

IPW3 – Polytechnique Montréal Results

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Polytechnique Montréal

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IPW3 - Polytechnique Montréal Results



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September 23, 2026

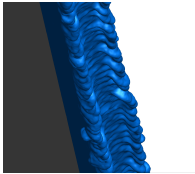


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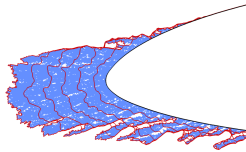
- ① Overview
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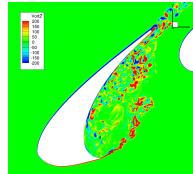
CHAMPS – Overview & Applications



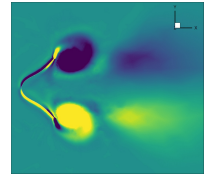
Deterministic Icing



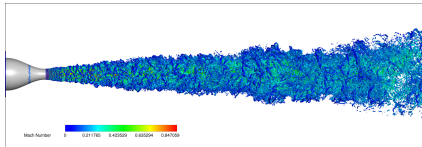
Stochastic Icing



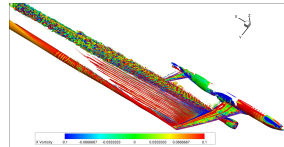
Scale-Resolving CFD (DDES)



Fluid-Structure Interaction



Contrails*



CHAMPS – Chapel MultiPhysics Software

In-house unstructured finite-volume framework developed at Polytechnique Montréal in Chapel for high-performance, multi-fidelity and multiphysics simulations, providing a unified computational framework for all simulation capabilities.

* Contrail modeling developed in collaboration with Prof. Roberto Paoli.



CHAMPS – Icing Framework

Model / Method	NACA0012	ONERA M6
Turbulence Model	Spalart–Allmaras (SA)	
Heat-Transfer Method	T_{rec}	
Droplet Model	Eulerian / Lagrangian	
Droplet Drag Model	Deformable Sphere [1]	
SLD Corrections	None	
Thermodynamic Model	Messinger	
Ice Density	Constant	
Surface Roughness	Constant	
Geometry Evolution	Algebraic (Single-shot) / Level Set (Multilayer)	
Accretion Strategy	Single-shot & 5 Layers	

* Flow equations use Roe convective fluxes with the Venkatakrishnan limiter; Eulerian droplet equations use an upwind scheme with the Van Albada limiter. Lagrangian simulations were performed to verify the Eulerian collection-efficiency predictions.



CHAMPS – Multilayer Ice-Accretion Approach

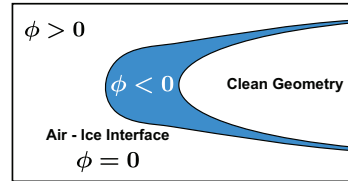
Level-Set Formulation

The ice-air interface is implicitly represented by the **0-level set** of a signed-distance function ϕ [2–5]:

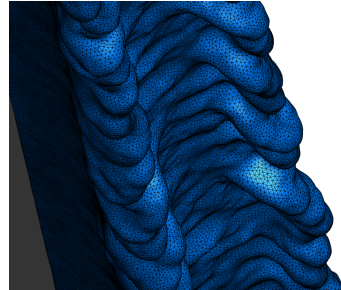
$$\frac{\partial \phi}{\partial t} + \nabla \cdot (\phi \mathbf{V}) - \phi \nabla \cdot \mathbf{V} = 0, \quad \mathbf{V} = \frac{h_{\text{ice}}}{\Delta t_{\text{layer}}} \mathbf{n}_{\phi_0}.$$

- $\mathbf{n}_{\phi_0}$ is computed from the initial wall-distance field ϕ_0 .
- The predicted ice thickness defines the interface velocity $\mathbf{V}$.
- The interface is advected through unsteady time stepping until the prescribed icing time or ice volume is reached.
- The $\phi = 0$ interface is extracted using Mmg [6], and the computational mesh is regenerated using automated Pointwise scripts.
- **Current caveats:** dedicated level-set meshes are required to avoid restrictive time steps associated with near-wall RANS refinement, and the Mmg-based interface extraction requires a triangular surface mesh.

Ice-Air Interface



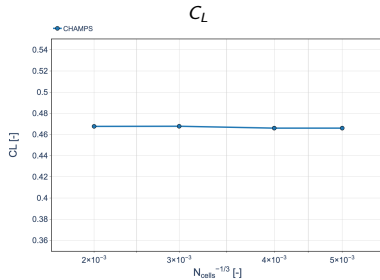
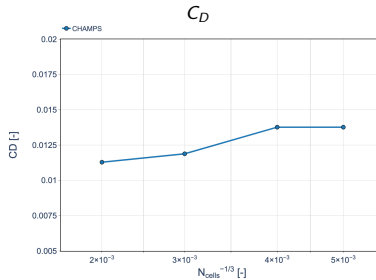
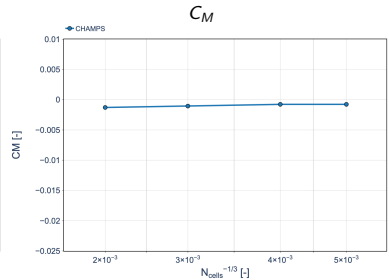
Extracted 3D Ice Geometry



NACA0012 RESULTS



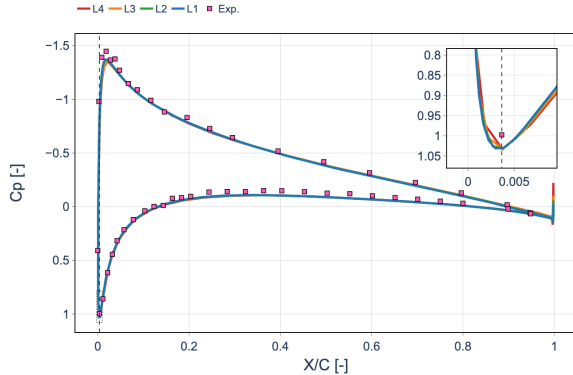
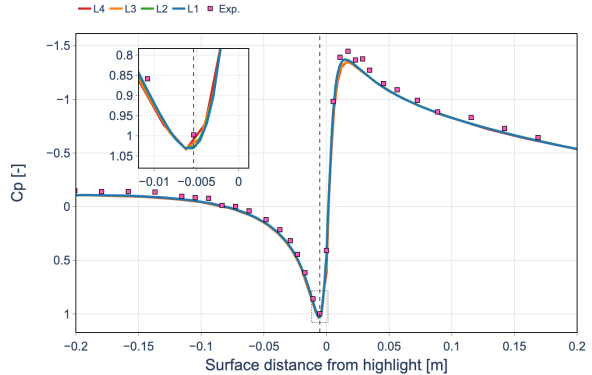
NACA0012 – Integrated Aerodynamic Coefficients



	C_L	C_D	C_M
CHAMPS	0.4677	0.01129	-0.00128
IPW3 L1 Median	0.4677	0.01087	0.00002
Difference	0.00%	+3.78%	-0.00131

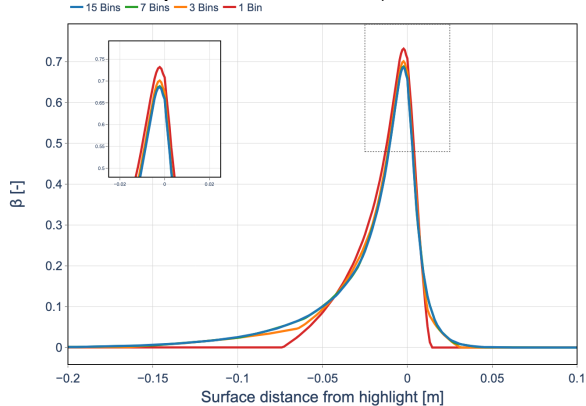


NACA0012 – Pressure-Coefficient Distribution

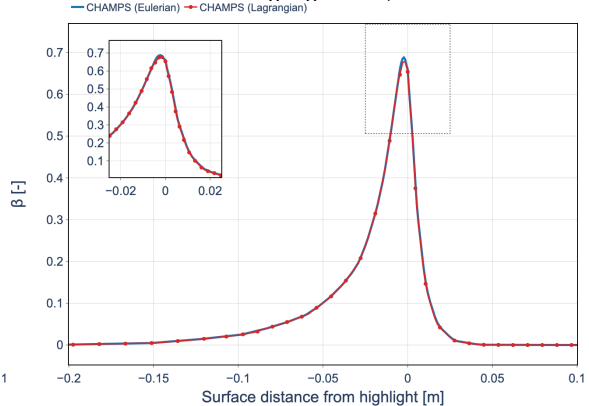
 C_p vs. x  C_p vs. s 

NACA0012 – Droplet Impingement

Droplet-Bin Refinement – L1, Eulerian



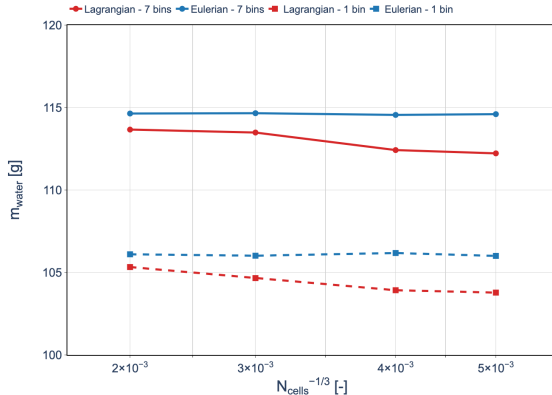
Eulerian vs. Lagrangian – L1, 7 Bins



Impingement Assessment

- Droplet-bin refinement significantly affects the peak collection efficiency and impingement limits.
- Eulerian and Lagrangian formulations show close agreement, with minor differences near the peak collection efficiency.

NACA0012 – Eulerian vs. Lagrangian Droplet Impingement



01-bin distribution

Grid	Lag. [g]	Eul. [g]	Δ [%]
L4	103.78	106.00	2.14
L3	103.92	106.18	2.17
L2	104.66	106.02	1.30
L1	105.33	106.10	0.73

07-bin distribution

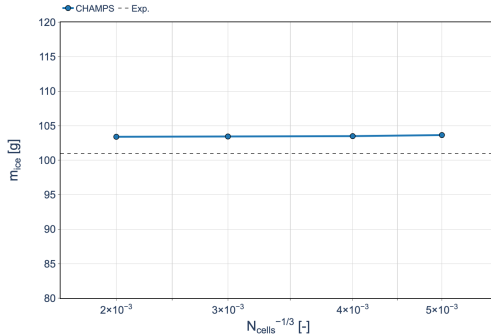
Grid	Lag. [g]	Eul. [g]	Δ [%]
L4	112.22	114.60	2.12
L3	112.42	114.56	1.90
L2	113.49	114.66	1.03
L1	113.66	114.64	0.86

Assessment

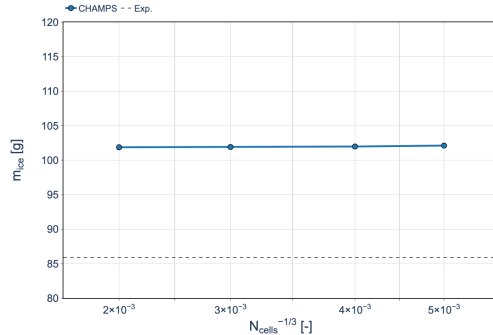
- Eulerian and Lagrangian formulations show good agreement, with differences in collected water mass decreasing from approximately 2% on L4 to 0.8% on L1 as the grid is refined.

NACA0012 – Ice-Mass Prediction (15 Bins)

AE3932



AE3933

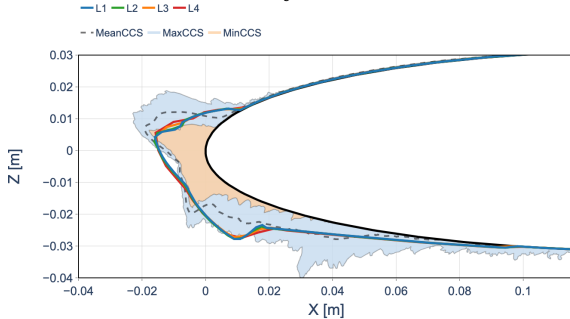


Ice-Accretion Assessment

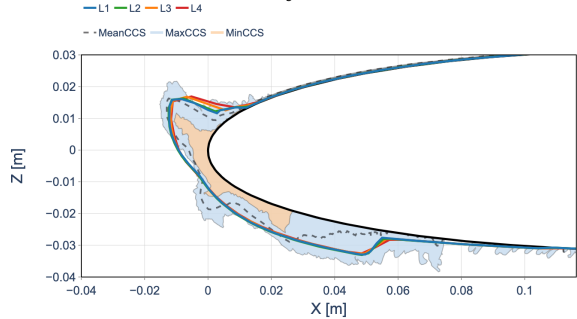
- With the 15-bin distribution on L1, the predicted AE3932 ice mass is 103.4 g, compared with 101.1 g experimentally (+2.3%), with limited sensitivity to spatial grid refinement.
- For AE3933, the predicted ice mass decreases by approximately 1.5 g ($\sim 1.5\%$), compared with the $\sim 15\%$ reduction measured experimentally.
- Approximately 88–90% of the impinging water mass freezes, with the remainder lost through evaporation.

NACA0012 – Single-Layer Ice-Shape Comparison

AE3932 - $K_s = 0.5334\text{mm}$



AE3933 - $K_s = 0.5334\text{mm}$



Single-Layer Ice Shapes Assessment

- Ice shapes are consistent across the grid hierarchy, with limited sensitivity to spatial refinement.
- Predictions remain largely within the experimental envelope, with the main differences concentrated near the horn regions.
- Unlike the ice mass, the ice shape captures the effect of the warmer AE3933 condition, with a clear change in upper-horn orientation.

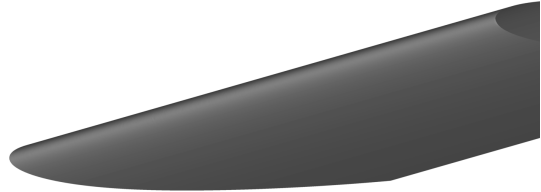


NACA0012 – Multilayer Ice Shapes

AE3932 – $K_s = 0.2667$ mm



AE3933 – $K_s = 0.2667$ mm

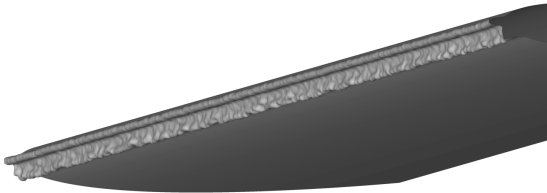


Multilayer Ice Shapes Assessment

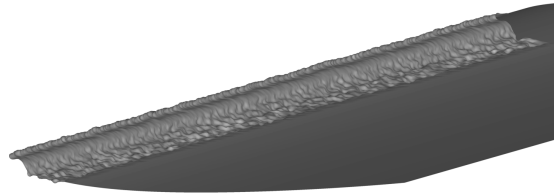
- The multilayer simulations capture the spanwise development of the ice horns.
- Distinct three-dimensional ice morphologies are obtained for the two icing conditions, consistent with the differences observed in the experimental ice scans.

NACA0012 – Final Multilayer Ice Shapes

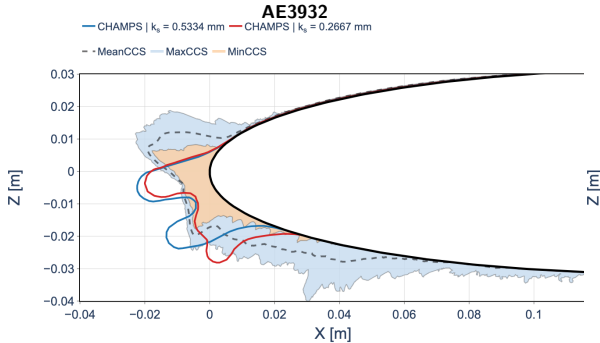
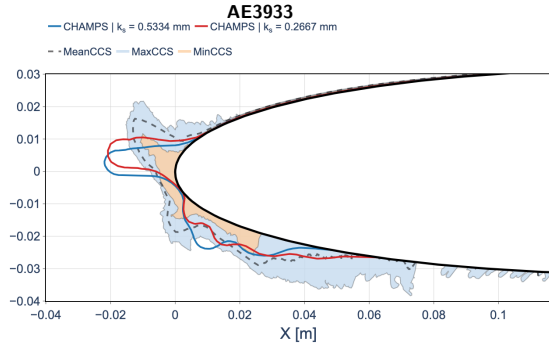
AE3932 – $K_s = 0.2667$ mm



AE3933 – $K_s = 0.2667$ mm



NACA0012 – Multilayer Ice Shapes: Roughness Sensitivity



Multilayer Ice Shapes Assessment

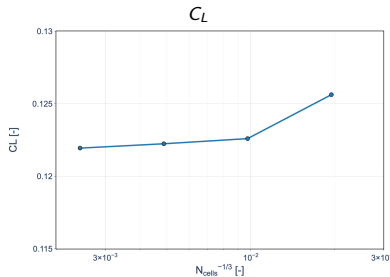
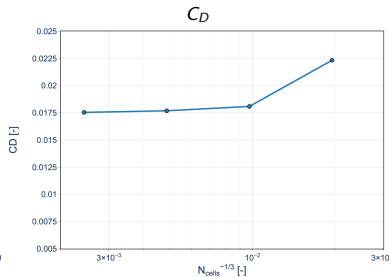
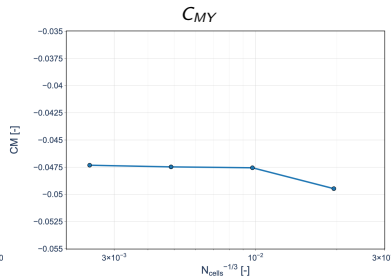
- Surface roughness has a pronounced influence on the multilayer ice shapes, particularly on horn development.
- The lower roughness height provides better overall agreement with the experimental cross sections, but still underpredicts the upper-horn angle.
- The present simulations assume a constant roughness height and constant ice density, which influences the predicted location and development of the horns. Future work will investigate more advanced roughness and ice-density models for these cases.



ONERA M6 RESULTS



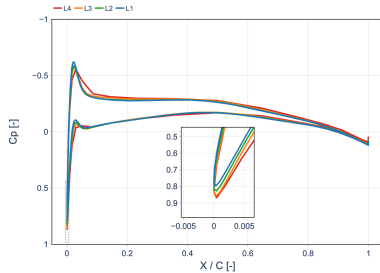
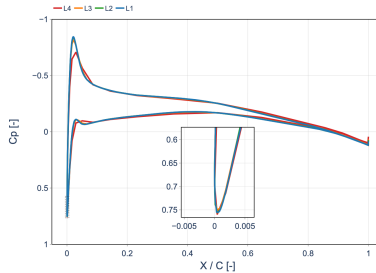
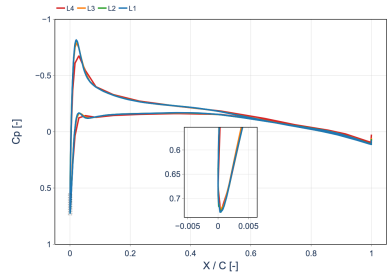
ONERA M6 – Integrated Aerodynamic Coefficients



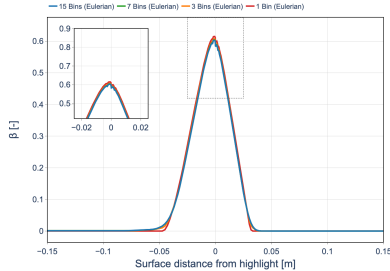
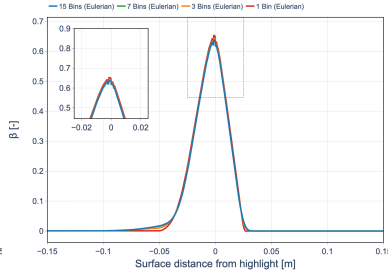
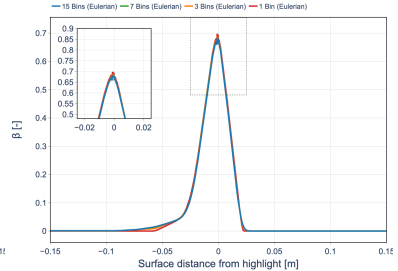
	C_L	C_D	C_{MY}
CHAMPS	0.12194	0.01754	-0.04732
IPW3 L1 Median	0.12213	0.01786	-0.04736
Difference	-0.15%	-1.78%	-0.09%



ONERA M6 – Pressure-Coefficient Distributions

 $y = 0.10 \text{ m}$  $y = 0.75 \text{ m}$  $y = 1.40 \text{ m}$ 

ONERA M6 – Droplet-Bin Refinement (L1 – Eulerian)

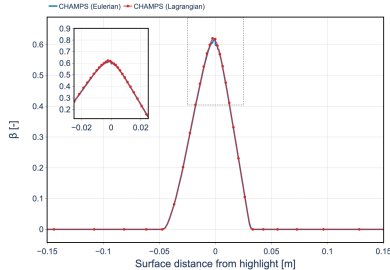
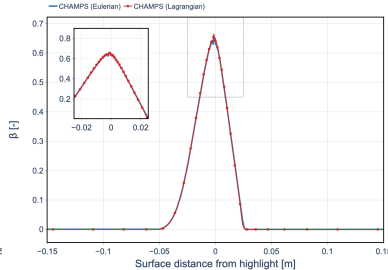
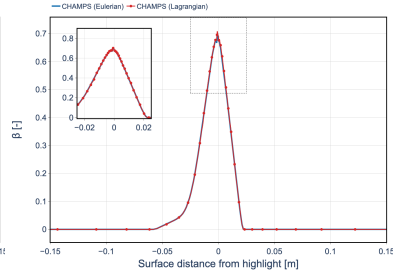
 $y = 0.10 \text{ m}$  $y = 0.75 \text{ m}$  $y = 1.40 \text{ m}$ 

Impingement Assessment

- Droplet-bin refinement has a limited influence on the collection-efficiency distributions at all three spanwise stations.
- Differences between the droplet distributions are less apparent than for the NACA0012 case, as the droplet-size distributions are more concentrated around the MVD.
- The remaining differences are primarily observed near the peak collection efficiency and at the impingement limits.



ONERA M6 – Droplet Collection Efficiency (L1, 1 Bin – Eulerian vs Lagrangian)

 $y = 0.10 \text{ m}$  $y = 0.75 \text{ m}$  $y = 1.40 \text{ m}$ 

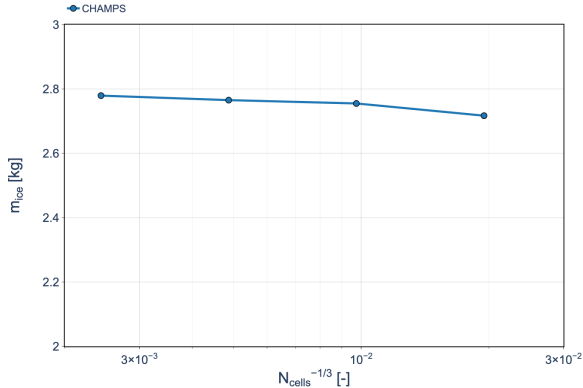
Impingement Assessment

Eulerian and Lagrangian formulations show good agreement in the collection-efficiency distributions across all three spanwise stations, with consistent peak values and impingement extents.

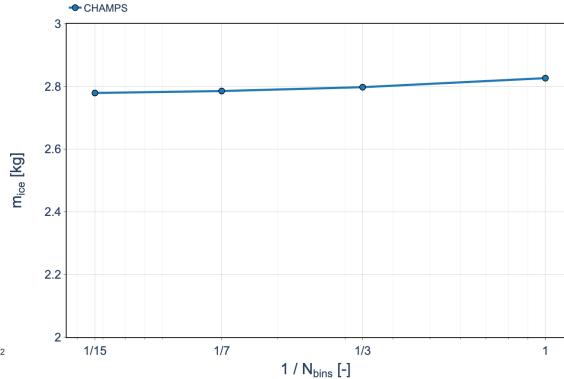


ONERA M6 – Ice-Mass Prediction

Grid Refinement – 15 Bins



Droplet-Bin Refinement – L1

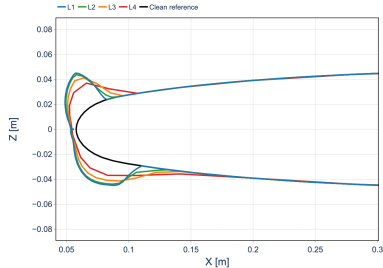


Ice-Accretion Assessment

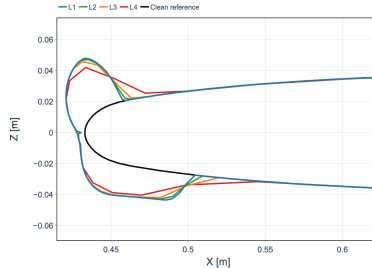
- The predicted ice mass is approximately 2.8 kg, with limited sensitivity to spatial grid refinement and droplet-bin discretization.
- Approximately 89% of the impinging water mass freezes, with the remainder predominantly lost through evaporation.

ONERA M6 – Single-Layer Ice-Shape Comparison ($K_s = 1 \text{ mm}$)

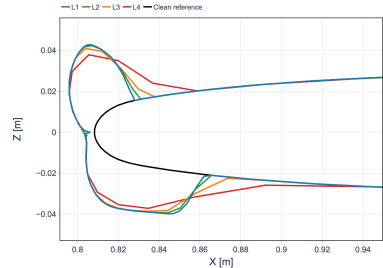
$y = 0.10 \text{ m}$



$y = 0.75 \text{ m}$



$y = 1.40 \text{ m}$

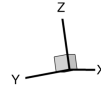
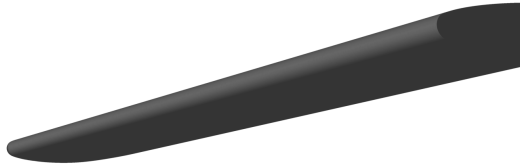


Single-Layer Ice Shapes Assessment

- Ice shapes show limited grid sensitivity, with L1–L3 providing similar predictions and the largest deviations on L4.
- The larger apparent ice extent on L4 is likely a result of its coarser surface discretization.



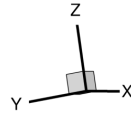
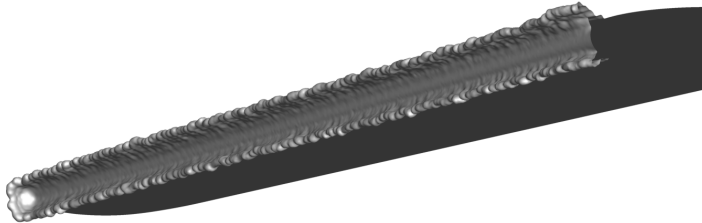
ONERA M6 – Three-Dimensional Multilayer Ice Shape ($K_s = 1$ mm)

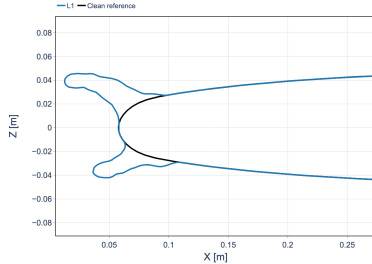
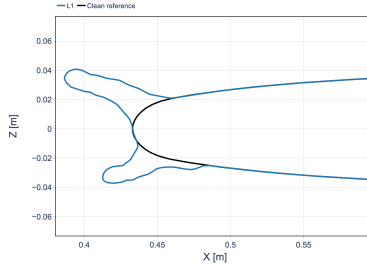
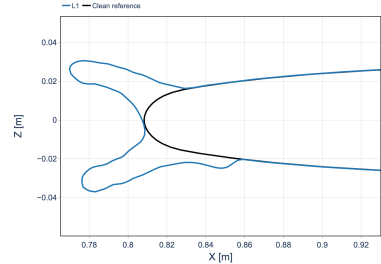


Multilayer Accretion

The level-set approach captures the three-dimensional evolution of the ice geometry and the spanwise development of the horn structures.



ONERA M6 – Final Three-Dimensional Multilayer Ice Shape ($K_s = 1 \text{ mm}$)

ONERA M6 – Multilayer Ice-Shape Comparison ($K_s = 1 \text{ mm}$) $y = 0.10 \text{ m}$  $y = 0.75 \text{ m}$  $y = 1.40 \text{ m}$ 

Multilayer Ice Shapes Assessment

- The multilayer simulations show a consistent ice morphology across the three spanwise locations.
- Horn size and extent vary along the span, reflecting the three-dimensional development of the accretion.



Conclusions

General Findings

- Results are generally consistent across the grid hierarchy and well positioned within the IPW3 code-to-code envelope.
- Eulerian and Lagrangian droplet formulations show good agreement in collection efficiency and collected water mass.

NACA0012

- Single-layer ice shapes capture the experimental horn orientation well.
- Multilayer predictions show larger deviations in horn orientation, while capturing complex three-dimensional ice morphology.

ONERA M6

- Single-layer ice shapes show limited grid sensitivity, with the largest deviations observed on L4.
- Multilayer simulations capture pronounced three-dimensional horn development and spanwise variations in the ice morphology.

Overall

- CHAMPS provides a consistent end-to-end icing framework, with the level-set approach enabling complex three-dimensional ice geometries in multilayer simulations.
- Future work will focus on improving the roughness and ice-density models.

Acknowledgments

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- Computations were performed on the Trillium supercomputer at the SciNet HPC Consortium, with computational resources provided through the Digital Research Alliance of Canada.



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