

AIAA IPW3: NACA0012 Code-to-Code Comparisons

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Presented 21 September 2026

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AIAA IPW3 : NACA0012 Code-to-Code Comparisons



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September 21, 2026



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Geometry and Aerodynamic Conditions



Wind-Tunnel View

Geometry

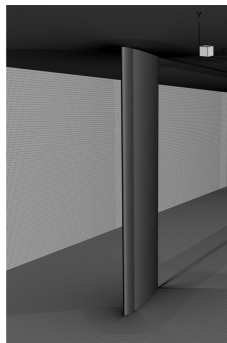
Parameter	Value
Airfoil	NACA0012
Chord, c [m]	0.5334
AOA, α [°]	4.0

Aerodynamic Conditions

Parameter	Value
$T_{0,\text{ref}}$ [K]	272.95
$T_{s,\text{ref}}$ [K]	267.75
M_{ref} [-]	0.3114
U_{ref} [m/s]	102.15
ρ_{ref} [kg/m ³]	1.19
$Re_{c,\text{ref}}$ [-]	3.8441×10^6

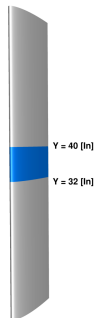


Icing Conditions



Mesh Tunnel View

Grid	Nodes	Elements
L1	60.45 M	59.86 M
L2	27.31 M	26.99 M
L3	11.23 M	11.08 M
L4	5.95 M	5.86 M



Integration Patch

Icing Conditions

	AE3932	AE3933
$T_{0,\text{ref}}$ [K]	267.51	271.0
$T_{s,\text{ref}}$ [K]	262.305	265.8
M_{ref} [-]	0.3151	0.3127
U_{ref} [m/s]	102.31	102.19
ρ_{ref} [kg/m ³]	1.21	1.2
$Re_{c,\text{ref}}$ [-]	3.9795×10^6	3.8947×10^6
LWC [g/m ³]	0.55	0.55
MVD [μm]	20	20
Exposure time [min]	7	7
Exp. ice mass [g]	101.0	85.9

Analysis Setup

- Data Extraction:** Aerodynamic coefficients integrated over the full profile span ($Y = 0\text{--}72$ in); icing quantities over the highlighted patch ($Y = 32\text{--}40$ in); slices extracted at $Y = 36$ in.
- Droplet Distribution:** 1-, 3-, 7-, and 15-bin distributions with preserved total LWC across all grid levels.



IPW3 – NACA0012 Case Participants

ID	Participant / Organization	Line Color
001	CIRA	
002	AeroTex	
003	NRC	
004	ONERA	
006	Dassault	
007	Polytechnique Montréal	
008	Collins Aerospace	
009	Sikorsky	
010	NASA	
013	Boeing	
014	Airbus	
019	Synopsys	
020	Bombardier	



Summary of Submitted Data

AE3932

ID	L1				L2				L3				L4			
	1	3	7	15	1	3	7	15	1	3	7	15	1	3	7	15
001	✓				✓				✓				✓			
002		✓	✓	✓		✓	✓	✓		✓	✓	✓		✓	✓	✓
003					✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
004	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
006				✓				✓								✓
007	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
008																
009																
010	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
013				✓				✓								
014	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
015																
019	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
020				✓				✓	✓	✓	✓	✓				✓
Total	6	6	6	9	7	7	7	10	8	8	8	8	7	7	7	9

AE3933

ID	L1				L2				L3				L4			
	1	3	7	15	1	3	7	15	1	3	7	15	1	3	7	15
001	✓	✓	✓	✓	✓				✓				✓			
002		✓	✓	✓		✓	✓	✓		✓	✓	✓		✓	✓	✓
003					✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
004	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
006				✓				✓								
007	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
008	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	
009	✓				✓				✓				✓			
010	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
013				✓				✓								
014	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
015																
019	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
020												✓				
Total	8	8	8	10	9	8	8	10	9	8	8	9	9	8	8	7



Modeling Choices Across Submissions

Model / Method	001	002	003	004	007	008	009	010	013	014	019
Turbulence	<i>k</i> - ω TNT	<i>k</i> - ω SST	SST-QCR	<i>k</i> - ω SST	SA	<i>k</i> - ω SST	<i>k</i> - ω SST	SA-neg-QCR	SA	SA-neg	<i>k</i> - ω SST
Droplet formulation	Eul.	Lag.	Lag.	Eul.	Eul.	Eul.	Eul.	Lag.	Lag.	Lag.	Eul.
HTC method	–	BL Int.	T_{rec}	T_{rec}	T_{rec}	EID	T_{rec}	2 T_w	1-sol. + RA	BL Int. + RA	T_{rec}
Thermodynamics	Mess.	Mess.	Mess.	Mess.	Mess.	ICE3D/EID	SWIM	Mess.	Mess.	Mess.	SWIM+
Geometry evolution	Lag./IB	Interp.	Pseudo-trans.	Alg.	Lag.	ALE	–	Prism. extr.	Extr.	Alg.	Lag./remesh

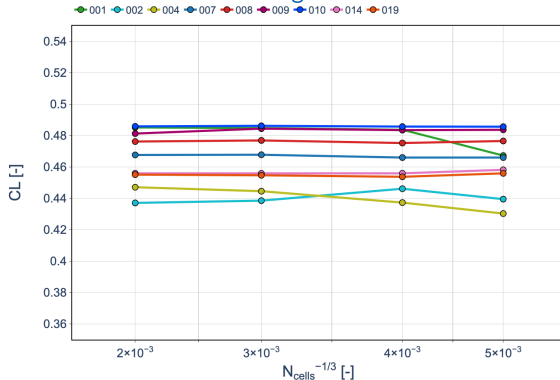
Eul. = Eulerian; *Lag.* = Lagrangian; *SA* = Spalart–Allmaras; *SA-neg* = negative *SA*; *QCR* = quadratic constitutive relation; *BL Int.* = boundary-layer integral; T_{rec} = recovery temperature; T_w = wall temperature; 1-sol. = one-solution method; *RA* = Reynolds analogy; *EID* = extended icing data; *Mess.* = Messenger; *SWIM* = shallow-water icing model; *IB* = immersed boundary; *ALE* = arbitrary Lagrangian–Eulerian; *Alg.* = algebraic; *Interp.* = interpolation; *Extr.* = extrusion; *Prism. extr.* = prismatoid extrusion; *Pseudo-trans.* = pseudo-transient; – = not reported.

Overall Trends

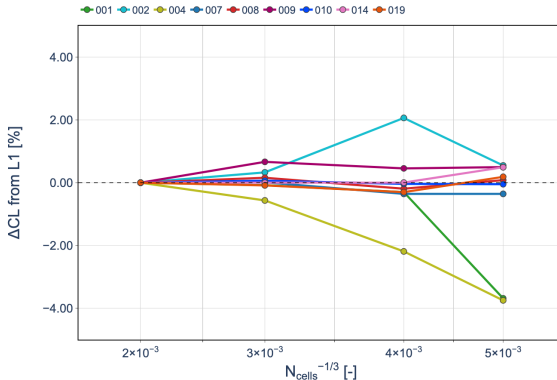
- **Turbulence:** *k*- ω -family formulations predominate (64%), with 36% using *SA*-family formulations.
- **Droplets:** Eulerian formulations are slightly predominant (55%), with 45% Lagrangian.
- **Heat transfer:** A variety of approaches are used, including recovery-temperature, boundary-layer integral/Reynolds-analogy, two- T_w , one-solution, and other methods.
- **Thermodynamics:** Messenger-based approaches predominate (73%), with *SWIM*-based methods also represented.
- **Geometry evolution:** Diverse approaches are used, including algebraic, displacement/extrusion, *ALE*, interpolation, remeshing, and pseudo-transient methods.
- **Notable approaches:** One submission employs an immersed-boundary formulation, while another uses a morphogenetic approach.
- **Ice accretion:** Workshop comparisons focus on single-shot results; 2 participants also submitted multilayer/multishot results.

* Based on reported data only.

Lift Coefficient Grid Convergence



Grid-Level Values



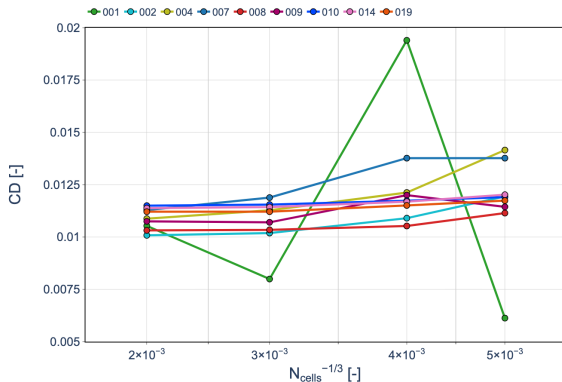
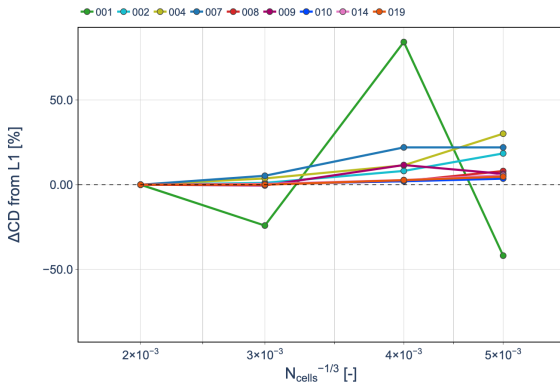
Relative to L1

Observations

- At L1, the median lift coefficient is $C_L = 0.4677$, with an IQR of 0.0262 (5.6%).
- Most submissions exhibit weak sensitivity to spatial grid refinement.
- Relative to L1, coarse-grid differences remain within approximately 4% across the submissions.

*IQR = interquartile range (75th percentile – 25th percentile).

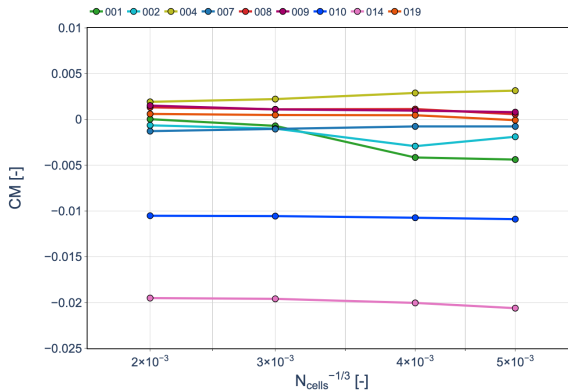
Drag Coefficient Grid Convergence



Observations

- At L1, the median drag coefficient is $C_D = 0.01088$ (108.8 drag counts), with an IQR of 7.57 drag counts (7.0%).
- C_D exhibits the greatest sensitivity to spatial grid refinement, with most coarse-grid deviations reaching approximately 30% from L1.

Pitching Moment Grid Convergence

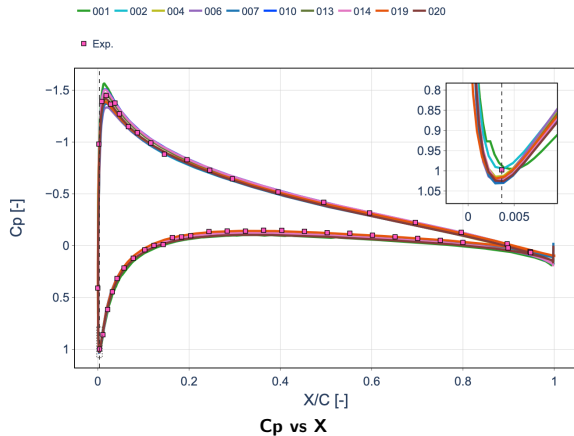
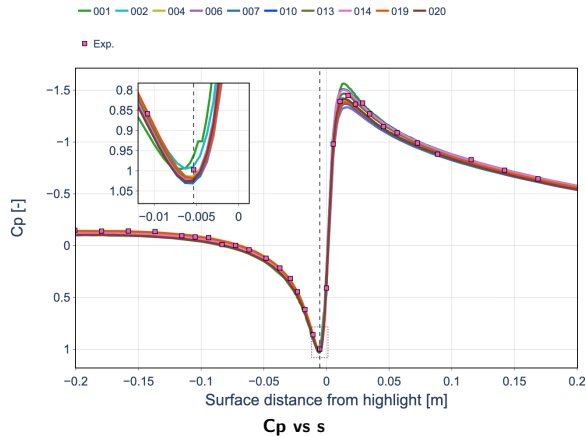


Grid-Level Values

Observations

- At L1, the median pitching-moment coefficient is $C_M \approx 2.50112 \times 10^{-5}$, with an IQR of 2.60×10^{-3} .
- Most submissions exhibit little variation in C_M across the grid hierarchy.

Surface Pressure Distribution (L1)



Observations

- The L1 C_p distributions are tightly clustered and show good overall agreement with the experimental measurements.
- The largest code-to-code differences are localized near the leading-edge suction peak and stagnation region.

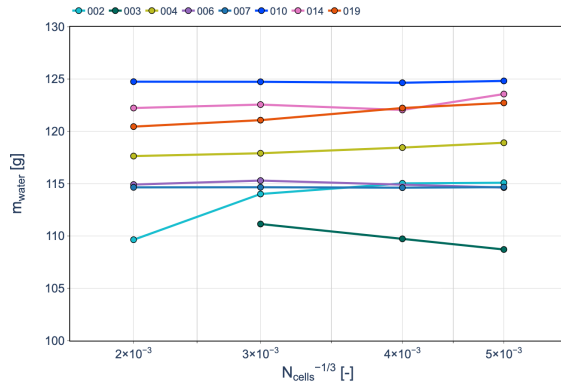
Aerodynamic Assessment Summary

Aerodynamic Assessment

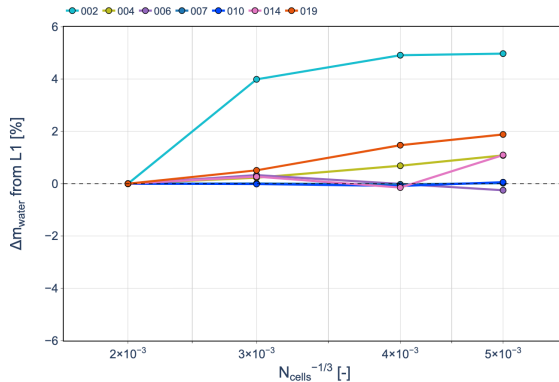
- C_L and C_M exhibit limited within-code sensitivity to grid refinement for most submissions.
- C_D shows greater and less uniform grid sensitivity, including non-monotonic behavior for selected submissions.
- For most submissions, code-to-code differences exceed the changes produced by spatial refinement.
- L1 C_p distributions are well clustered and show good agreement with experiment.



Water Mass Grid Convergence (15 Bins)



Grid-Level Values

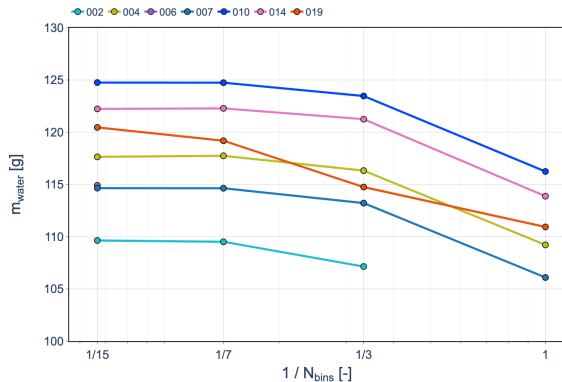


Relative to L1

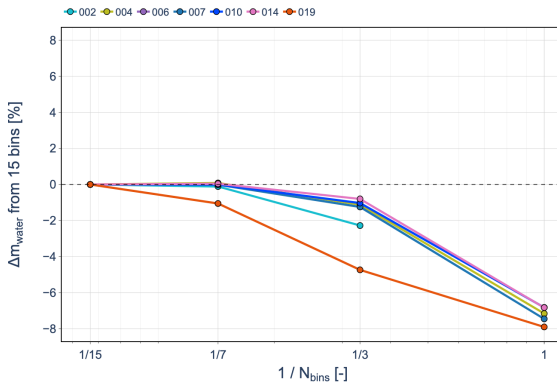
Observations

- For the 15-bin distribution, the L1 median impinged water mass is 119.05 g, with an IQR of 6.39 g (5.37%).
- Most submissions exhibit weak grid sensitivity and remain close to their L1 prediction across the grid hierarchy.

Droplet Distribution Sensitivity (L1)



Bin-Distribution Values

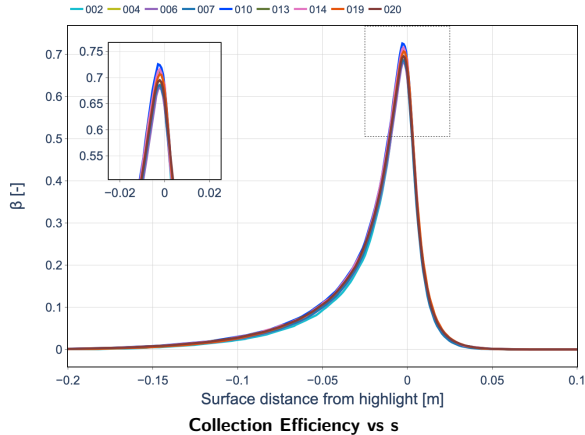


Relative to 15 Bins

Observations

- The 15- and 7-bin distributions give similar impinged water masses.
- Reducing to 3 bins introduces only modest additional differences.
- A single-bin reduces collected water mass by about 5–8% relative to 15 bins.

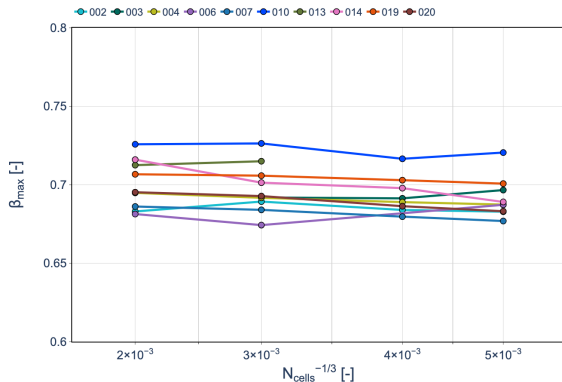
Collection Efficiency (L1, 15 Bins)



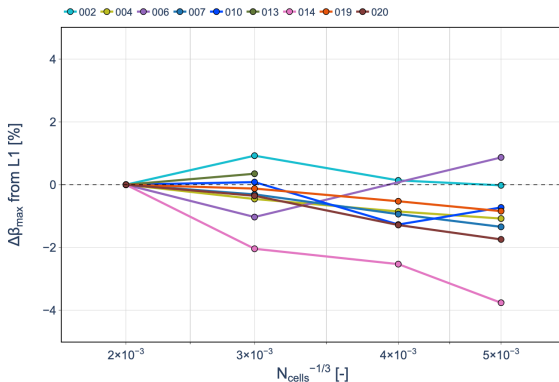
Observations

- The L1 collection-efficiency profiles are tightly clustered across submissions and exhibit very similar leading-edge behavior.
- Small differences are mainly observed near the peak region and impingement limits.

Peak Collection Efficiency Grid Convergence (15 Bins)



Grid-Level Values



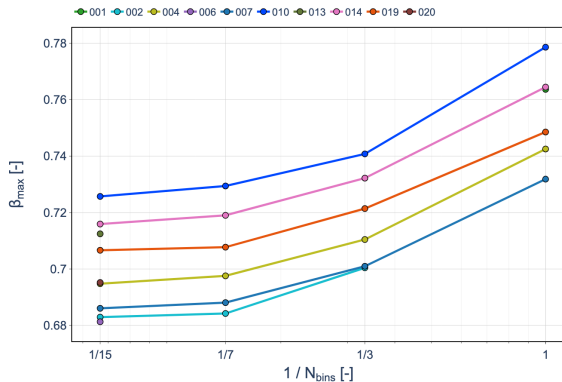
Relative to L1

Observations

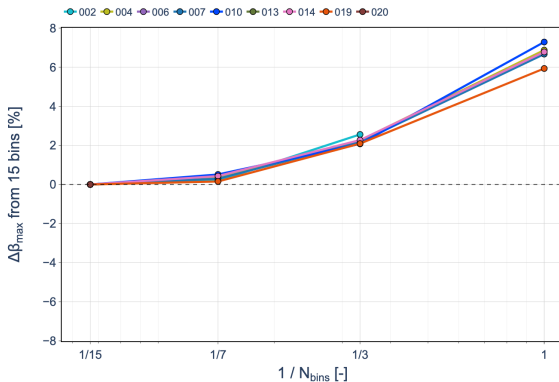
- At L1, the median $\beta_{\max} = 0.695$, with a 3.0% IQR.
- $\beta_{\max}$ shows limited sensitivity to spatial grid refinement.



Peak Collection Efficiency Droplet-Bin Convergence (L1)



Bin-Distribution Values



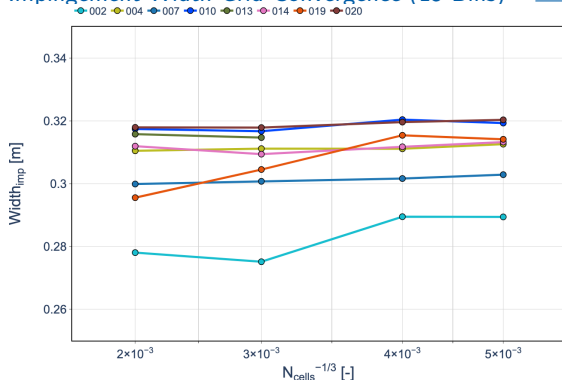
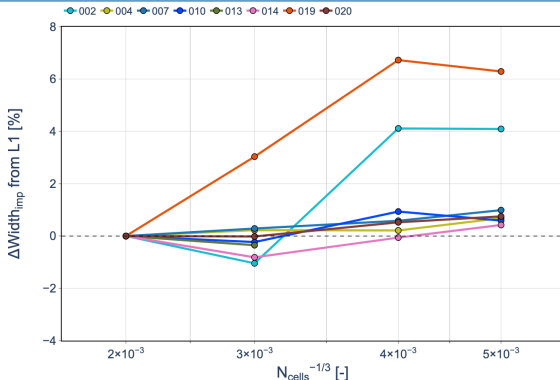
Relative to 15 Bins

Observations

- 7- and 15-bin predictions are nearly identical; 3 bins remain within 2–3%.
- A single bin increases β_{max} by approximately 7%.



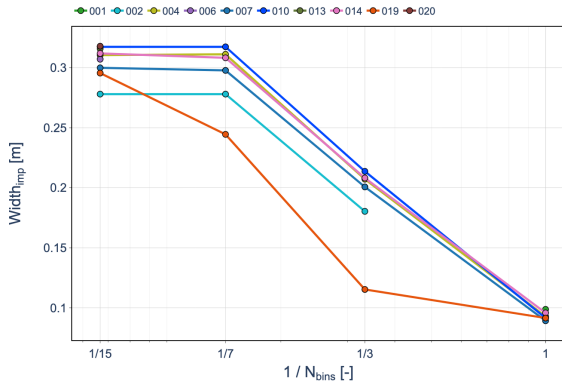
Impingement Width Grid Convergence (15 Bins)



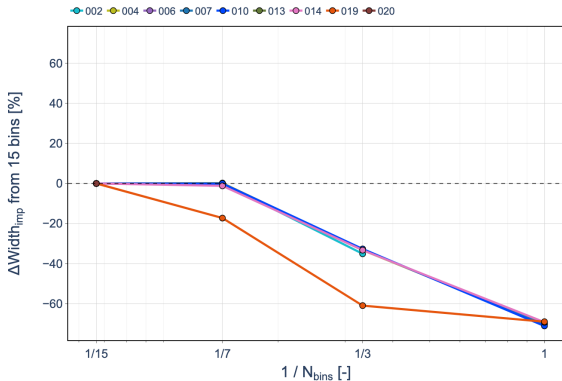
Observations

- Impingement limits: $\beta = 0.0001$ crossings; $\text{Width}_{\text{imp}} = s_{\text{upper}} - s_{\text{lower}}$.
- At L1, the median impingement width is 0.309 m, with a 5.4% IQR.
- Most grid-level differences remain within approximately $\pm 2\%$ of L1, with some deviations up to $\sim 4 - 6\%$.

Impingement Width Droplet-Bin Convergence (L1)



Bin-Distribution Values



Relative to 15 Bins

Observations

- 7 and 15 bins give nearly identical impingement widths (1 – 2% difference).
- 3 and 1 bin reduce the width by approximately 35% and 70%, respectively.



Droplet Impingement Assessment

Droplet Impingement Assessment

Spatial Grid Convergence

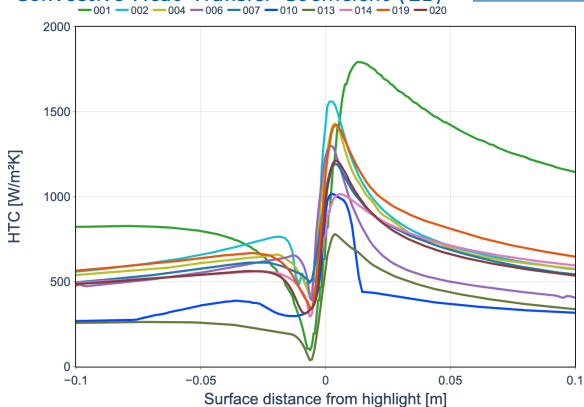
- Water mass, $\beta_{\max}$, and impingement width show limited grid sensitivity for most submissions.
- Code-to-code variability is generally comparable to or larger than the grid-refinement effect.
- Peak position was examined, but its sensitivity to the local leading-edge discretization prevented a clear convergence assessment.

Droplet-Size Effects

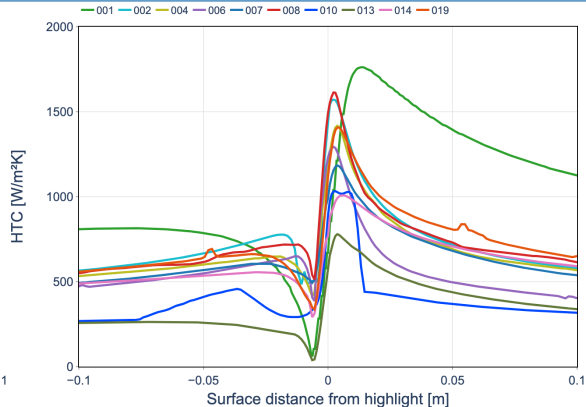
- The 7-bin distribution closely reproduces the 15-bin results, while the single-bin distribution overpredicts $\beta_{\max}$ and underpredicts impingement width and collected water mass.



Convective Heat-Transfer Coefficient (L1)



AE3932

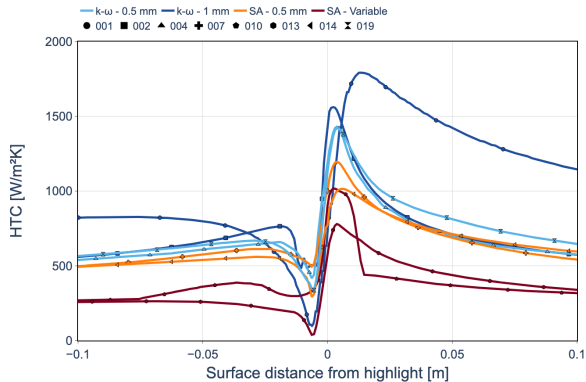


AE3933

Observations

- Significant *HTC* code-to-code variability is observed, particularly near the leading edge.
- Turbulence modeling and roughness height appear to be primary contributors to the spread, while differences in *HTC* computation methodology also play a role.

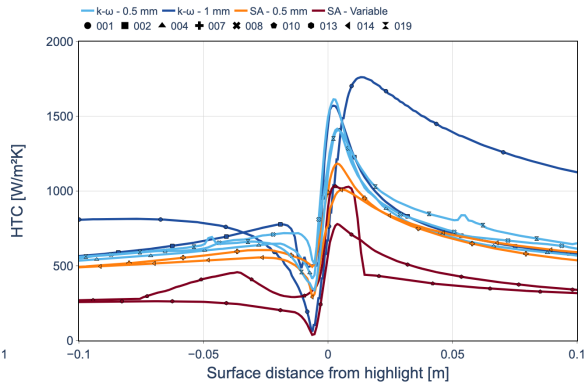
Convective Heat-Transfer Coefficient (L1)



AE3932

Grouped by Turbulence Model / Roughness

Note: Colors indicate Turbulence Model / Roughness groups and are not associated with participant IDs.



AE3933

Observations

- Significant HTC code-to-code variability is observed, particularly near the leading edge.
- Turbulence modeling and roughness height appear to be primary contributors to the spread, while differences in HTC computation methodology also play a role.

Integrated Convective Heat Transfer

Grid-Convergence Metric

To assess whether the differences in the local HTC distributions translate into a clear grid-convergence behavior, an integrated convective heat-transfer quantity is evaluated along the surface slice:

$$Q'_c = \int HTC(s) [T_s(s) - T_{rec}(s)] ds \quad [Q'_c] = W/m.$$

The submitted HTC and surface temperature T_s are used directly. The recovery temperature T_{rec} , however, was not part of the submitted dataset and must therefore be reconstructed.

Recovery Temperature Reconstruction

The submitted pressure coefficient is used to estimate the local external-flow state and subsequently the recovery temperature:

$$C_p(s) \longrightarrow p_e(s) \longrightarrow M_e(s) \longrightarrow T_e(s) \longrightarrow T_{rec}(s)$$

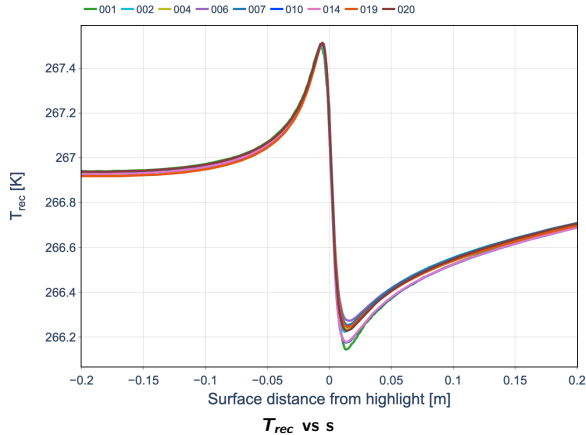
Assuming $p_s \simeq p_e$ and an isentropic external flow,

$$\frac{p_e}{p_\infty} = 1 + \frac{\gamma}{2} M_\infty^2 C_{p,e}, \quad M_e^2 = \frac{2}{\gamma - 1} \left[\left(\frac{p_0}{p_e} \right)^{(\gamma-1)/\gamma} - 1 \right],$$

$$T_e = \frac{T_0}{1 + \frac{\gamma-1}{2} M_e^2}, \quad T_{rec} = T_e \left[1 + r \frac{\gamma-1}{2} M_e^2 \right], \quad r = Pr^{1/3} \approx 0.9.$$



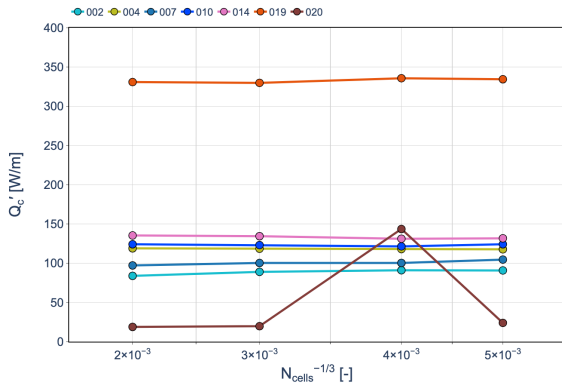
Reconstructed Recovery Temperature (L1)



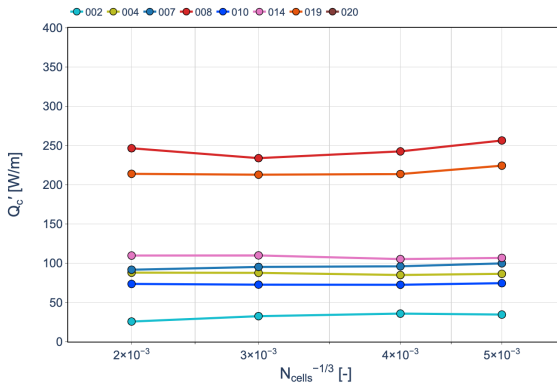
Observations

- T_{rec} is closely clustered, consistent with the agreement in C_p .
- Variability in Q'_c therefore will originate primarily from HTC and T_s .

Integrated Convective Heat Transfer Grid Convergence



AE3932



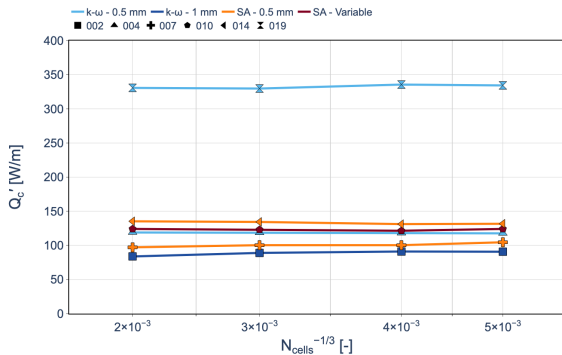
AE3933

Grouped by Turbulence Model / Roughness

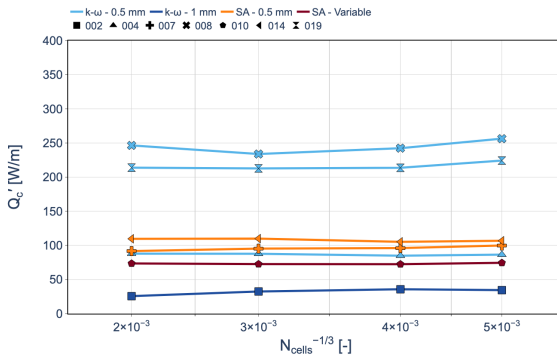
Observations

- Q'_c shows limited grid sensitivity for most submissions.
- Grouping by turbulence model and roughness does not clearly explain the observed spread, as Q_c also depends strongly on T_s (and, to a lesser extent, T_{rec}) and on the HTC spread.

Integrated Convective Heat Transfer Grid Convergence



AE3932



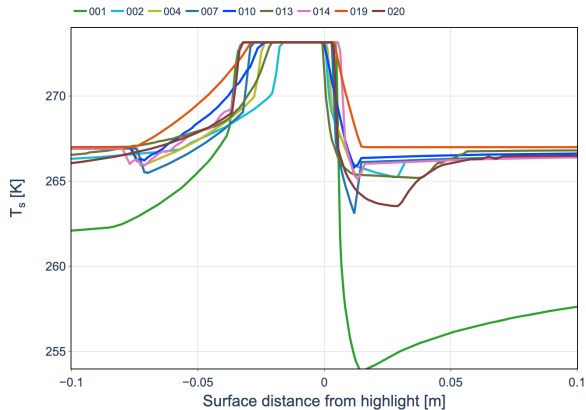
AE3933

Grouped by Turbulence Model / Roughness

Observations

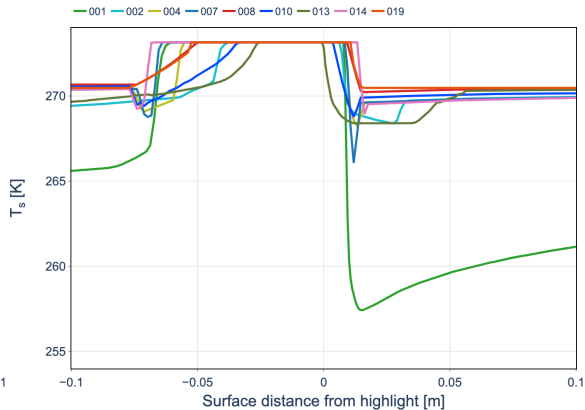
- Q_c' shows limited grid sensitivity for most submissions.
- Grouping by turbulence model and roughness does not clearly explain the observed spread, as Q_c also depends strongly on T_s (and, to a lesser extent, T_{rec}) and on the HTC spread.

Surface Temperature Comparison (L1)



AE3932

Grouped by Turbulence Model / Roughness

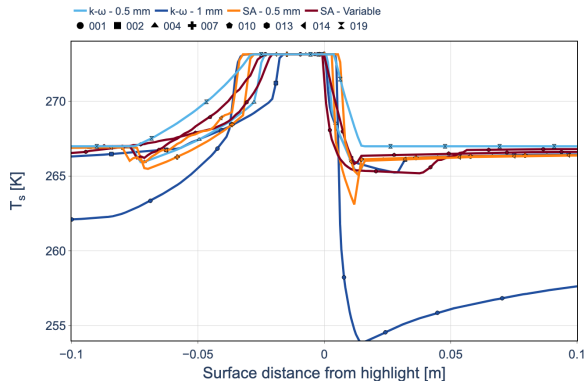


AE3933

Observations

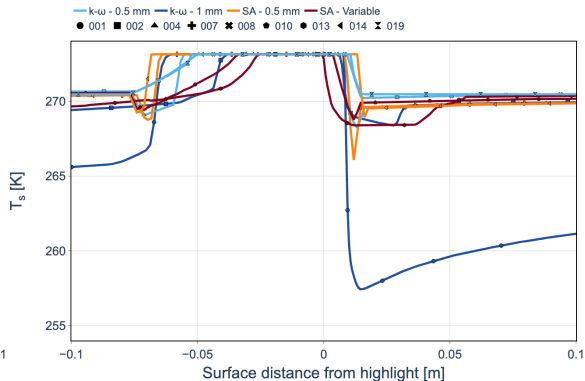
- Surface temperature shows substantial code-to-code variability; AE3933 exhibits a broader near-freezing region.
- Grouping by turbulence model, roughness, or thermodynamic model (not shown) reveals no clear systematic trend.

Surface Temperature Comparison (L1)



AE3932

Grouped by Turbulence Model / Roughness

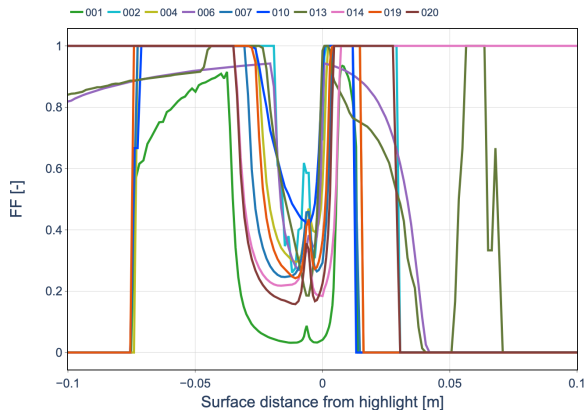


AE3933

Observations

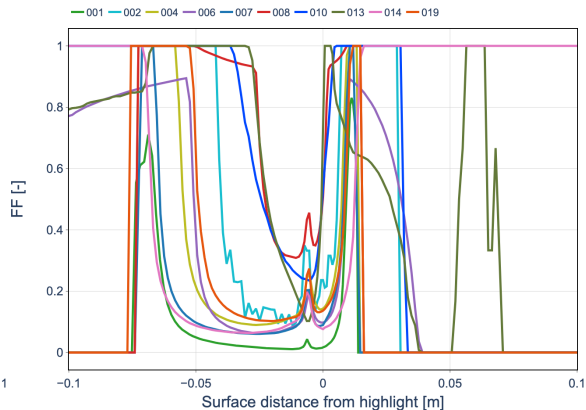
- Surface temperature shows substantial code-to-code variability; AE3933 exhibits a broader near-freezing region.
- Grouping by turbulence model, roughness, or thermodynamic model (not shown) reveals no clear systematic trend.

Freezing Fraction Comparison (L1)



AE3932

Grouped by Turbulence Model / Roughness

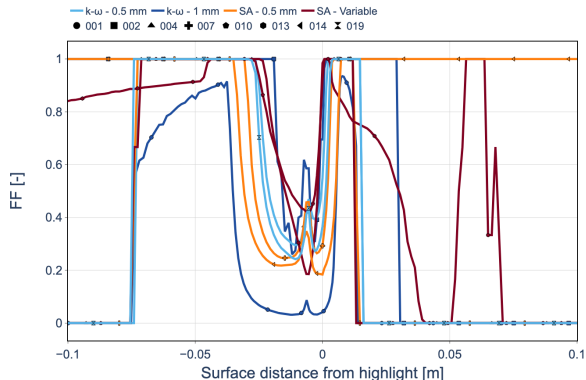


AE3933

Observations

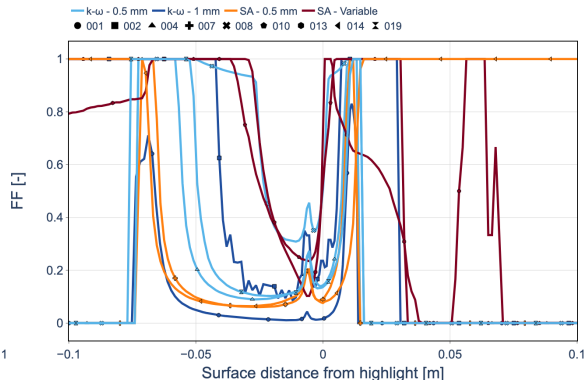
- Freezing fraction exhibits substantial code-to-code variability, with AE3933 showing a broader low-freezing-fraction region, consistent with its broader near-freezing surface-temperature region.
- Grouping by turbulence model, roughness, or thermodynamic model reveals no clear systematic similarities.

Freezing Fraction Comparison (L1)



AE3932

Grouped by Turbulence Model / Roughness



AE3933

Observations

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HTC & Thermodynamics Assessment

HTC & Thermodynamics Assessment

Convective Heat Transfer

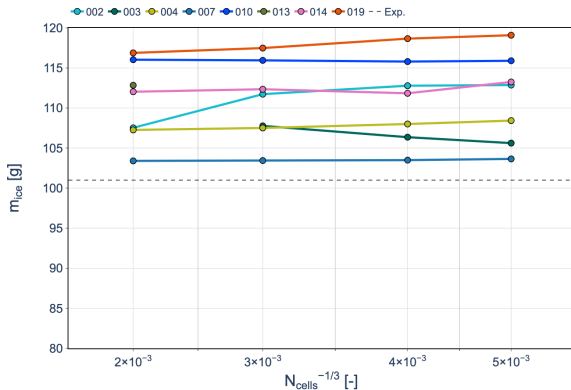
- Local HTC exhibits substantial code-to-code variability; turbulence modeling and roughness help explain the observed spread, while differences in HTC computation methodology also play a role.
- Integrated convective heat transfer over the submitted data slice exhibits limited grid sensitivity for most submissions.

Thermodynamic Response

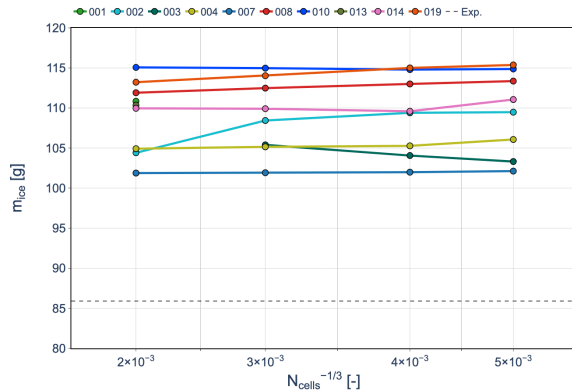
- The code-to-code differences observed in HTC are maintained in the surface temperature and freezing-fraction predictions, with no clear systematic trend when grouped by turbulence modeling or roughness height.
- The warmer AE3933 condition generally produces a wider near-freezing surface-temperature region and a correspondingly wider low-freezing-fraction region.



Ice Mass Grid Convergence (15 Bins)



AE3932

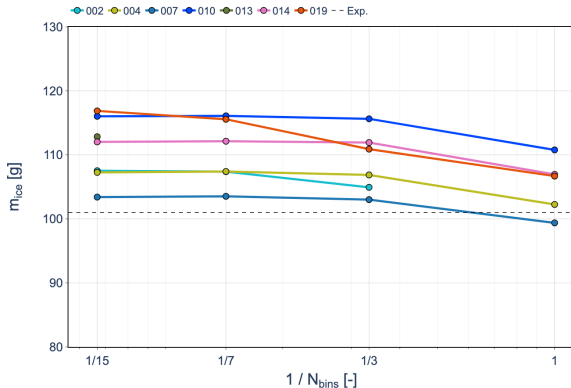


AE3933

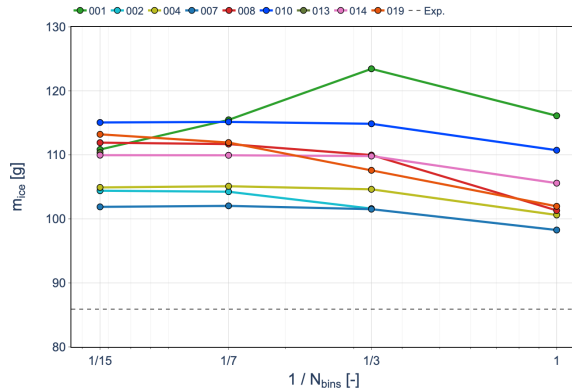
Observations

- At L1, the median ice mass is approximately 110 g for both conditions, with a relative IQR of about 7%.
- Grid sensitivity is limited for most submissions, with deviations generally remaining within approximately 5% of L1.
- AE3933 predicts at most a $\sim 3\%$ reduction in ice mass relative to AE3932, compared with $\sim 15\%$ experimentally.

Ice Mass Sensitivity to Droplet Distribution (L1)



AE3932

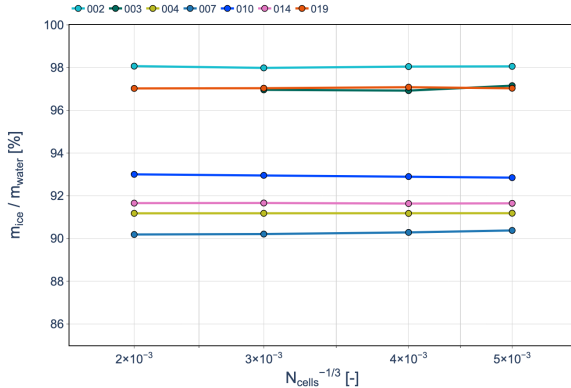


AE3933

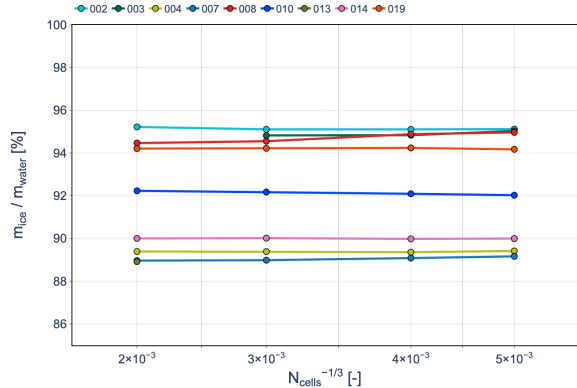
Observations

- The 15- and 7-bin distributions produce comparable ice masses.
- Sensitivity increases for 3 bins and is greatest for the single-bin.

Ice-to-Water Mass Ratio



AE3932

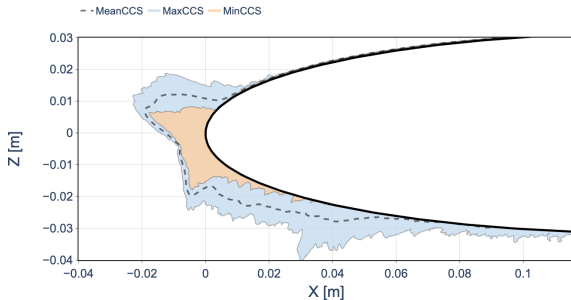


AE3933

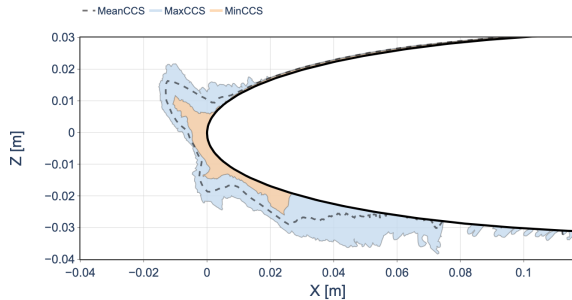
Observations

- Approximately 90 – 98% of the impinged water is converted into ice for both conditions.
- AE3933 exhibits a lower ice-to-water ratio, indicating greater water loss.
- Including evaporation closes the mass balance to approximately 100%, identifying evaporation as the primary water-loss mechanism.

Ice Shapes (L2, 15 Bins)



AE3932 – Experiment



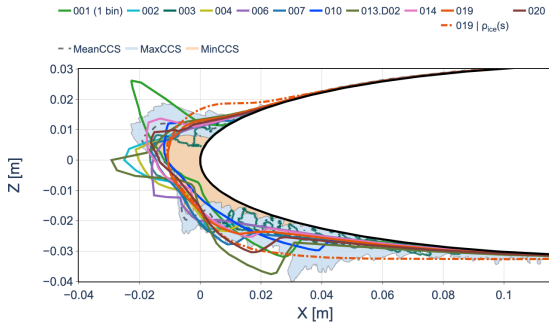
AE3933 – Experiment

Observations

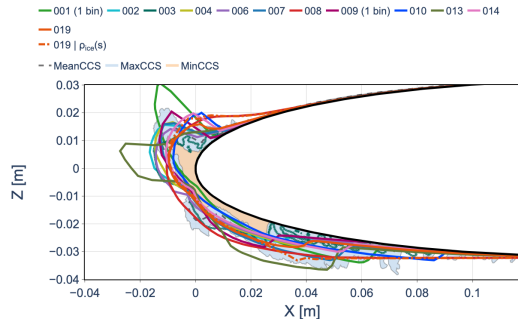
- Experiments show a clear difference in ice shape, particularly in upper-horn orientation.
- Code-to-code variability is reflected in the predicted ice shapes and horn angles.
- The experimental difference between conditions is reproduced to varying degrees.
- Horn orientation is influenced by turbulence modeling and roughness height, with the geometry-extrusion method playing a major role.



Ice Shapes (L2, 15 Bins)



AE3932

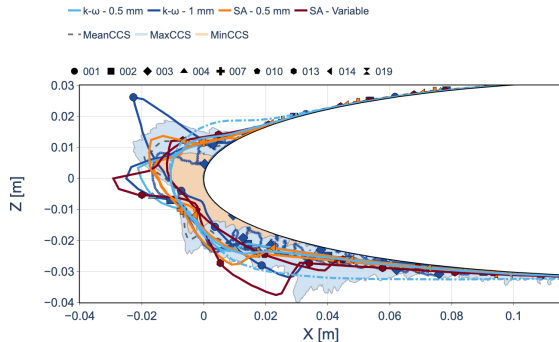


AE3933

Observations

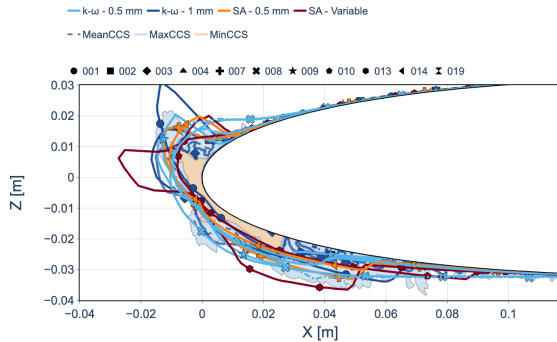
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Ice Shapes (L2, 15 Bins)



AE3932

Grouped by Turbulence Model / Roughness

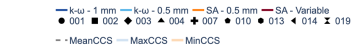


AE3933

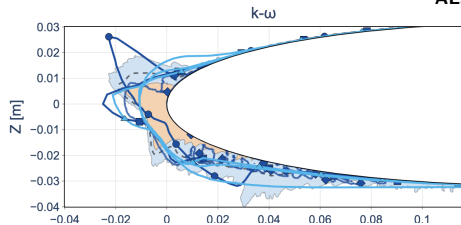
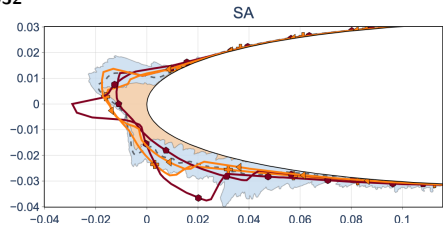
Observations

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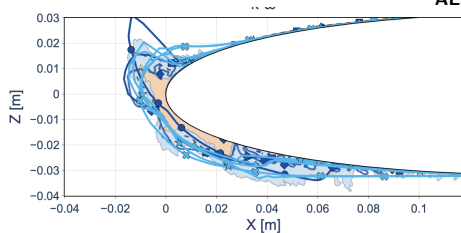
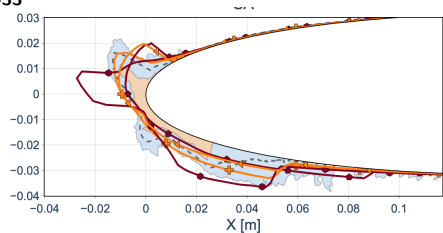
Ice Shapes (L2, 15 Bins)



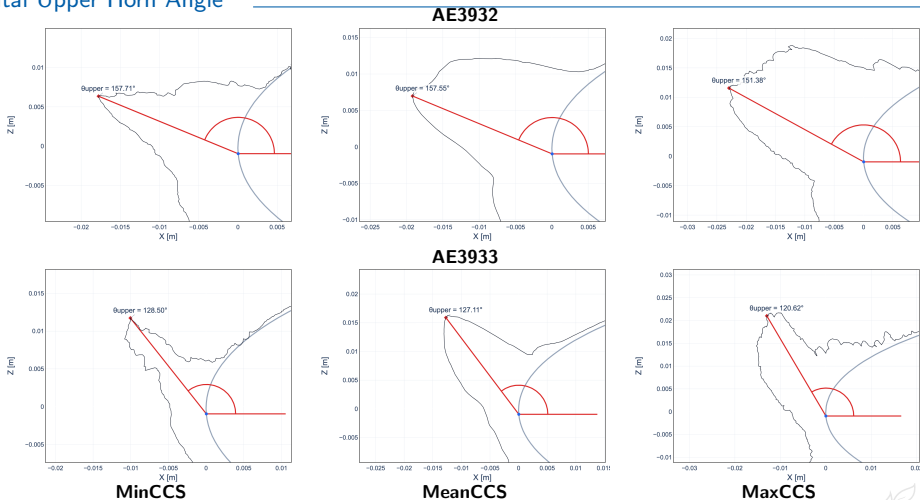
AE3932



AE3933



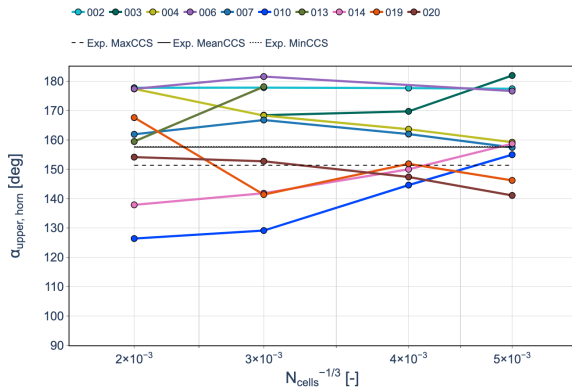
Experimental Upper Horn Angle



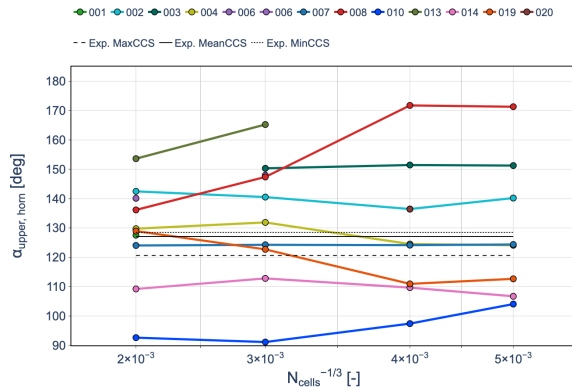
Experimental Reference

- The experimental upper-horn angle ranges from approximately $151\text{--}158^\circ$ for AE3932 and $121\text{--}129^\circ$ for AE3933.

Upper Horn Angle Grid Convergence (15 Bins)



AE3932

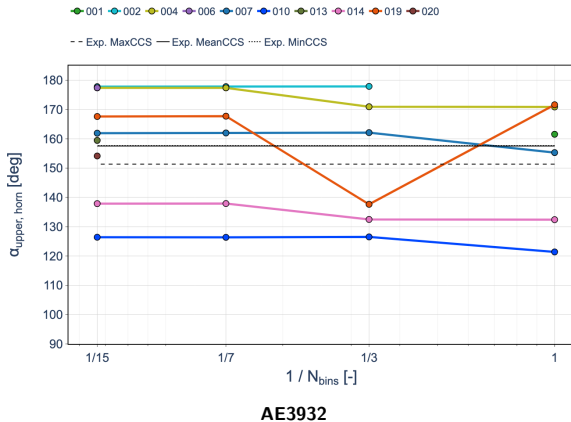
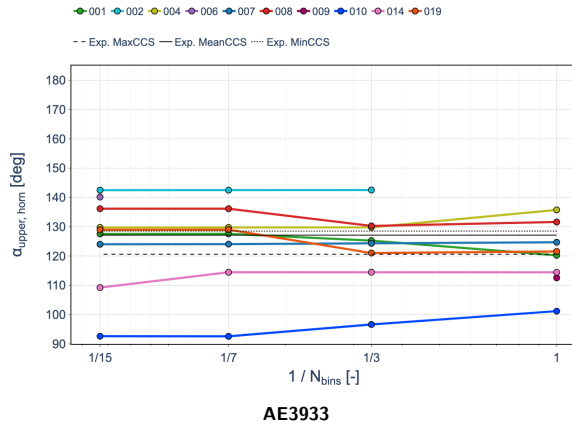


AE3933

Observations

- Horn-angle variability reflects the code-to-code scatter observed in the ice shapes.
- AE3933 predicts smaller upper-horn angles than AE3932, consistent with experiment.
- L1 scatter is comparable between conditions (IQR $\approx 16\%$ and 13%).

Upper Horn Angle Sensitivity to Droplet Distribution (L1)



Observations

- Upper-horn angle shows limited sensitivity to droplet-size discretization.

Ice Accretion Assessment

Ice Accretion Assessment

Ice-Mass Prediction

- Ice mass shows limited grid sensitivity, with 15- and 7-bin distributions producing comparable results.
- Approximately 90% of the impinged water is converted into ice, with evaporation accounting for most of the remaining water mass.

Response to Icing Condition

- AE3933 predicts less ice than AE3932, but substantially underestimates the experimental $\sim 15\%$ reduction.
- The smaller AE3933 upper-horn angle is consistently captured, in agreement with the experimental trend.

Ice-Shape Prediction

- Horn-angle variability reflects the code-to-code scatter observed in the ice shapes.
- Horn orientation is influenced not only by turbulence modeling and roughness height, but also by the geometry-extrusion method, which plays a major role.
- Horn angle shows limited sensitivity to droplet-size discretization.



Overall Assessment

Overall Assessment

- **Aerodynamics:** Predictions are well clustered; C_p agrees well with experiment, while C_D shows the greatest grid sensitivity.
- **Droplet Impingement:** Limited grid sensitivity is observed, with 7-bin results closely reproducing the 15-bin reference.
- **HTC & Thermodynamics:** Local HTC exhibits substantial code-to-code variability, influenced by turbulence modeling, roughness, and computation methodology; surface temperature and freezing fraction reflect similar code-to-code differences.
- **Ice Accretion:** Ice mass is relatively consistent, but the experimental AE3933 mass reduction is substantially underpredicted; final ice geometry remains strongly code-dependent.

Overall Takeaway

Aerodynamics, impingement, and ice mass are comparatively consistent across submissions, while larger variability emerges in thermodynamics and final ice geometry. The AE3932–AE3933 change in horn orientation is captured, but the experimental reduction in ice mass remains substantially underpredicted.

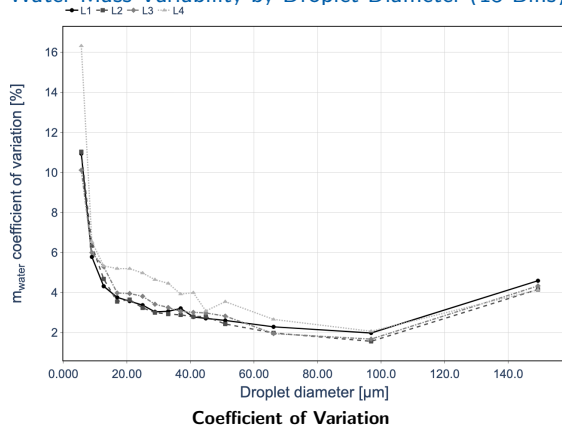
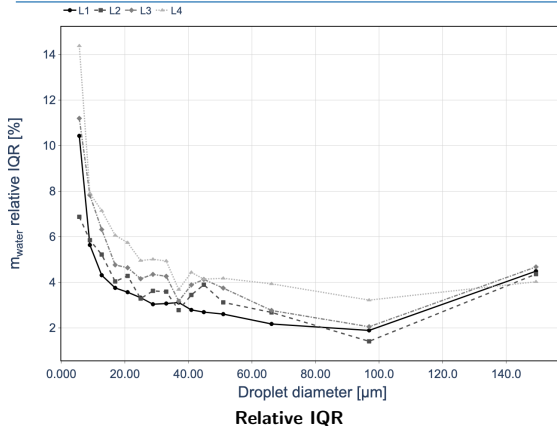


Additional Material

Backup Slides



Water-Mass Variability by Droplet Diameter (15 Bins)

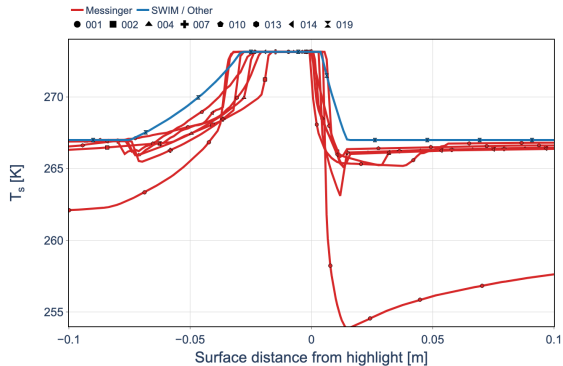


Observations

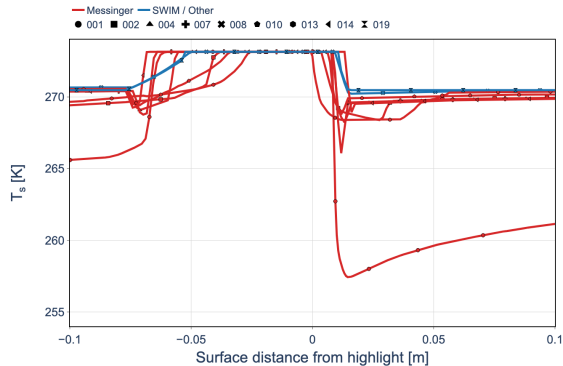
- Variability is evaluated from the optionally submitted water mass per droplet diameter, across all available participants and grid levels.
- Code-to-code variability is greatest for the smallest droplets and lowest across intermediate diameters.
- Coarser grids generally show greater spread.

NACA0012 – Surface Temperature by Thermodynamic Model

AE3932

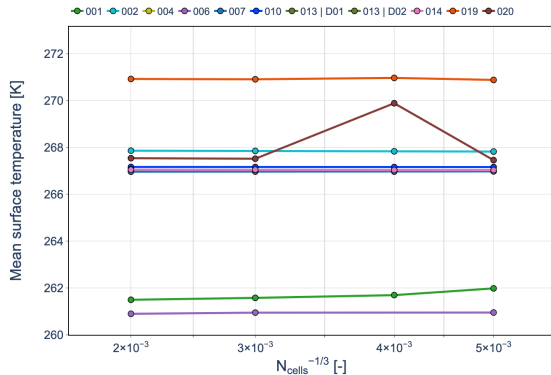


AE3933

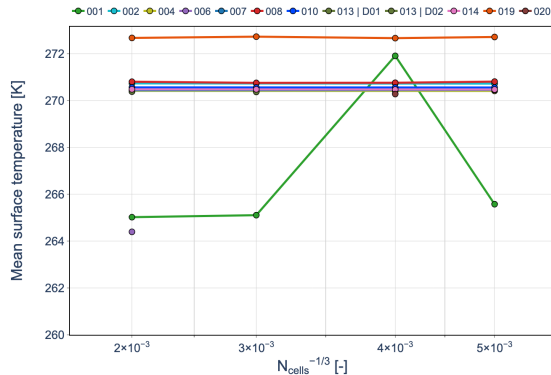


NACA0012 – Mean Surface Temperature

AE3932



AE3933

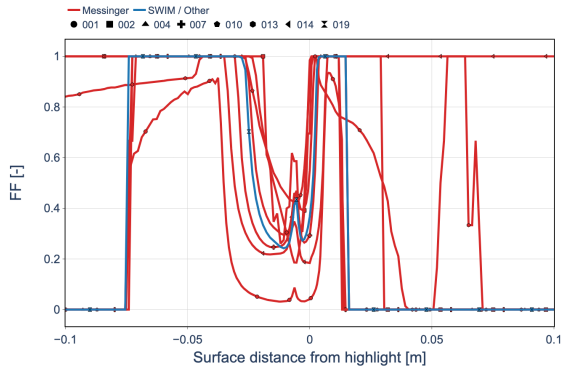


Note: Mean surface temperature is computed only over regions with ice thickness > 0 .

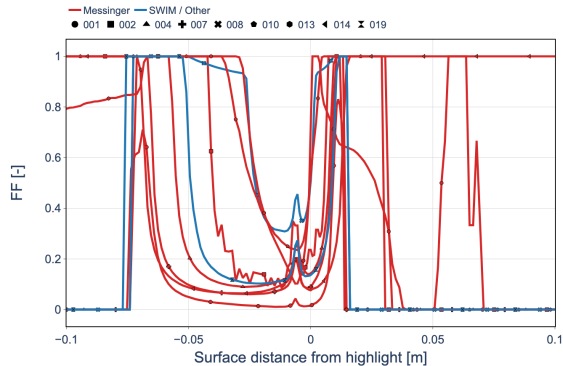


NACA0012 – Freezing Fraction by Thermodynamic Model

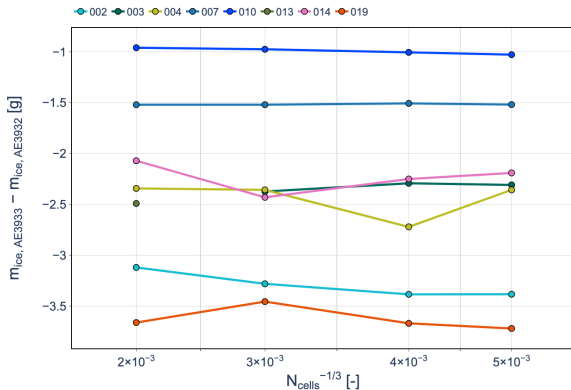
AE3932



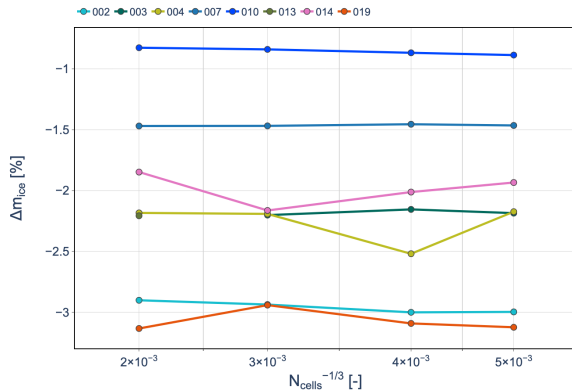
AE3933



Ice Mass Difference Between Conditions (15 Bins)



AE3933 – AE3932

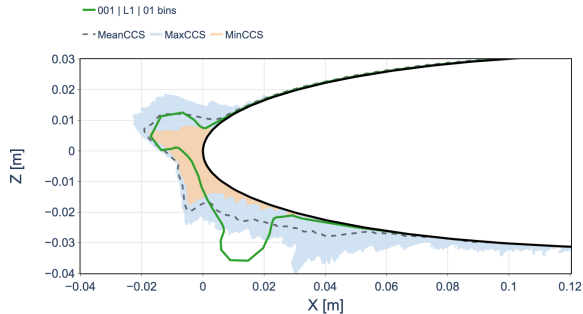


AE3933 vs. AE3932 (%)

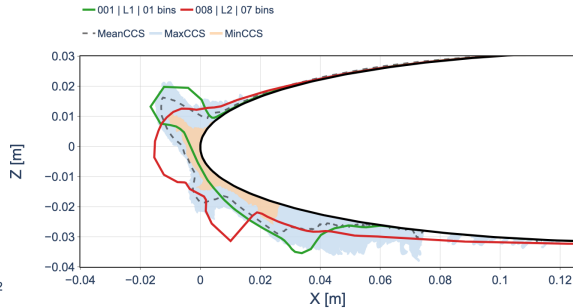
Observations

- AE3933 predicts consistently less ice for most matched submissions.
- The reduction is at most ~ 3.5 g ($\sim 3\%$), compared with $\sim 15\%$ experimentally.

Multilayer Ice-Shape Comparison



AE3932



AE3933

Observations

- Multilayer predictions suggest slight improvement, but the limited dataset prevents a conclusive assessment.

