

CIRA Analyses for the 3rd IPW

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CIRA analyses for 3rd IPW

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Italian Aerospace Research Centre – CIRA Scpa

3rd Ice Prediction Workshop

21-24 September 2026

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Numerical Methodology

Model / Method	NACA0012	ONERAM6
CFD Model	Cartesian Immersed Boundary RANS	Cartesian Immersed Boundary RANS
Turbulence Model	k-omega TNT	k-omega TNT
HTC Method	Reynolds analogy (Kays & Crowford)	Reynolds analogy (Kays & Crowford)
Droplet Formulation	Eulerian	Eulerian
Droplet Drag Model	Spherical (Schiller and Naumann)	Spherical (Schiller and Naumann)
SLD Effects	Splashing/Bouncing (Wright model)	Full deposition
Thermodynamic Model	Messinger	Messinger
Ice Density Model	Constant -917Kg/m ³	Constant - 680 kg/m ³
Roughness Height	Constant	Constant
Geometry Evolution	Algebraic Lagrangian growth	Algebraic Lagrangian growth
Ice Accretion Steps	Single-shot / 5-layers	Single-shot / 3-layers

CIRA Cartesian Method

Comput. Domain

Unstructured 2D/3D Cartesian with adaptive mesh refinement (AMR).

Air-phase

RANS/URANS or hybrid RANS-LES, FV IB-method, 2nd order skew-symmetric CDS, wall-modelling, static and dynamic multi-component surfaces.

Water-phase

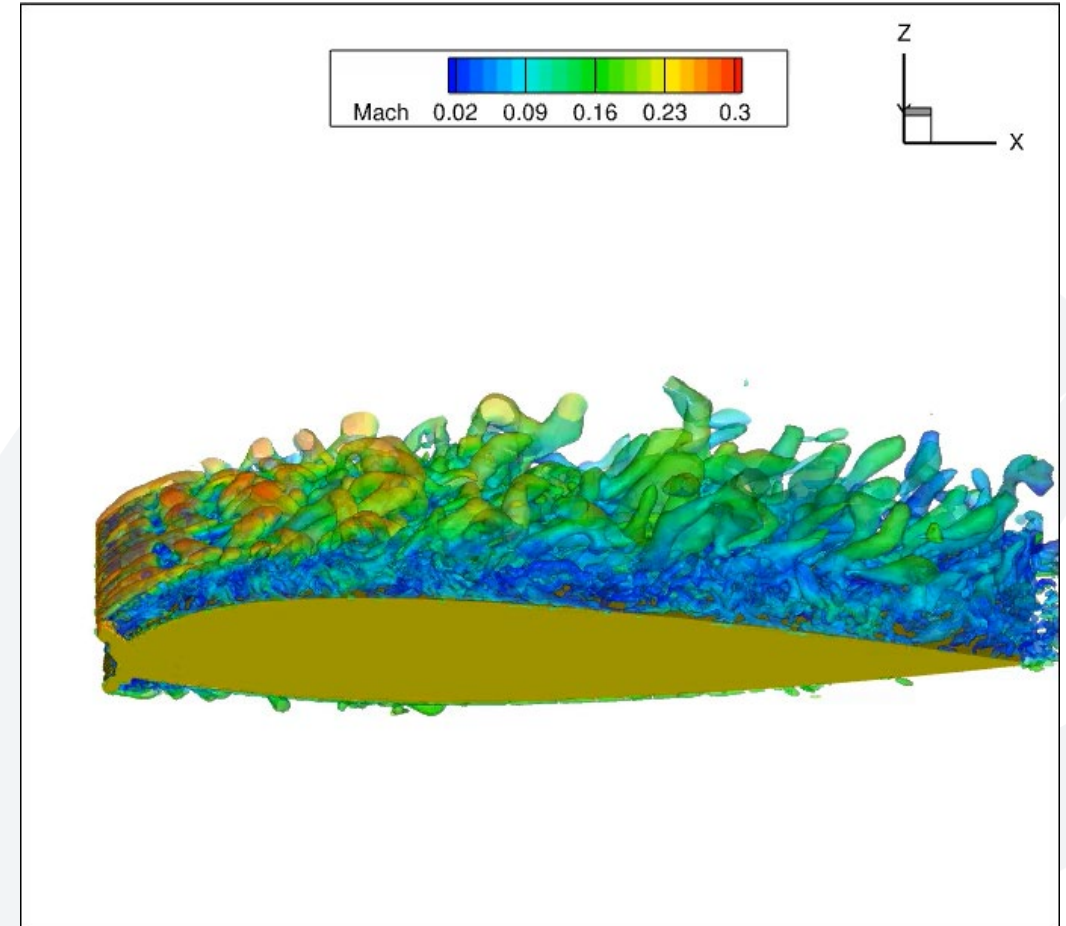
Eulerian droplet mass momentum and energy balances, FV IB-method, 2nd order CDS. SLD modelling available.

Thermodynamics

Messinger water-film module fully integrated into the Cartesian simulation framework.

Geometry update/handling

- Lagrangian based ice-accretion
- Developing a new Eulerian Level-Set based chain



(Capizzano et al., JCP 2019, SAE 2023, JOA 2025)

In-Flight ONERA-M6 Case

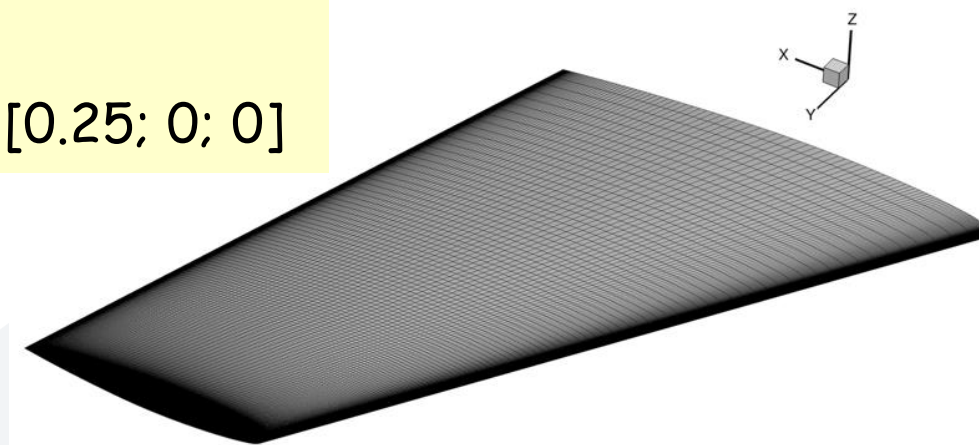
In-Flight ONERA-M6 Case

In-flight free-stream conds.:

- $U_{\infty} = 131.034 \text{ m/s}$
- $T_{s,\infty} = 267.15 \text{ }^{\circ}\text{K}$
- $\rho_{\infty} = 0.68301 \text{ Kg/m}^3$
- $P_{\infty} = 52377.824 \text{ Pa}$
- $a_{\infty} = 327.66 \text{ m/s}$
- $M_{\infty} = 0.40$
- $Re/m = 5.3087 \cdot 10^6$
- $Re_{mac} = 4.2558 \cdot 10^6$
- $AOA = 2^{\circ}$

Geometric params. :

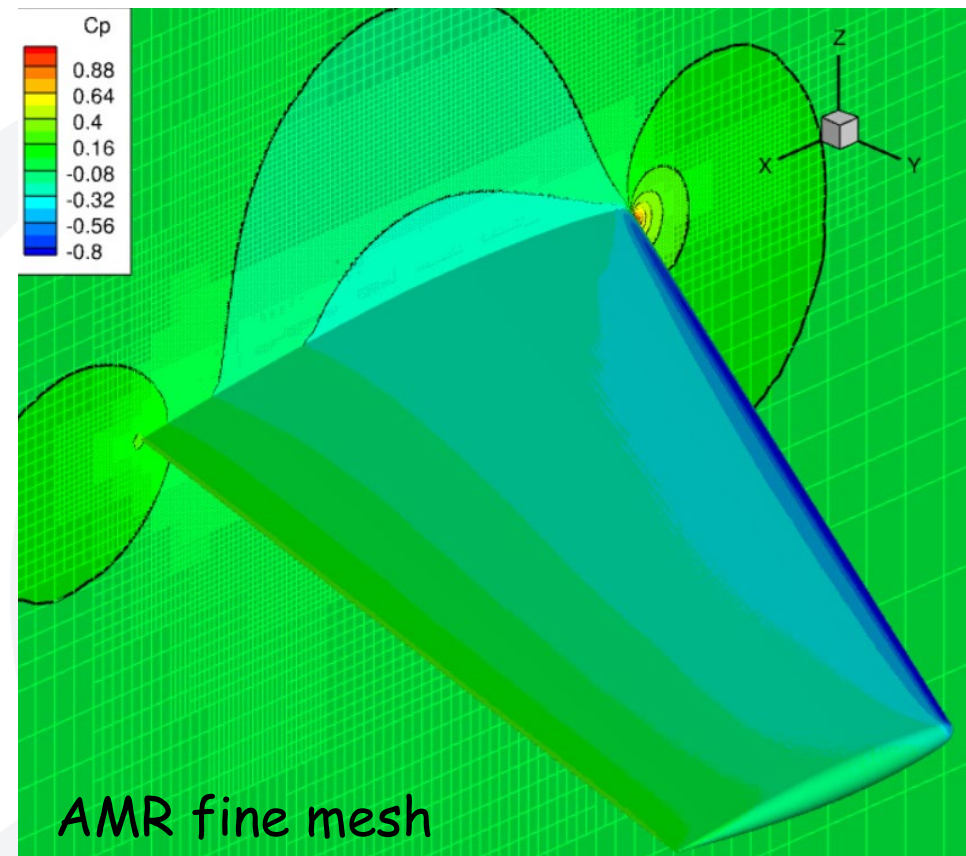
- Root chord = 1 m
- $b/2 = 1.476018 \text{ m}$
- $A_{ref} = 1.1532 \text{ m}^2$
- $AR = 3.78$
- $MAC = 0.801673$
- Moment pole $[X,Y,Z] = [0.25; 0; 0]$



172,414 triangles

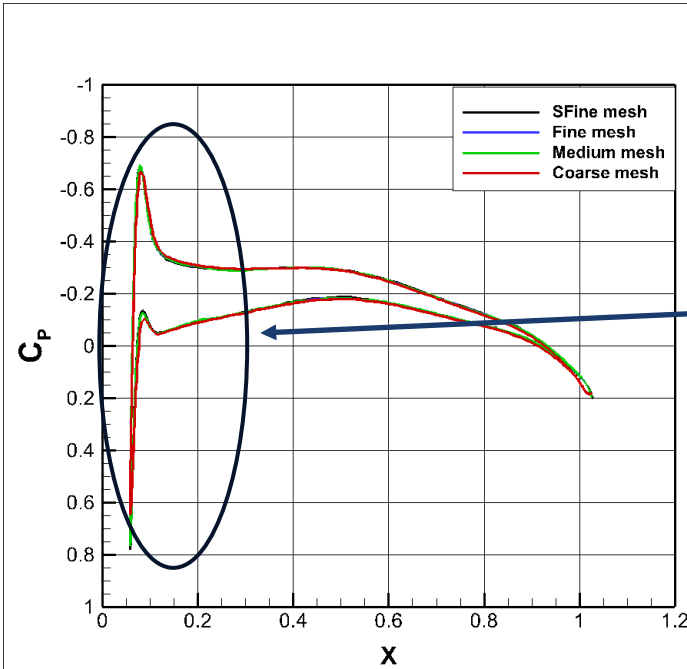
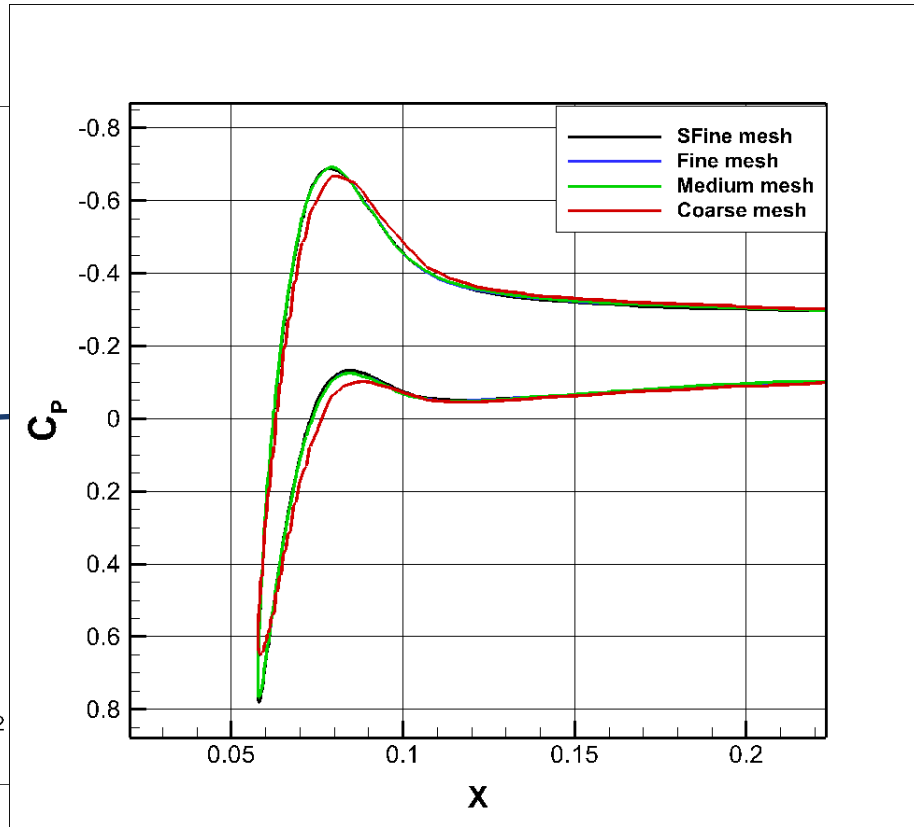
Mesh convergence studies

Cartes. Mesh (AMR)	N_{cells}^{tot}	Δ_{min}^{wall} (m)	Smooth surface		
			CL	CD (counts)	C_{my}
Coarse (L4)	~4M	$2.44 \cdot 10^{-3}$	0.1304	80	-0.04137
Medium (L3)	~16M	$1.22 \cdot 10^{-3}$	0.1302	89	-0.04132
Fine (L2)	~32M	$6.10 \cdot 10^{-4}$	0.1301	97	-0.04165
SFine (L1)	~170M	$3.05 \cdot 10^{-4}$	0.1300	96	-0.04155

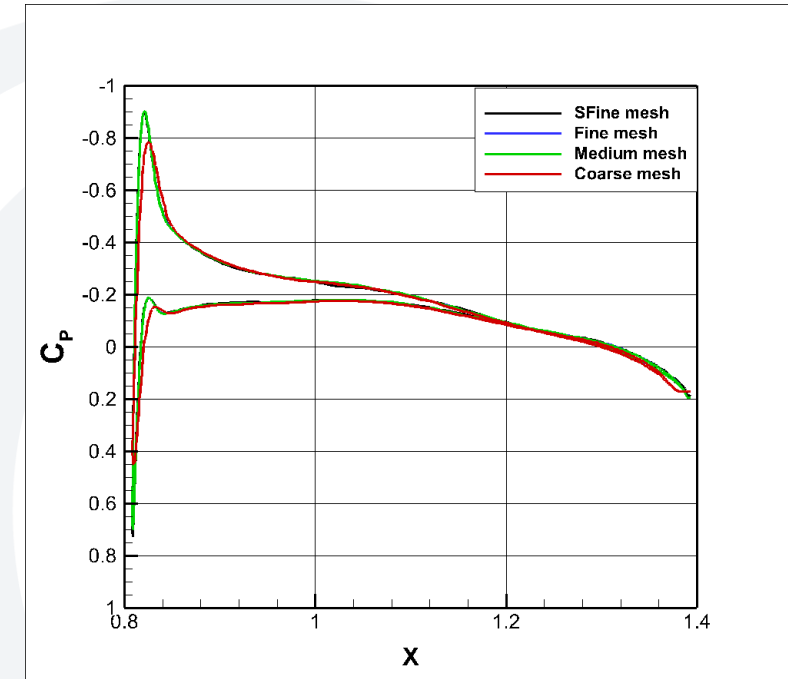


Mesh convergence: air-phase

$Y = 0.1 \text{ m}$



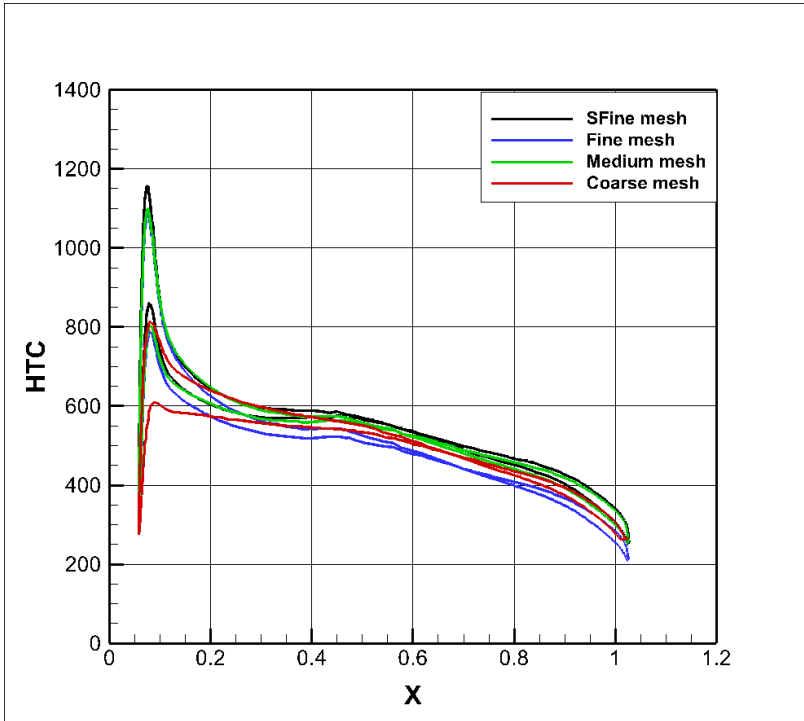
$Y = 1.4 \text{ m}$



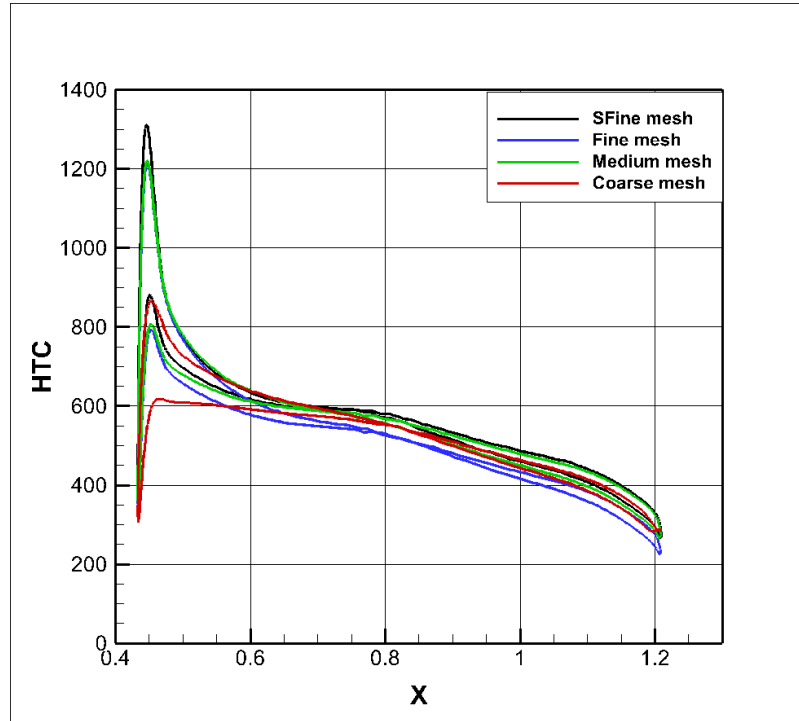
- Full mesh convergence was obtained along the wing-span
- Good accuracy already on the MEDIUM mesh (L3)

HTC convergence: $k_s = 1 \text{ mm}$

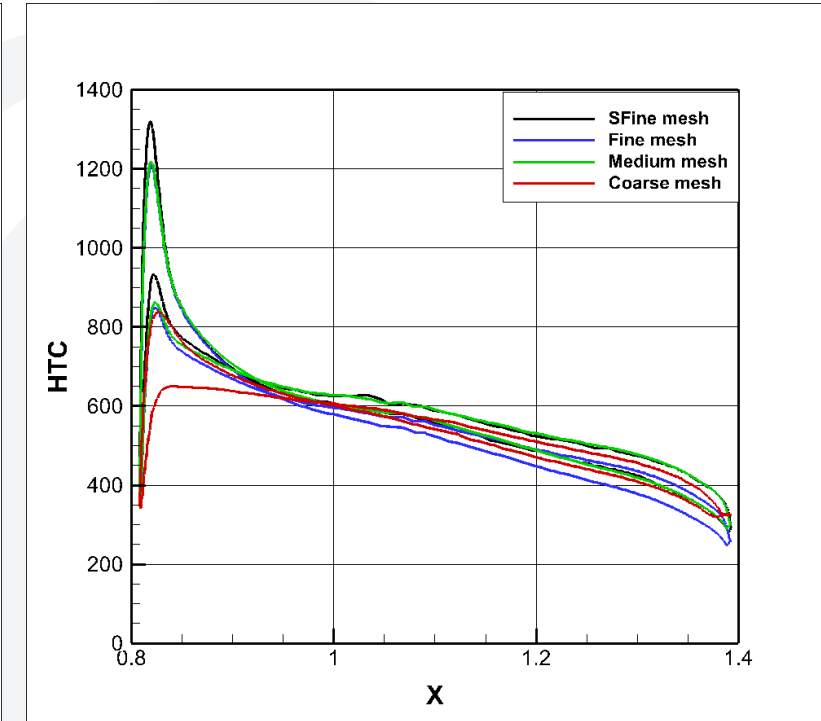
$Y = 0.1 \text{ m}$



$Y = 0.75 \text{ m}$



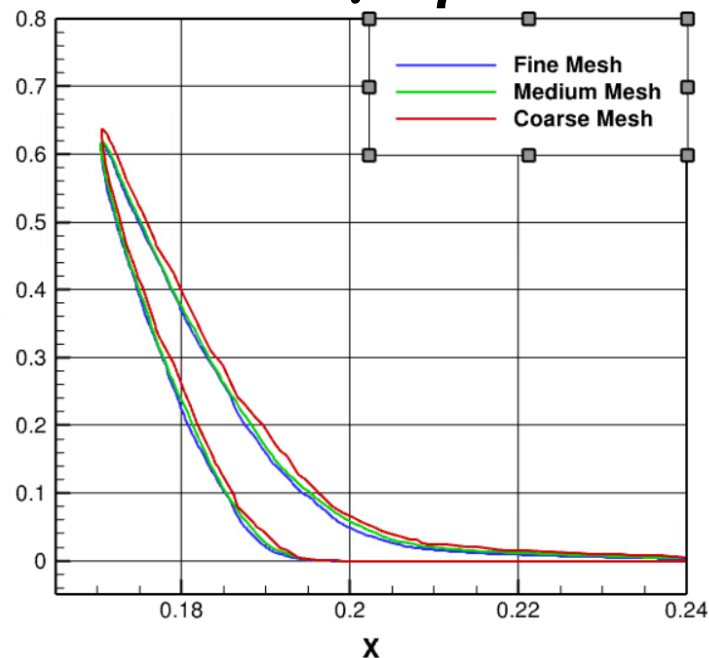
$Y = 1.4 \text{ m}$



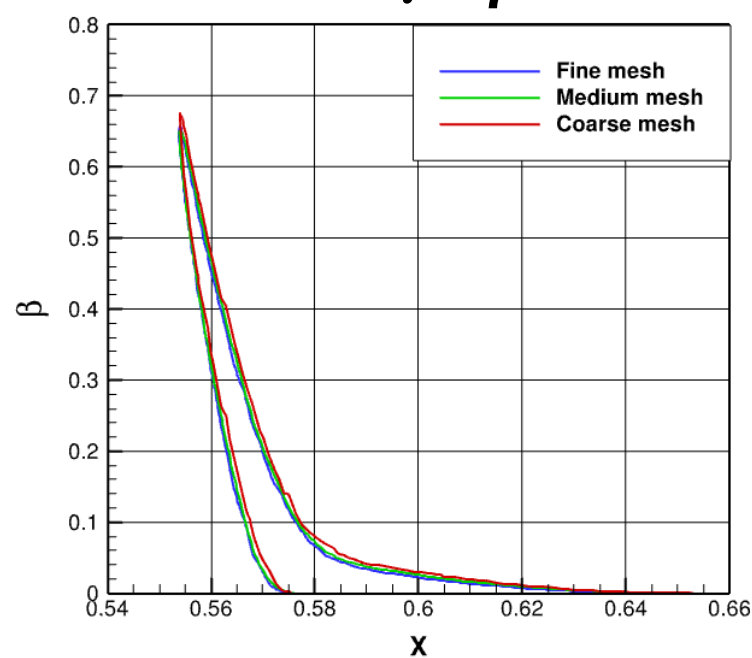
- Consistent trend was obtained along the wing-span for HTC
- Fine mesh data slightly out of trend at TE due to a non-fully converged flow-field

Mesh convergence studies: water-phase

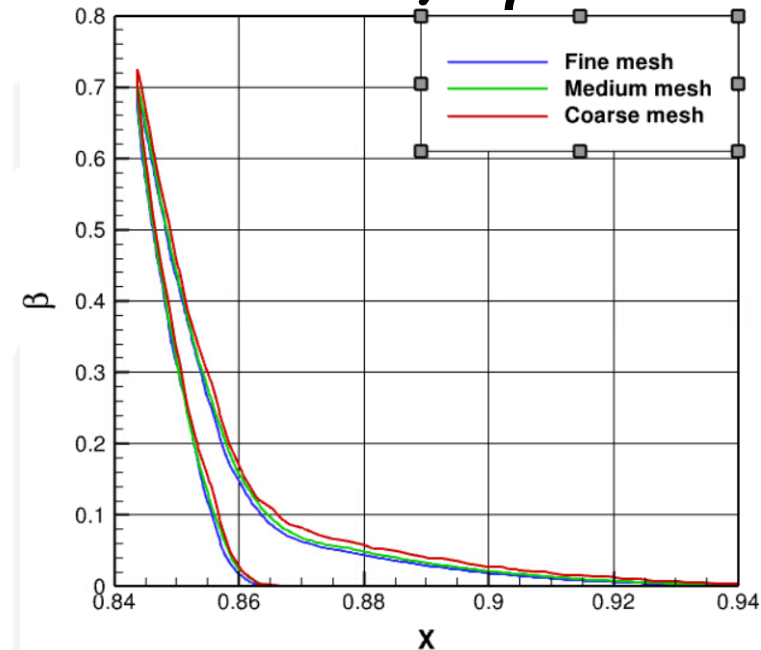
15-bin, $\eta = 20\%$



15-bin, $\eta = 65\%$



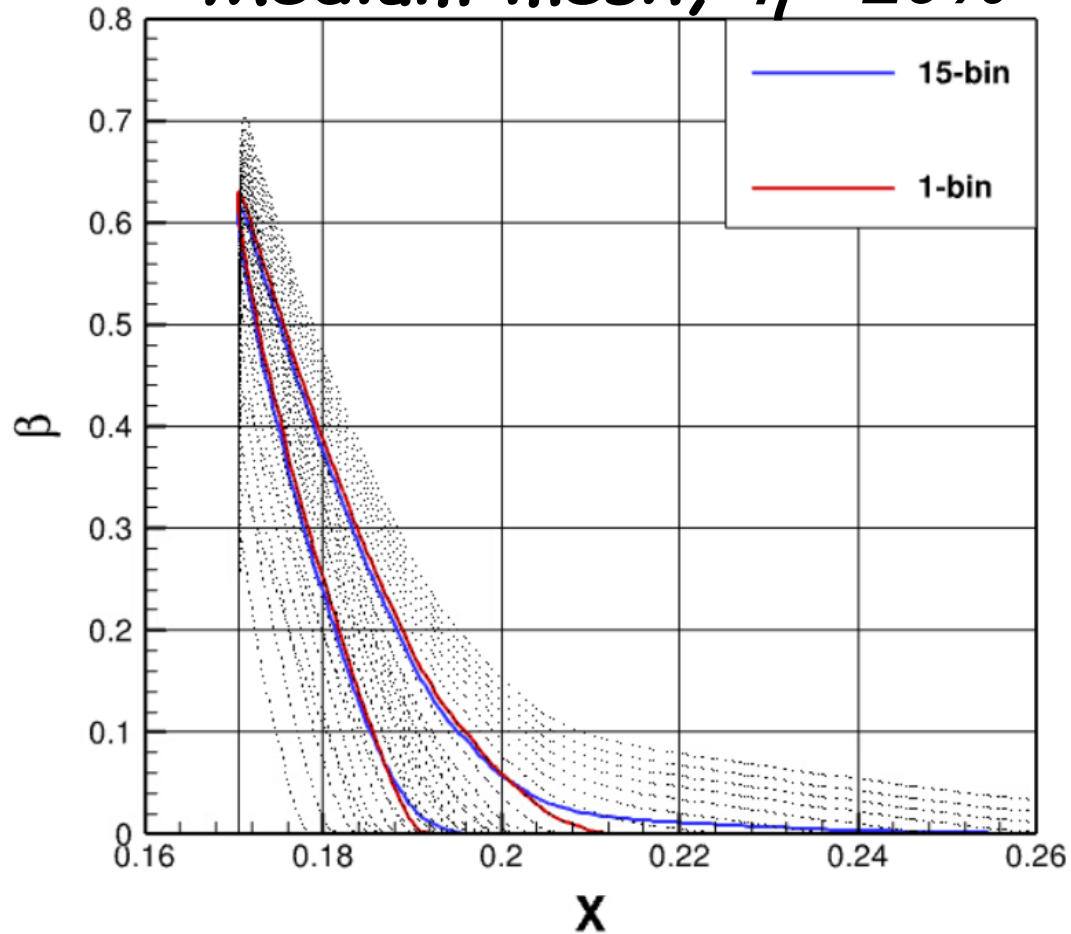
15-bin, $\eta = 99\%$



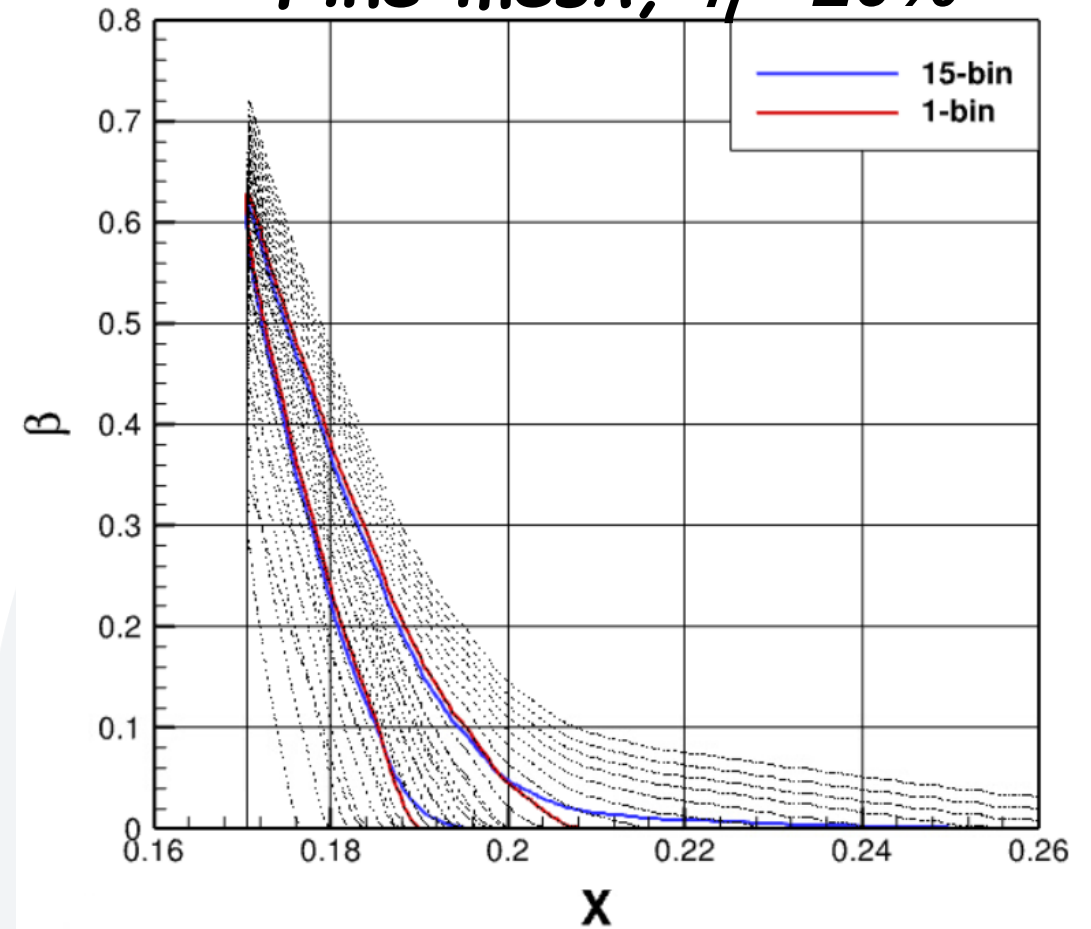
- Full mesh convergence was obtained on collection efficiency
- Confirmed a good accuracy even with the MEDIUM mesh (L3)

Multi-bin analyses

Medium mesh, $\eta = 20\%$



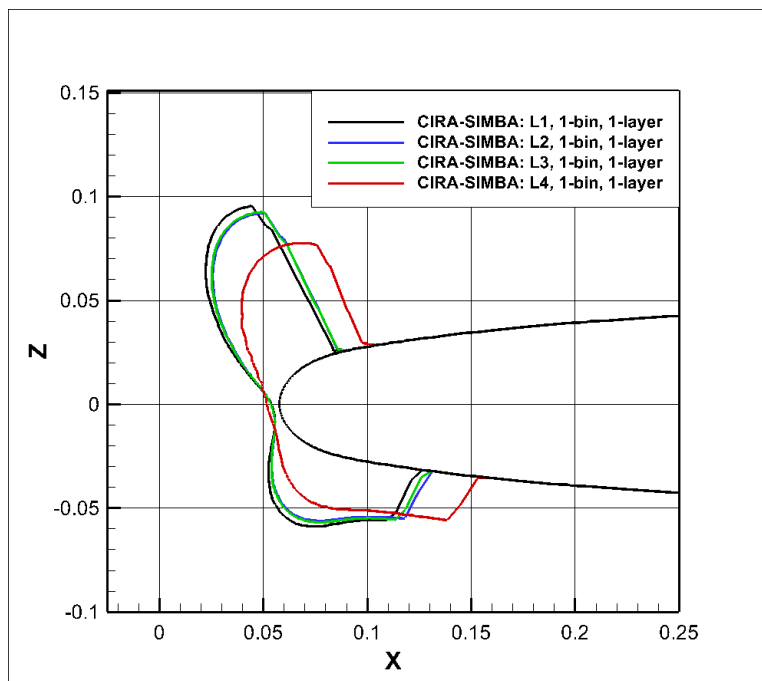
Fine mesh, $\eta = 20\%$



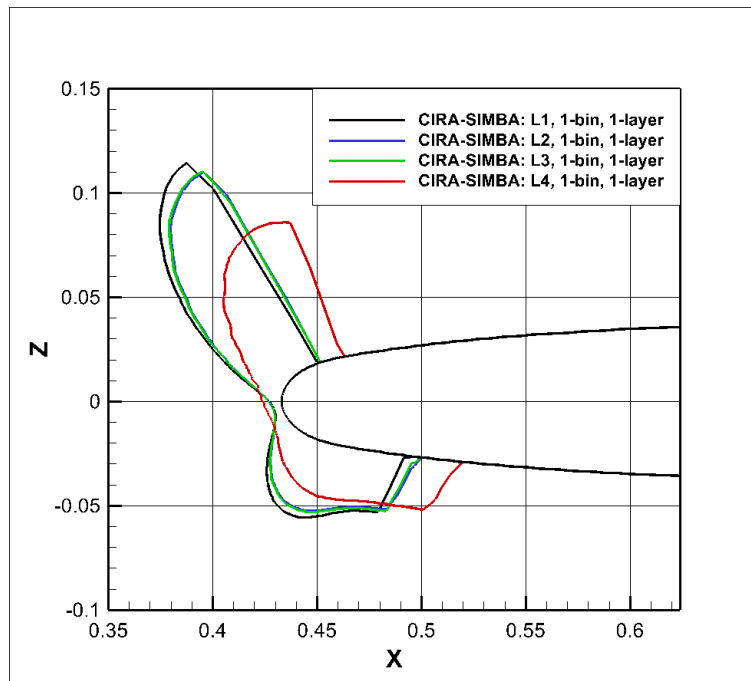
- Multi-bin analyses confirm a good accuracy on MEDIUM mesh
- Small differences are expected at the ice-growth limits for different droplet spectra

Ice-growth mesh convergence: 1 layer

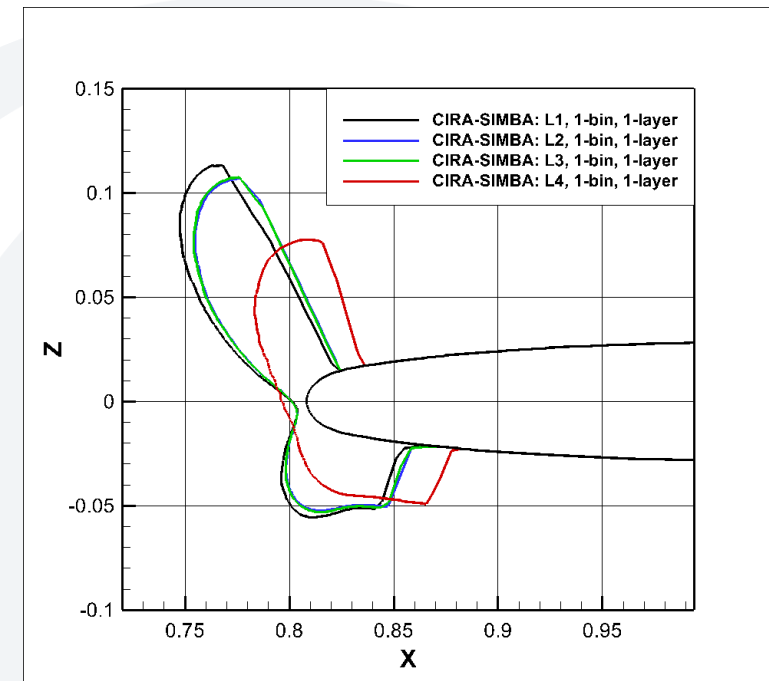
1-bin, $Y = 0.1\text{ m}$



1-bin, $Y = 0.75\text{ m}$



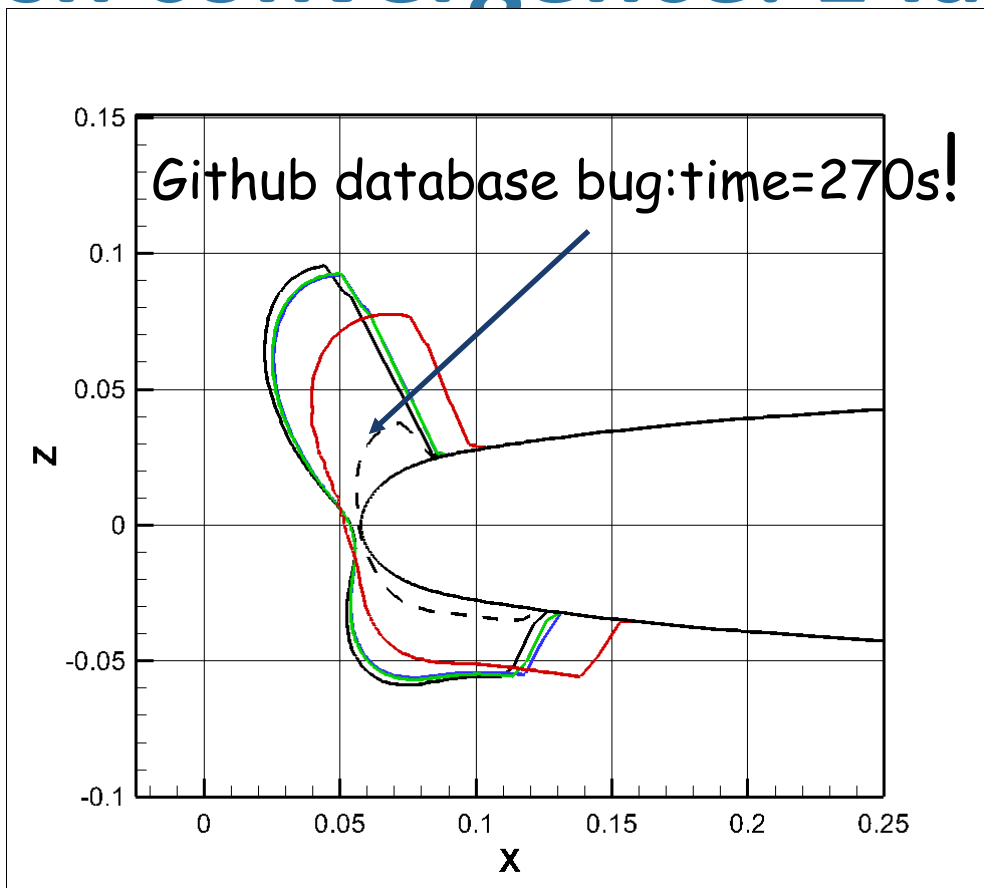
1-bin, $Y = 1.4\text{ m}$



- Consistent trend is visible as the mesh is refined
- Full grid independence cannot be conclusively established
- Medium mesh L3 confirms good accuracy w.r.t finest ones

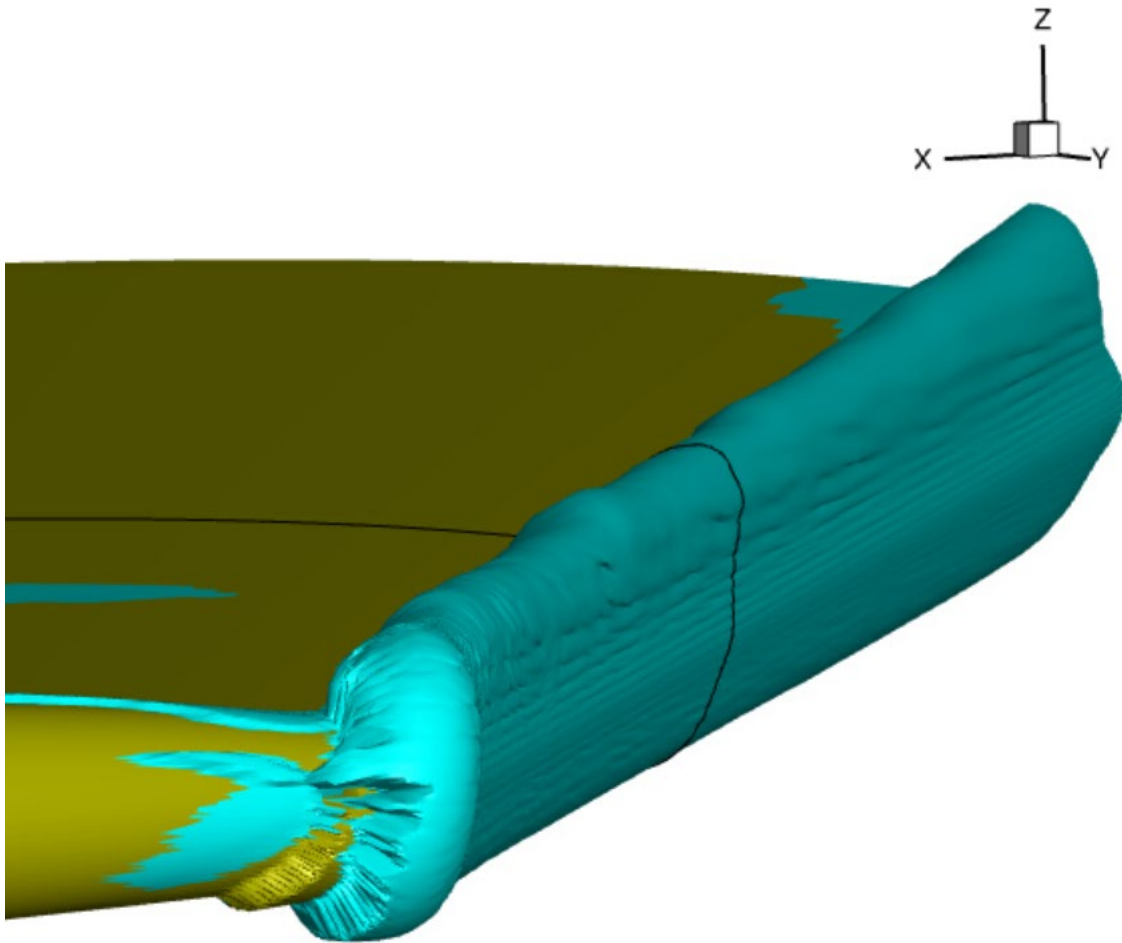
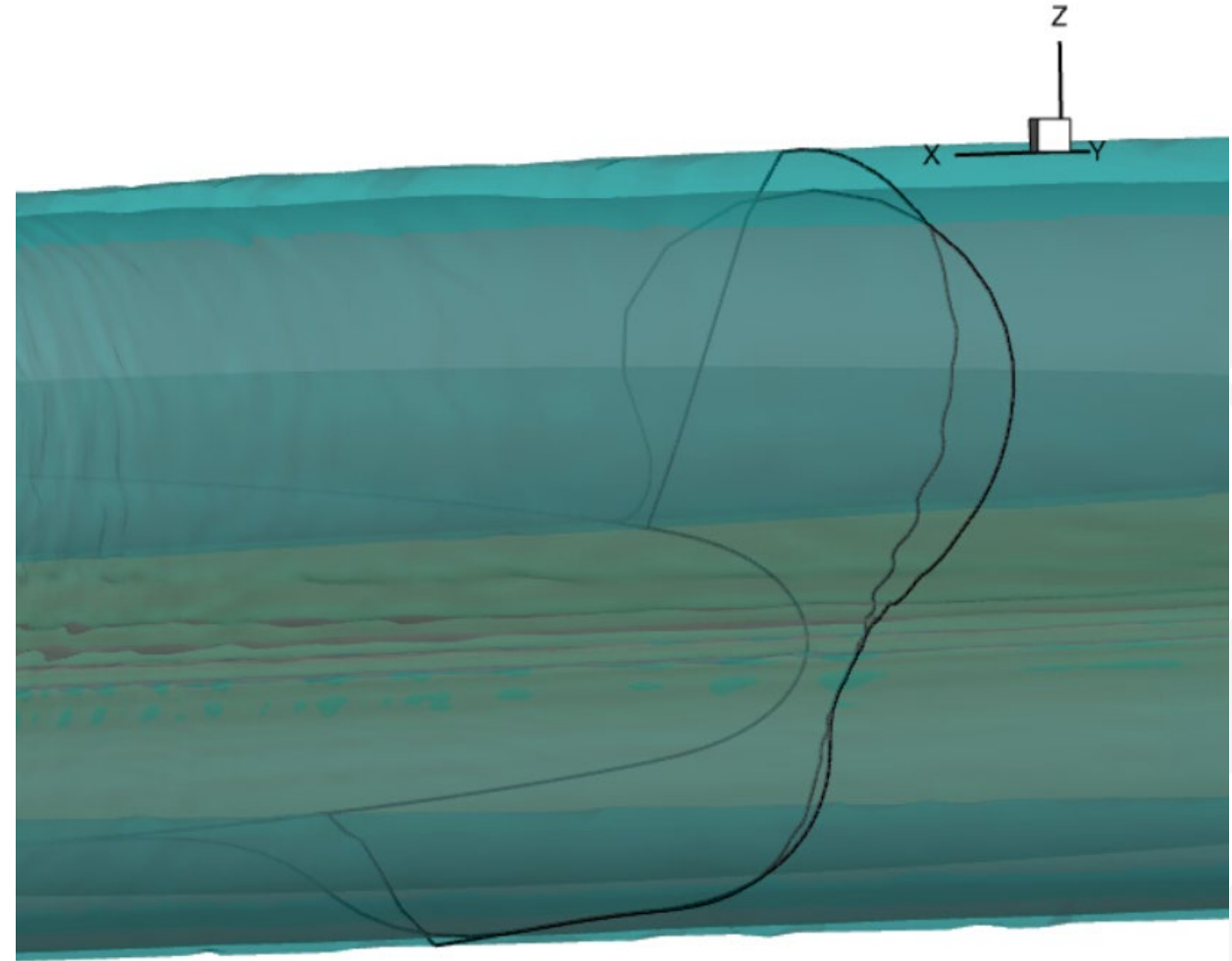
Ice-growth mesh convergence: 1 layer

1-bin, $Y = 0.1\text{ m}$



- Consistent trend is visible as the mesh is refined
- Full grid independence cannot be conclusively established
- Bug for the L1 ice-growth on the database (270s instead of 1350s)...will be updated!

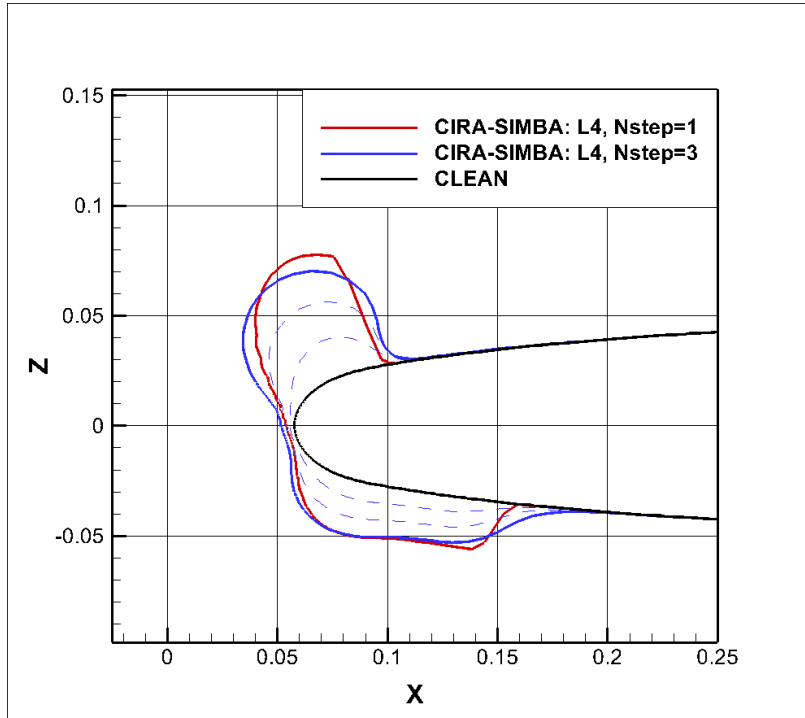
One-shot vs. multi-step



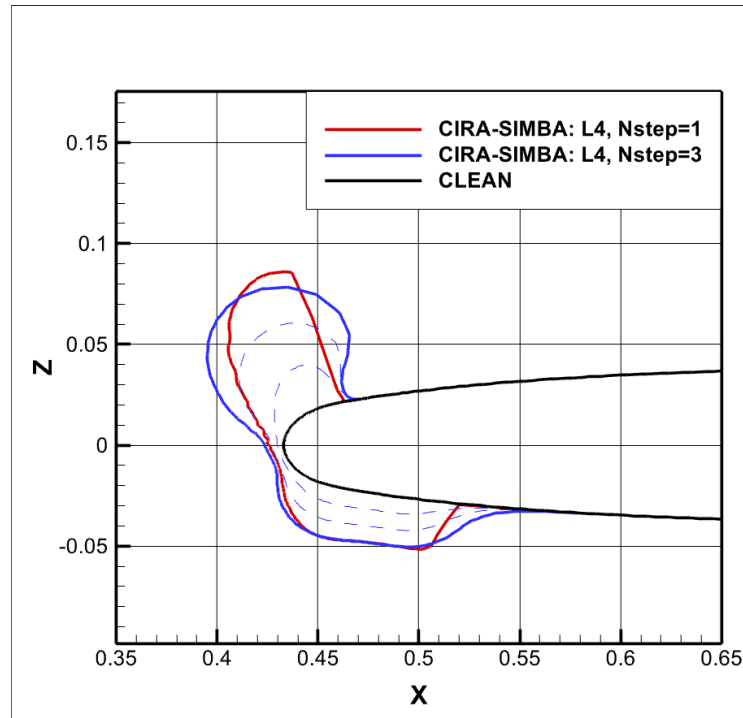
One-shot vs. 3 steps

One-shot vs. multi-step (3 layers)

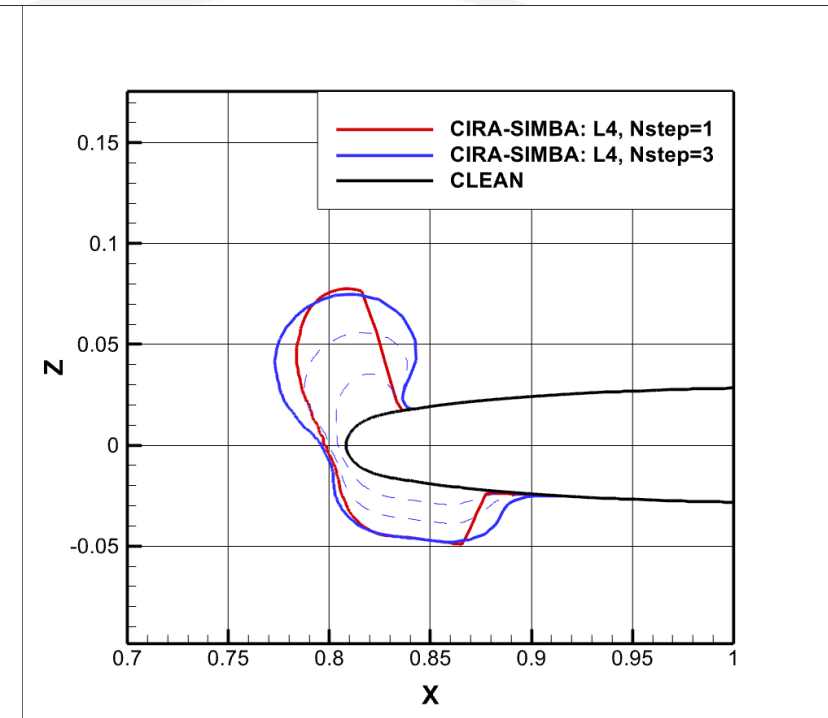
$Y = 0.1 \text{ m}$



$Y = 0.75 \text{ m}$



$Y = 1.4 \text{ m}$



- Multi-step mainly affects the local redistribution of the accreted ice
- MS generates larger lateral extent of the upper horn and a more rounded horn structure

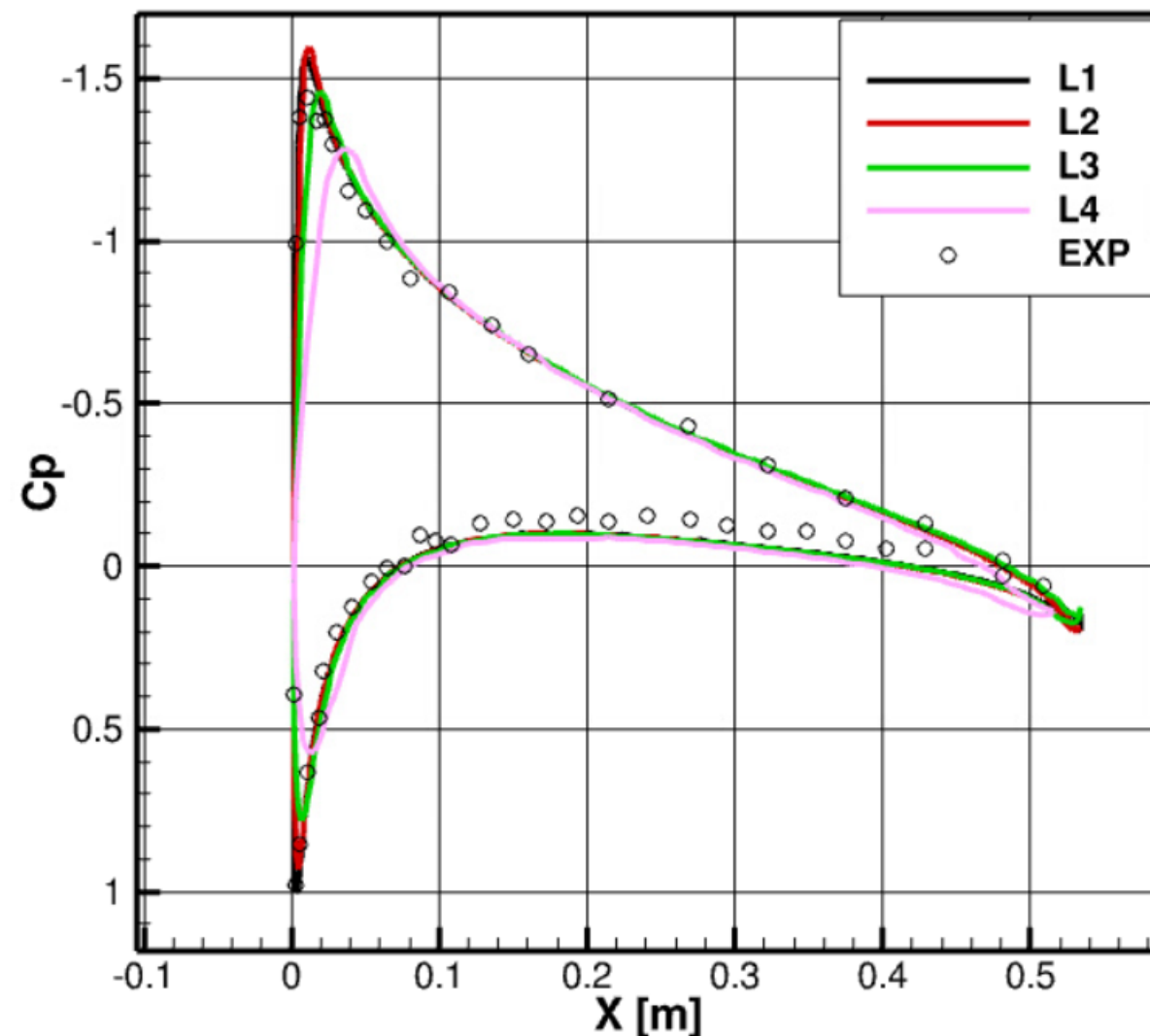
NACA 0012

NASA Icing Research Tunnel

Grid Convergence

MESH SIMBA Cartesian-IBM	Nomenclature	Dmin	Ncells
Coarse	L4	6.5942E-03	26637
Medium	L3	3.2971E-03	30965
Fine	L2	1.6486E-03	39296
Super Fine	L1	8.2428E-04	55838

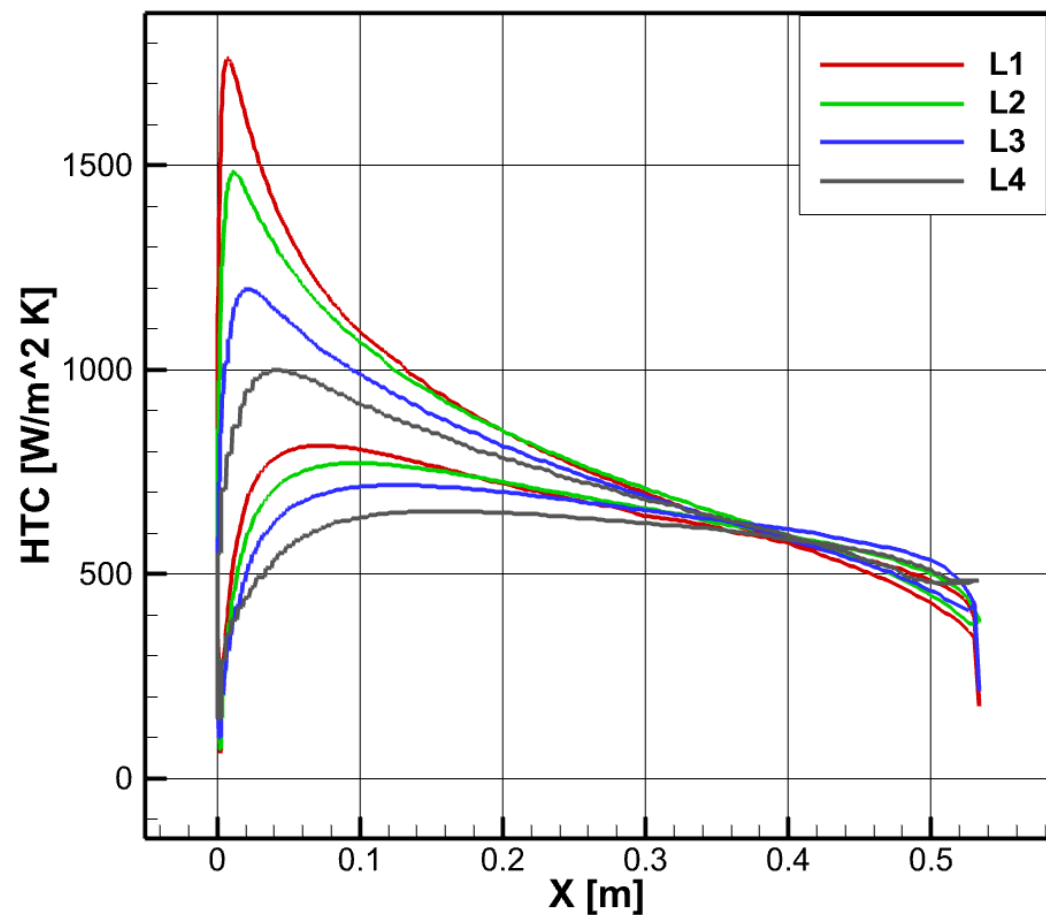
- ✓ Bottom and upper body pressure coefficients are close to experimental data from L3 grid.
- ✓ L2 and L1 grids well describe the whole surface pressure coefficients.



NACA 0012 - AE3933

NASA Icing Research Tunnel

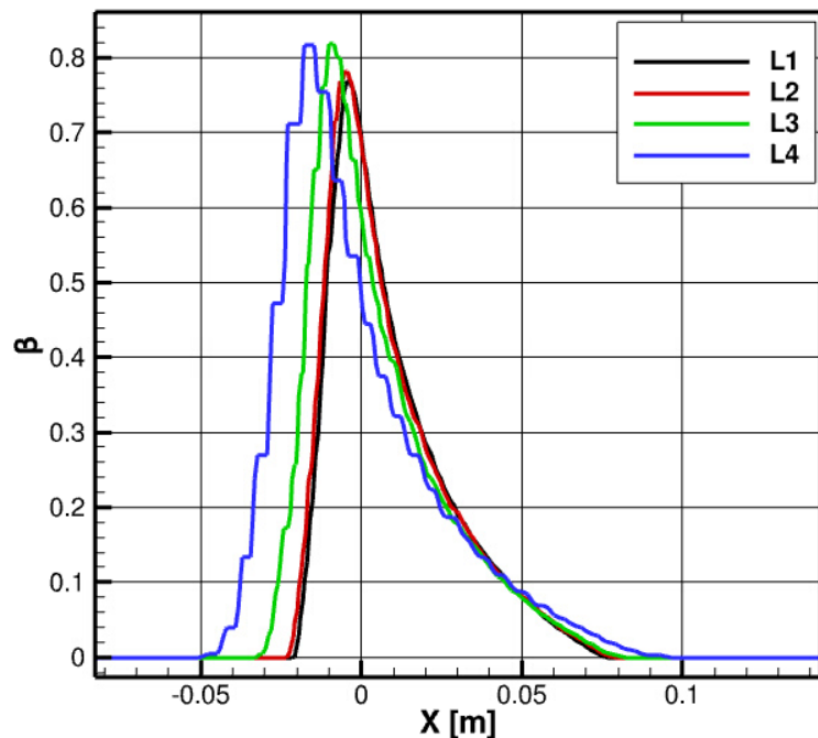
HTC mesh convergence



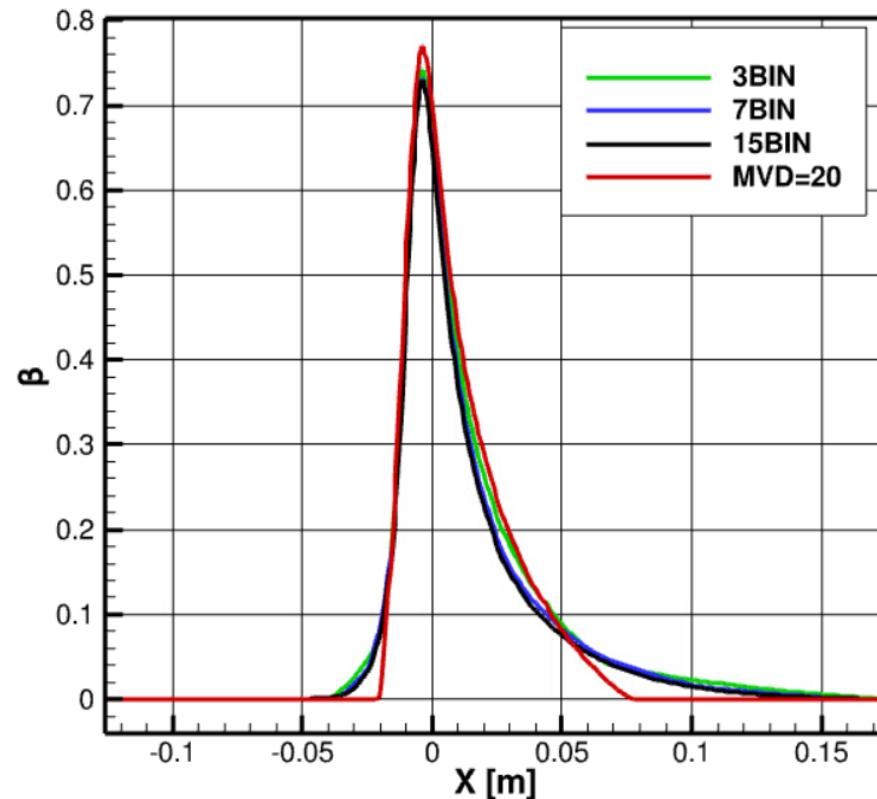
As the mesh is refined, the HTC shows good trend towards L1 data, even though grid-sensitivity remains

Collection Efficiency study

Mesh Convergence



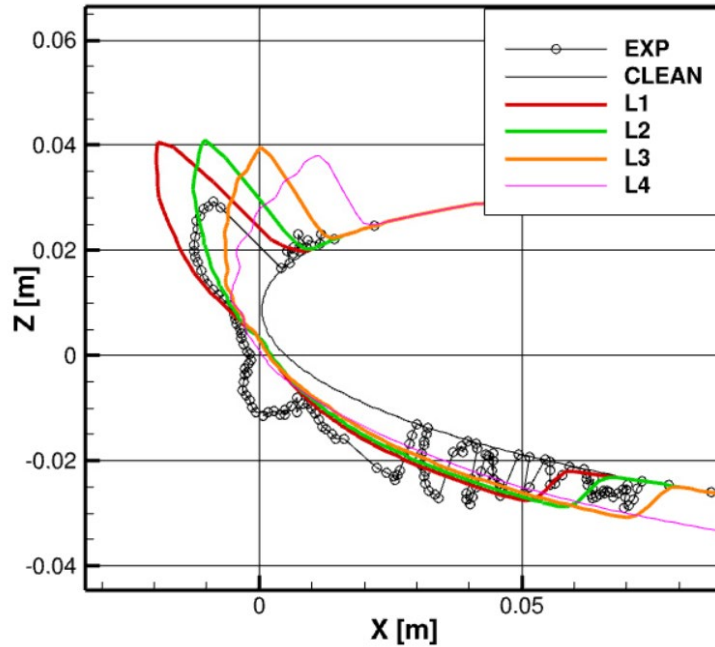
BIN Convergence



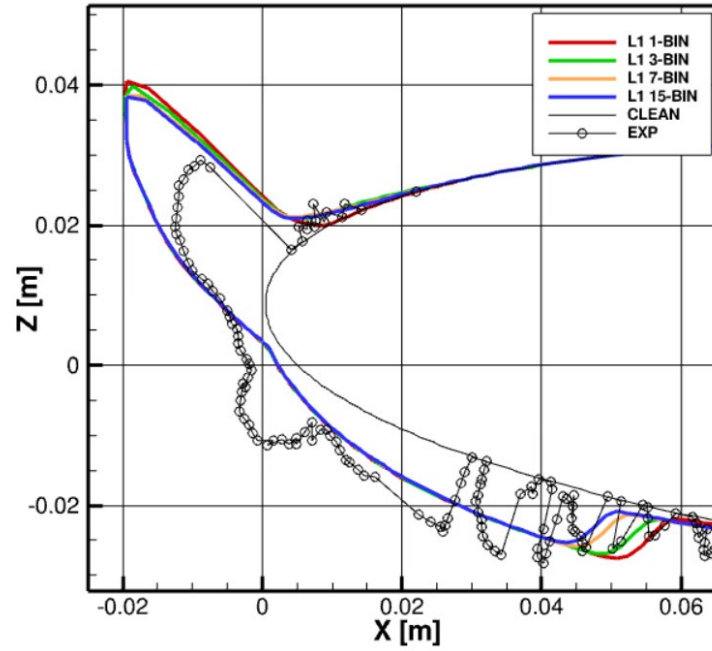
- ✓ The collection efficiency exhibits grid independence starting from grid L2.
- ✓ The multi-bin approaches yield a lower peak collection efficiency and spreads the water impact over a wider surface area.

Ice Shapes Convergence – Single Shot

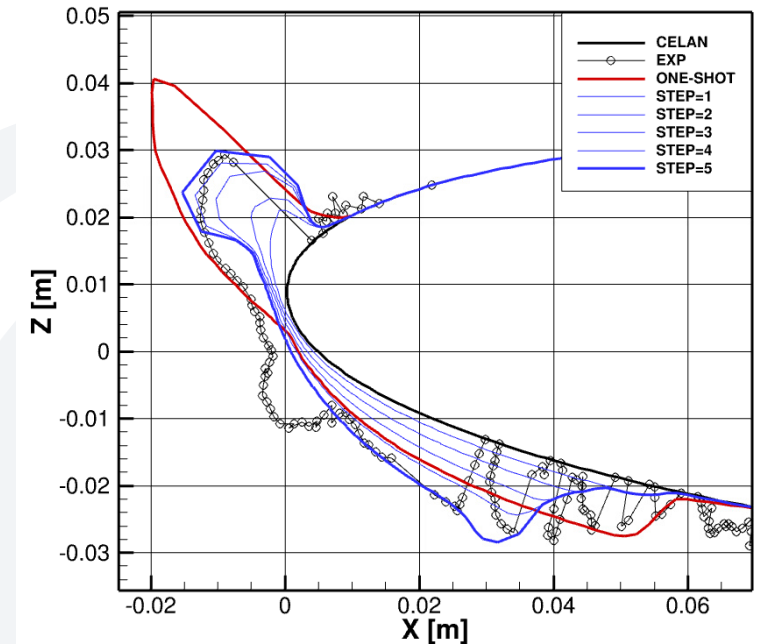
Single-Shot, Single-Bin: Grid Convergence



Multi-Bin (L1 Grid)



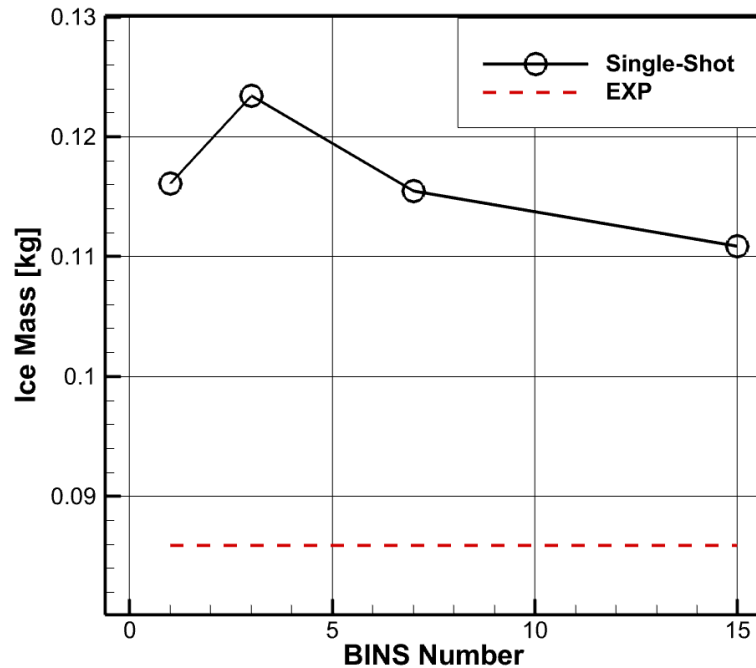
Multi-Shot Single-Bin (L1)



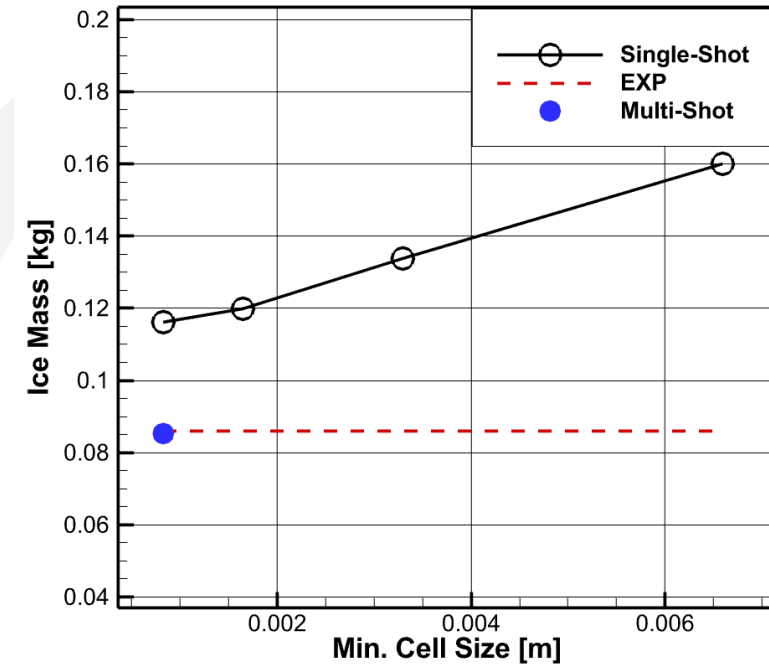
- ✓ The single-shot analyses exhibit strong grid dependency. However, the L1 data successfully replicates the angle and position of the upper horn, while predicting a greater height.
- ✓ The multi-bin analysis results in small differences regarding upper horn position and height, while its primary impact is visible on the lower surface icing limit.
- ✓ Overall, the multi-shot approach achieves better agreement with experiment in terms of horn height prediction.

Ice Mass Convergence

BIN Convergence
L1 GRID Single Step



GRID Convergence
SINGLE BIN

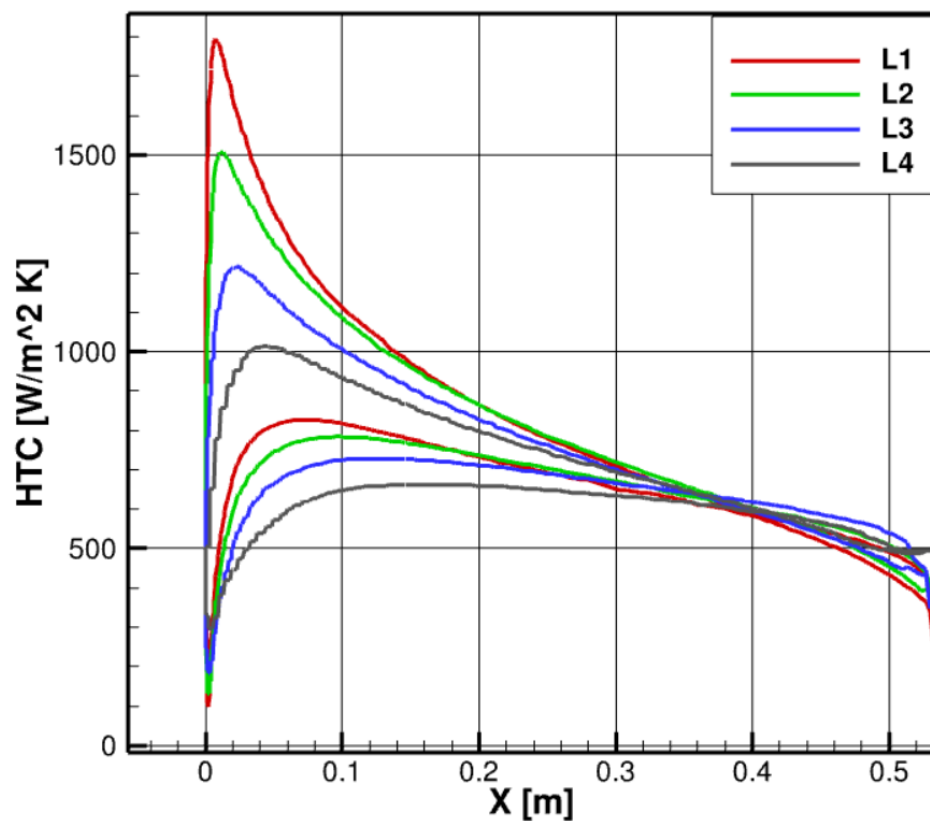


- ✓ Ice Mass results show a convergence tendency for both grid refinement and BINS number. The convergence value is higher than the experimental one.
- ✓ Ice Mass obtained by a multi-shot approach with grid L1 is in good agreement with experimental data.

NACA 0012 - AE3932

NASA Icing Research Tunnel

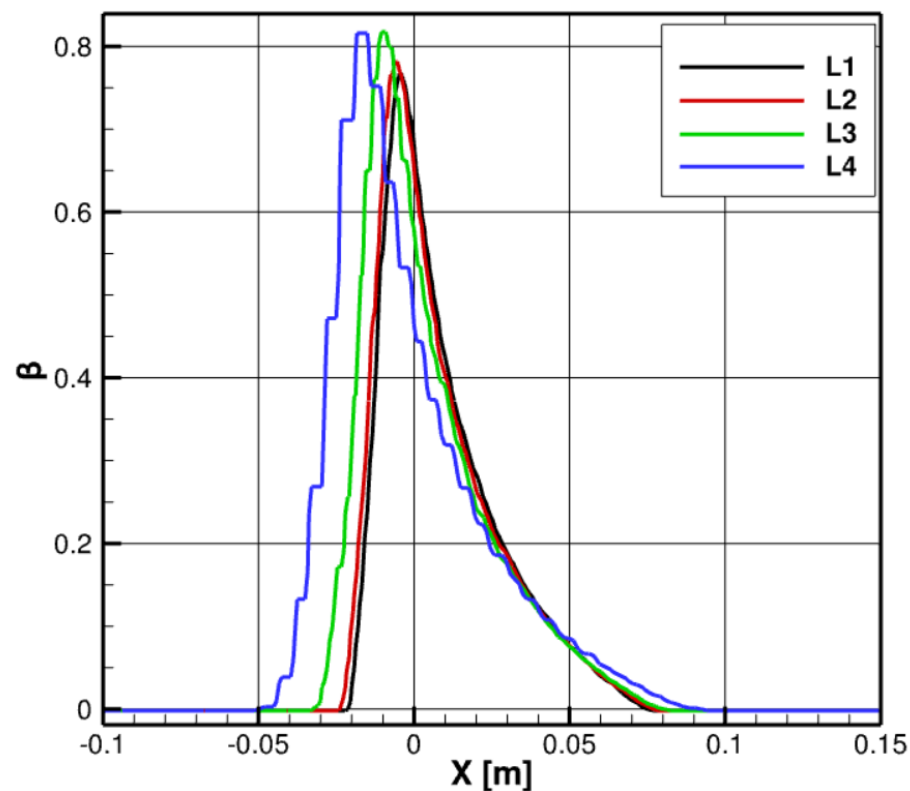
HTC Mesh convergence



From grid L4 to L1, HTC grows towards the finest distribution; however, grid independence cannot be established.

Collection Efficiency convergence

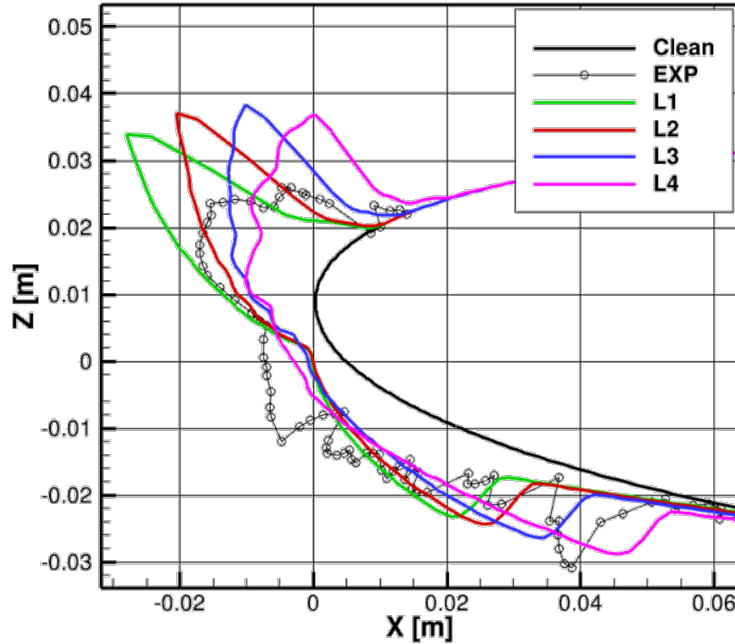
Grid Convergence



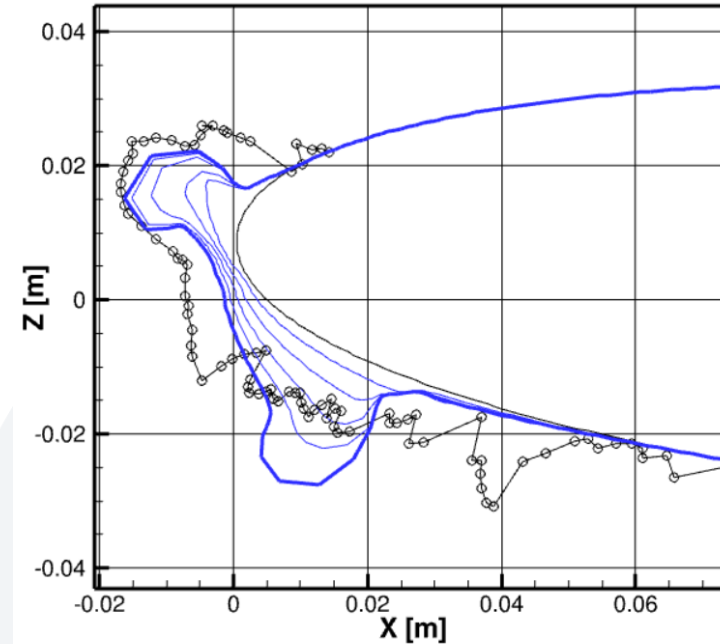
The collection efficiency exhibits mesh convergence starting from grid L2.

Ice Shapes Convergence – Single Shot

Single-Shot, Single-Bin: Grid Convergence

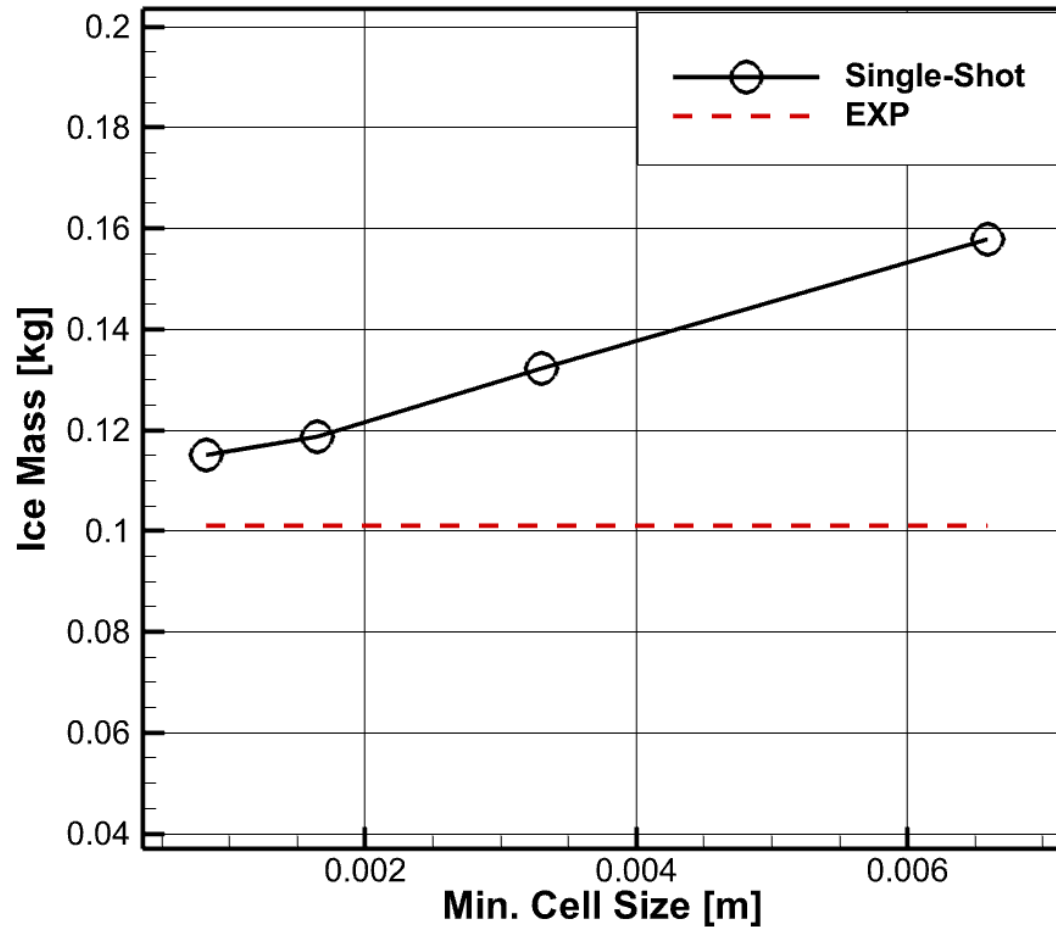


Multi-Shot Single-Bin (L1)



- ✓ As the mesh is refined, single-shot shows ice-growth consistent with experimental horn-angle and position but overpredicts the horn height.
- ✓ No convergence is reached.
- ✓ On the contrary, the multi-shot solution better captures the horn height.
- ✓ A second horn is just appearing on the pressure side.
- ✓ Differences are visible around the ice limits.

Ice Mass convergence: 1-bin



- ✓ Even for the colder case, ice Mass converges as the mesh is refined.
- ✓ Again the L1 is higher than the experimental one.

Conclusions

- Good mesh convergence was obtained for aerodynamic and water-phase on both ONERA-M6 and NACA0012 configurations. The same cannot be stated for the icing-quantities.
- L2-L3 Cartesian meshes provides a good cost/accuracy compromise especially for OneraM6.
- Multi-bin spectra mainly affect icing limits rather than peak accretion.
- Potentially, multi-step simulations can improve horn-shape and ice-mass estimate.

Next steps

- Effort on thermal wall-model for improving ice-horn estimates.
- Participation in SAE 2027 (Canada) with further improvements and systematic comparisons against IPW3 benchmarks.

Thank You