling, aerodynamic degradation due to icing

- Acknowledgements
  - William Wright, NASA Glenn Icing Branch for ice geometries and experimental data