Summary of Test Cases and Motivation for TFG-2 of IPW3

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Summary of Test Cases and Motivation for TFG-2 of IPW3

September 21, 2026

AIAA Third Ice Prediction Workshop

Thomas Ozoroski

Motivation and Summary of IPW3 TFG-2

Definitions Being Used Here

Solution Verification

"The process of determining the correctness of the input data, the numerical accuracy of the solution obtained, and the correctness of the output data for a particular simulation"

Have we reduced the error in our analysis as much as possible to obtain an accurate solution – solution convergence, mesh resolution, trajectory convergence, cloud representation, etc.

Model Validation

"*The process of determining the degree to which a model is an accurate representation of the real world from the perspective of the intended uses of the model*"

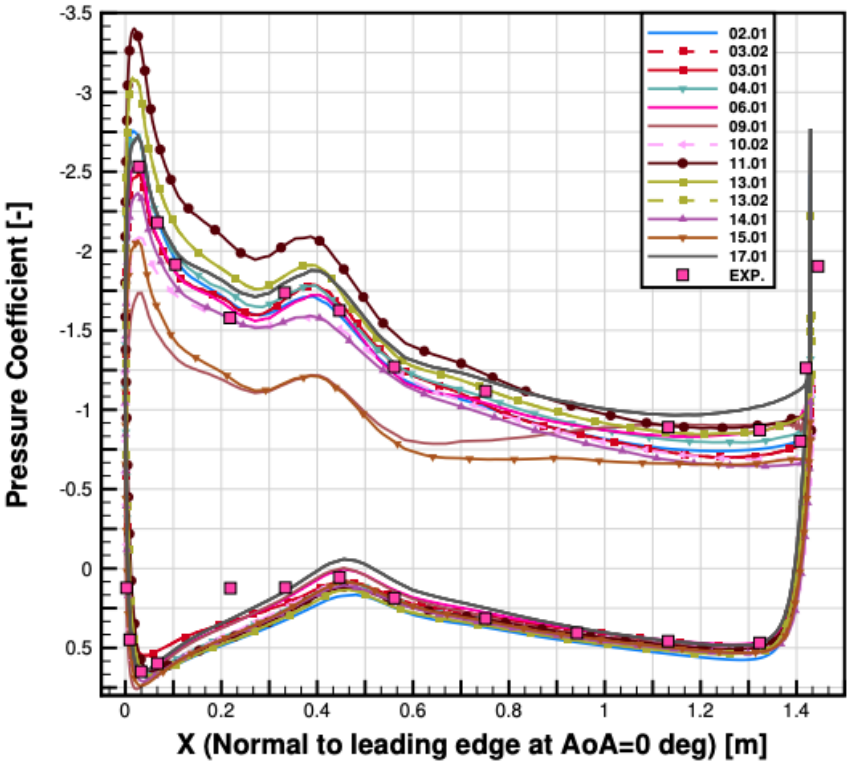
How do our results compare to the experimental ice shape properties and ice shape we are attempting to predict.

"*Quantification of the accuracy of the computational model results by comparing the computed system response quantities (SRQs) of interest with the experimentally measured SRQs.*"

As defined and discussed by Oberkampf and Roy – Verification and Validation in Scientific Computing

Motivation

- IPW2 incurred drastic differences in the C_p profiles and attachment line location
- The reason for these discrepancies are multifaceted
- Grid and solution convergence is influenced by the CFD solver, turbulence model, and flux schemes
- Lack of agreement in computational solutions leads to
  - Icing tools being applied to completely different solutions
  - Increased spread of icing results
- These issues impede conclusions and do not convey sound numerical practices being utilized to outside parties
- Improved consistency leads to improved conclusions

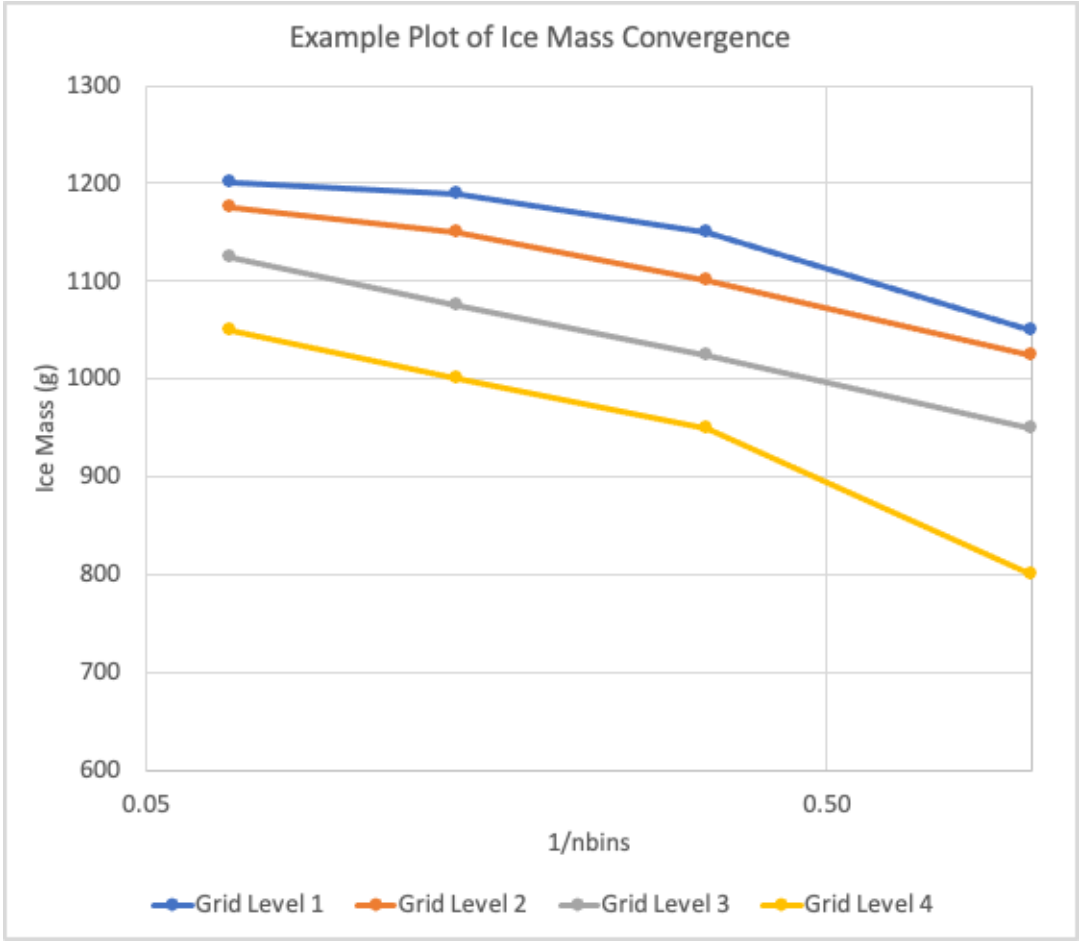


From IPW2 Comparisons by Blanchet Case 1, Slide 10

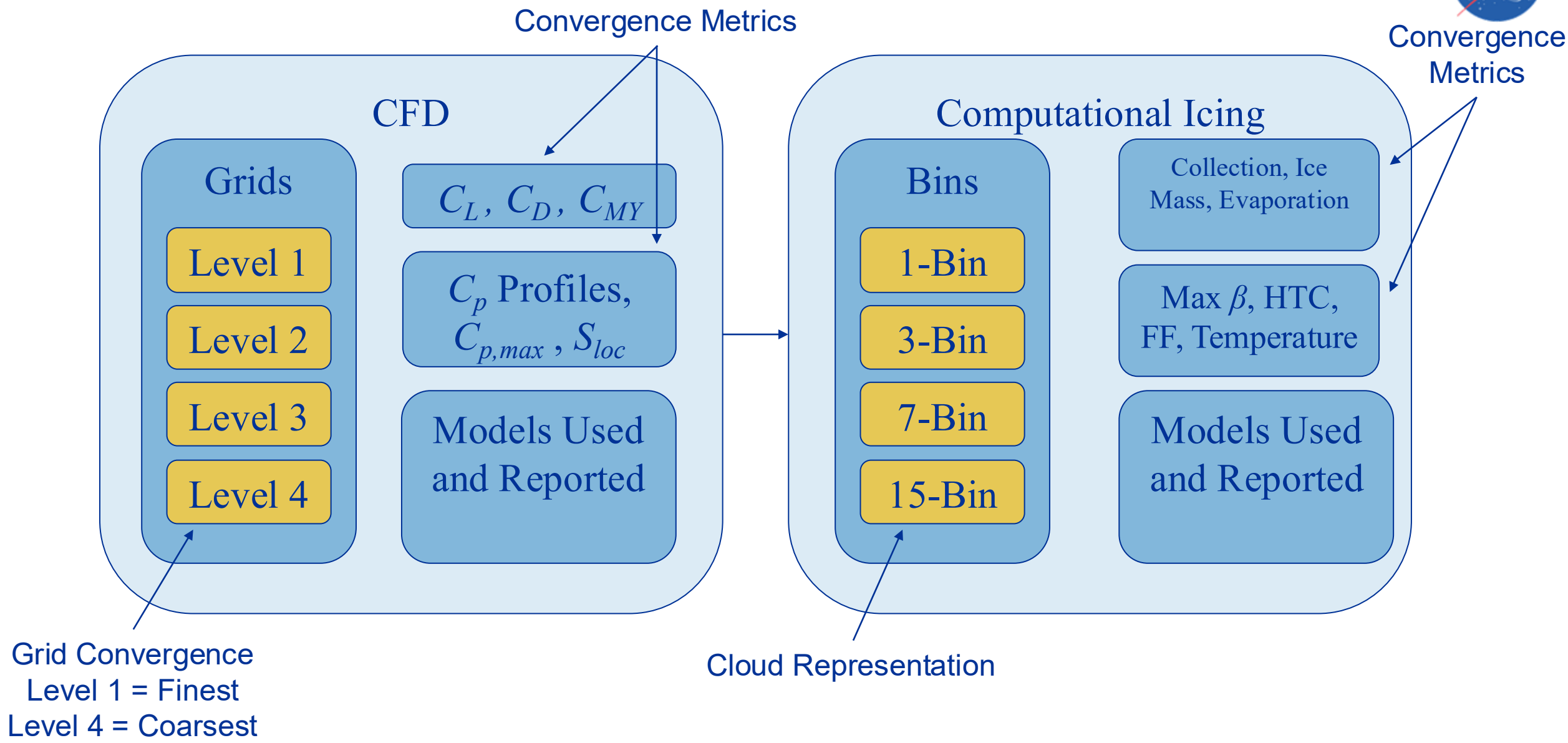
We don't have one problem to get right, we have two

Evaluation Goals

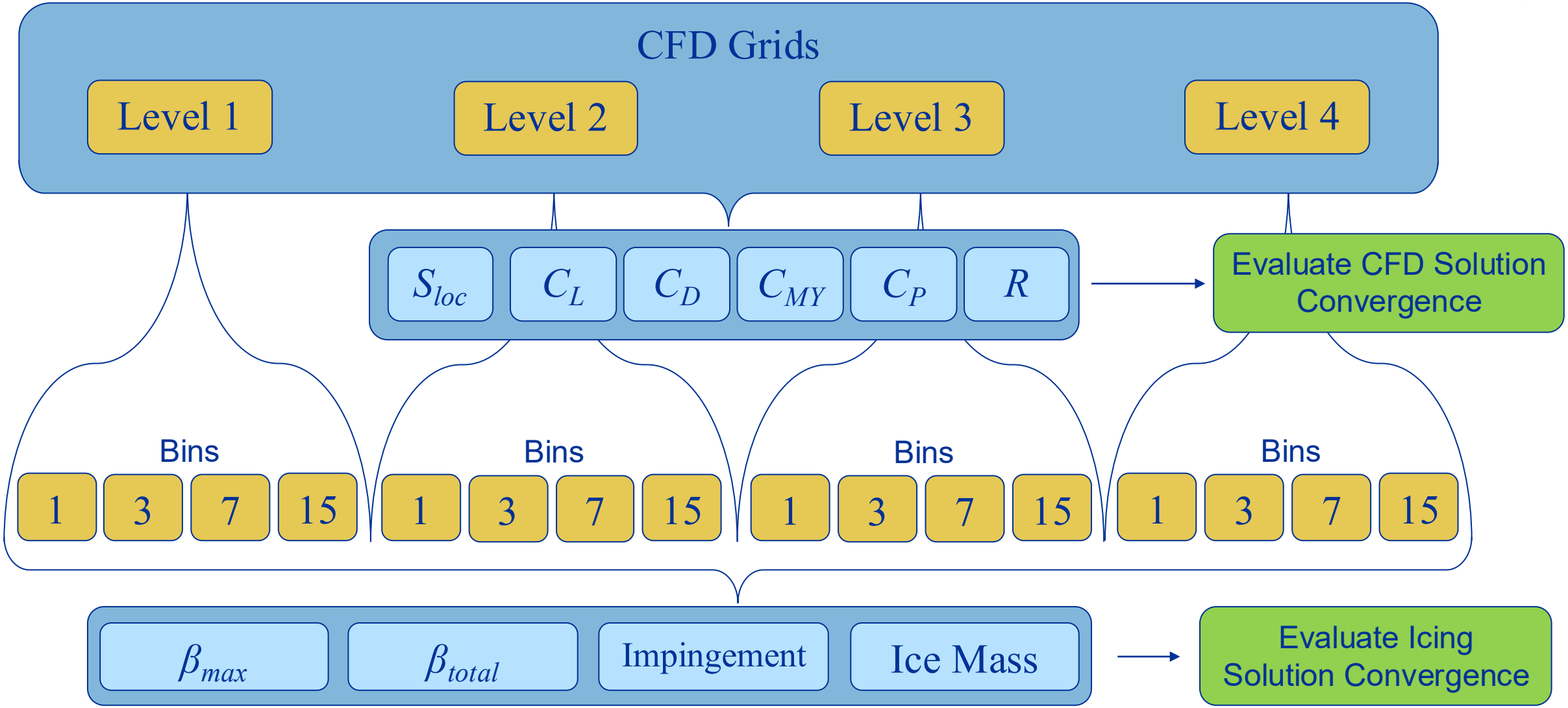
- Evaluate each CFD grid computationally through a grid study and evaluation of attachment line parameters
- Evaluate icing codes based on properties such as
  - Mass
  - Impinging Water
  - Maximum Local Collection Efficiency
  - Total Collection Efficiency
- Demonstrate convergence of both the CFD and Icing solutions
- Once we have a converged solution
  - Compare ice shapes (Participants)
  - Compare properties (Participants)
  - Compare to experimental data (Mass, Volume, Ice Shape)



Assuming Single Shot



Process Workflow



Validation Test Case

TEST CASE 1
NASA ICING RESEARCH TUNNEL
21-INCH NACA 0012

Geometry Definition

- Test section is modeled as a rectangular prism
  - -600 in ≤ X ≤ 600 in
  - 0 in ≤ Y ≤ 72 in
  - -54 in ≤ Z ≤ 54 in
- Model spans the test section from floor to ceiling
- The model has a 21-inch chord with s_0 = 0 in at
  X, Y, Z (in) = 0, 36, 0 (unrotated)
- Extraction region from:
  32 in ≤ Y ≤ 40 in
- AOA = 4˚ about ¼ Chord location of X = 5.25 in

Inches:
Reference area = 1512 in^2
Aspect ratio (span^2/area) = 3.4286
Mean aerodynamic chord (M.A.C.) = 21 in
X, Y, Z moment center [in] = 5.25, 0, 0

Meters:
Reference area = 0.97548 m^2
Aspect ratio (span^2/area) = 3.4286
Mean aerodynamic chord (M.A.C.) = 0.5334 m
X, Y, Z moment center [m] = 0.13335, 0, 0

Use these for any non-dimensionalization of integrated properties

Cp CFD Conditions

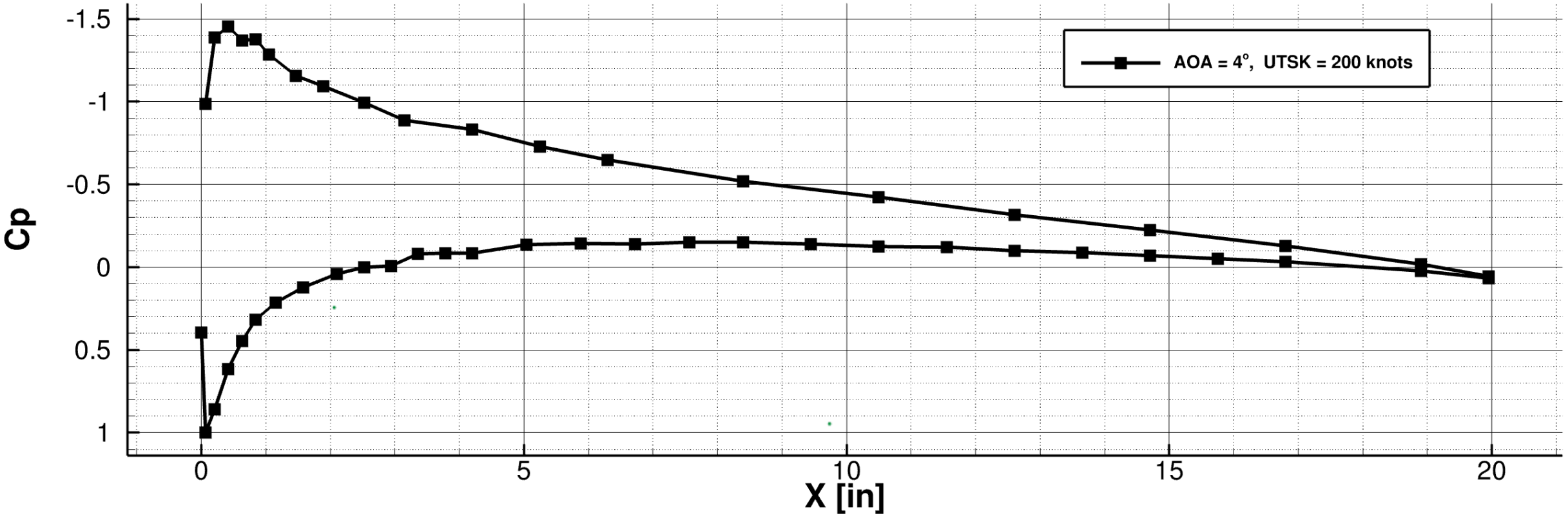
- M_{ref} = 0.3114
- U_{ref} [m/s] = 102.15
- AOA [deg] = 4
- $T_{s,ref}$ [K] = 267.75
- $T_{0,ref}$ [K] = 272.95
- ρ_{ref} [kg/m^3] = 1.1884
- P_{ref} [Pa] = 91337
- $P_{0,ref}$ [Pa] = 97688
- a_{ref} [m/s] = 328.03
- μ_{ref} [kg/m-sec] = 1. 68917E-05
- $Re_{L,ref}$ [/m] = 7.1861E6
- $Re_{c,ref}$ = 3.8441E6

Setting Tunnel Conditions:

- These values should be used to match the test section conditions
- This would be done by sampling upstream to get close to the necessary value for Mach number
- For simplicity, the sampling can be done at:
  (X, Y, Z) [in] = (-139, 45.58, 0)
- It is recommended that participants try a purely isentropic analysis first and then adjust from there if outside of a +/- 0.5 m/s difference in U_{ref} or +/- 0.01 difference in M_{ref}
- It should be noted that all conditions (Cp, AE3932, AE3933) fall within these uncertainty bounds. It is up to the participants discretion whether they take into account the changes in Reyolds number, Density, and Pressure

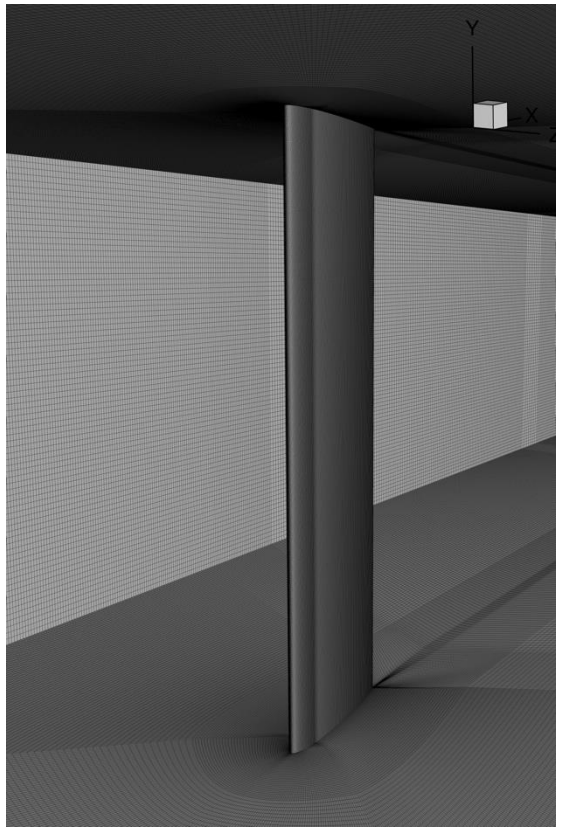
Aero Cp Evaluation

- Pressure taps are located at Y = 20 in above the floor

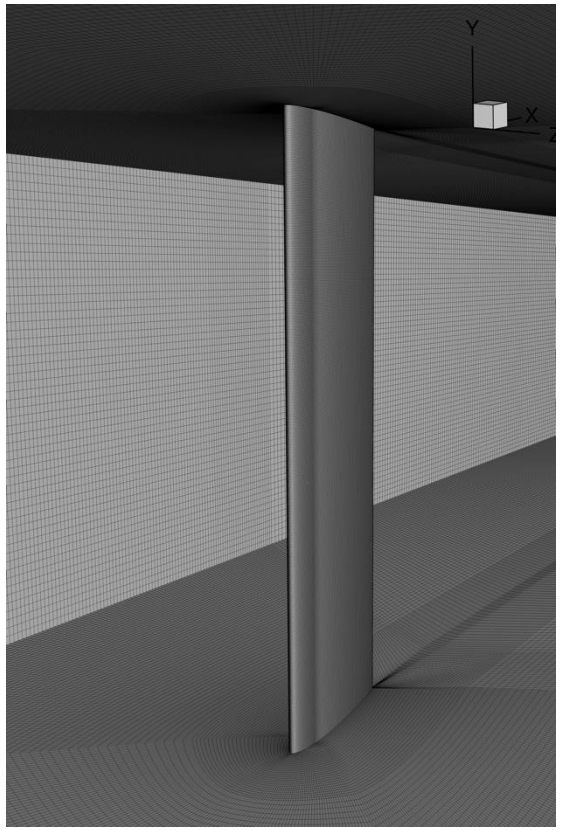


Grid Levels

Level	1	2	3	4
Nodes	60,450,029	27,308,300	11,234,674	5,947,691



Level 1



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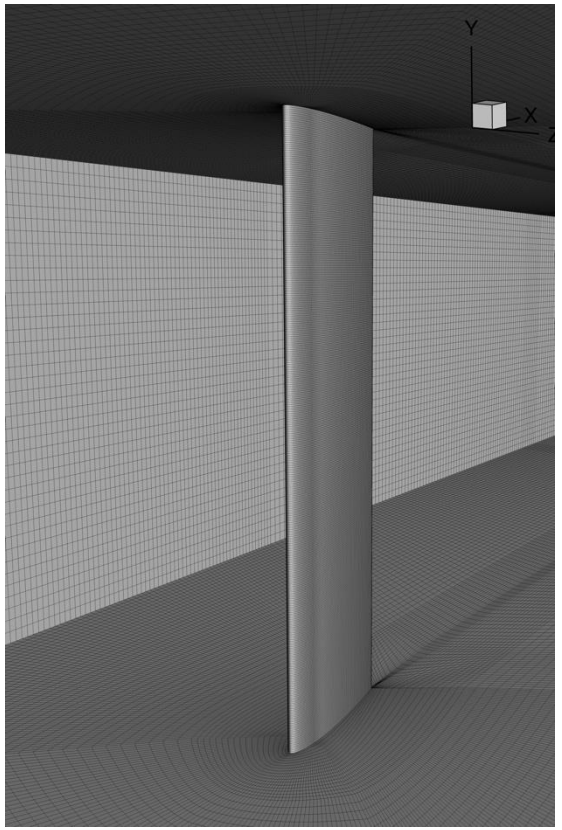
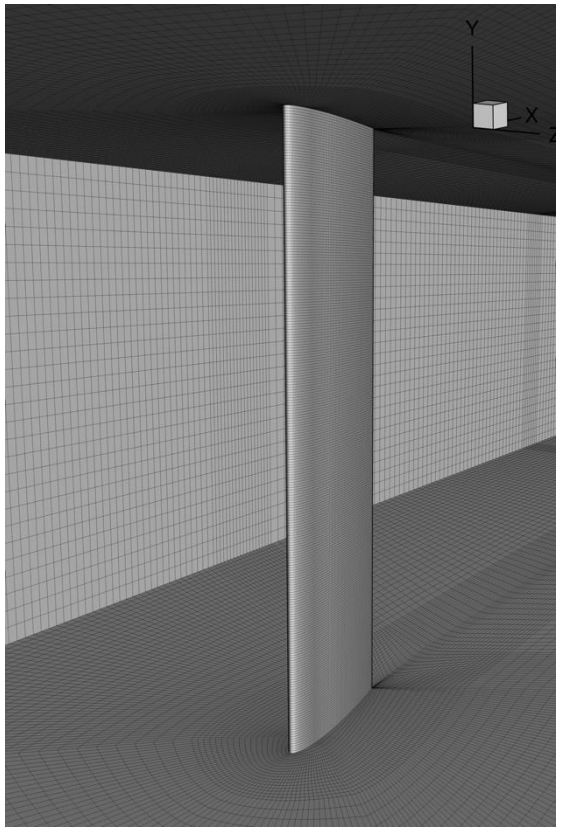


Level 3



Level 4

Boundary Conditions and Naming Convention

Boundary 1:
- Name: NACA0012_TE
- Type: Fully Viscous Wall
- Conditions: u, v, w (wall) = 0.0 m/s, explicitly set a no-slip condition

Boundary 2:
- Name: NACA0012_WING_ZPOS_YNEG
- Type: Fully Viscous Wall
- Conditions: u, v, w (wall) = 0.0 m/s, explicitly set a no-slip condition

Boundary 3:
- Name: NACA0012_WING_ZNEG_YNEG
- Type: Fully Viscous Wall
- Conditions: u, v, w (wall) = 0.0 m/s, explicitly set a no-slip condition

Boundary 4:
- Name: FLOOR
- Type: Fully Viscous Wall
- Conditions: u, v, w (wall) = 0.0 m/s, explicitly set a no-slip condition

Boundary 5:
- Name: CEILING
- Type: Fully Viscous Wall
- Conditions: u, v, w (wall) = 0.0 m/s, explicitly set a no-slip condition

Boundary 6:
- Name: INLET
- Type: Subsonic Inflow

Boundary 7:
- Name: OUTLET
- Type: Subsonic Outflow

Boundary 8:
- Name: TUNNEL_WALL_ZPOS
- Type: Fully Viscous Wall
- Conditions: u, v, w (wall) = 0.0 m/s, explicitly set a no-slip condition

Boundary 9:
- Name: TUNNEL_WALL_ZNEG
- Type: Fully Viscous Wall
- Conditions: u, v, w (wall) = 0.0 m/s, explicitly set a no-slip condition

Boundary 10:
- Name: NACA0012_WING_ZPOS_CENTER
- Type: Fully Viscous Wall
- Conditions: u, v, w (wall) = 0.0 m/s, explicitly set a no-slip condition

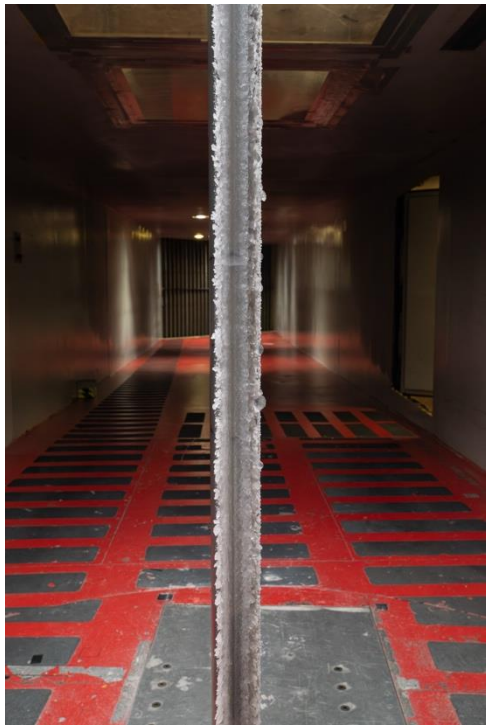
Boundary 11:
- Name: NACA0012_WING_ZNEG_CENTER
- Type: Fully Viscous Wall
- Conditions: u, v, w (wall) = 0.0 m/s, explicitly set a no-slip condition

Boundary 12:
- Name: NACA0012_WING_ZNEG_YPOS
- Type: Fully Viscous Wall
- Conditions: u, v, w (wall) = 0.0 m/s, explicitly set a no-slip condition

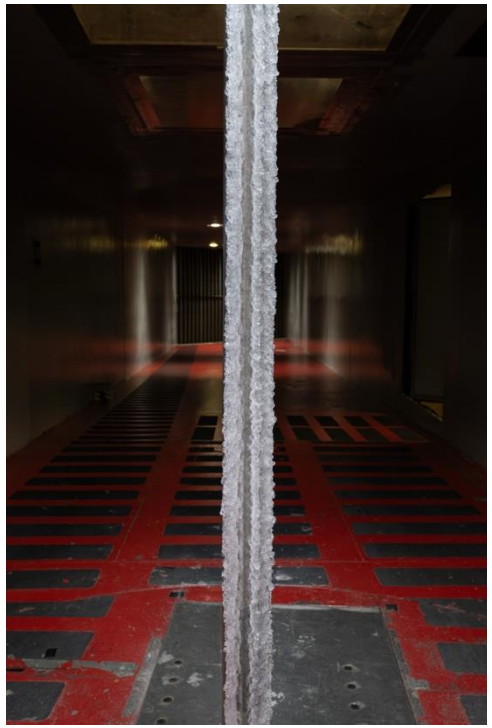
Boundary 13:
- Name: NACA0012_WING_ZPOS_YPOS
- Type: Fully Viscous Wall
- Conditions: u, v, w (wall) = 0.0 m/s, explicitly set a no-slip condition

Icing Conditions

CASE ID	Velocity (kts)	T_0 (˚C)	LWC (g/m^3)	MVD (μm)	Time (min)	AOA [deg]	Freezing Fraction	Mass (g)
AE3932	200	-5.6	0.55	20.0	7.0	4.0	0.5	101
AE3933	200	-2.2	0.55	20.0	7.0	4.0	0.3	85.9

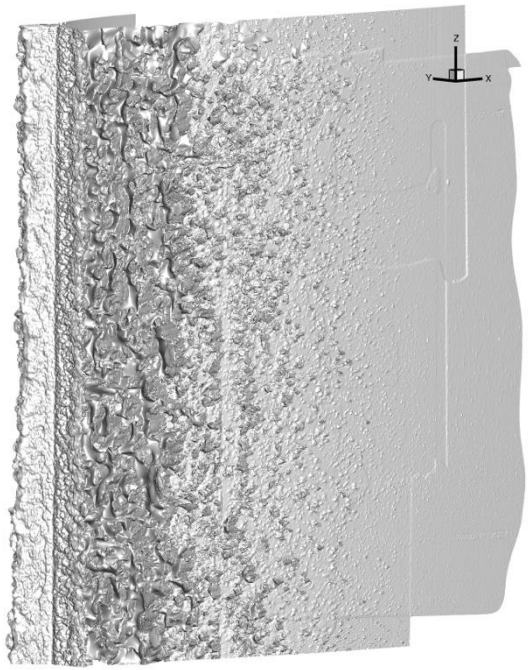


AE3932

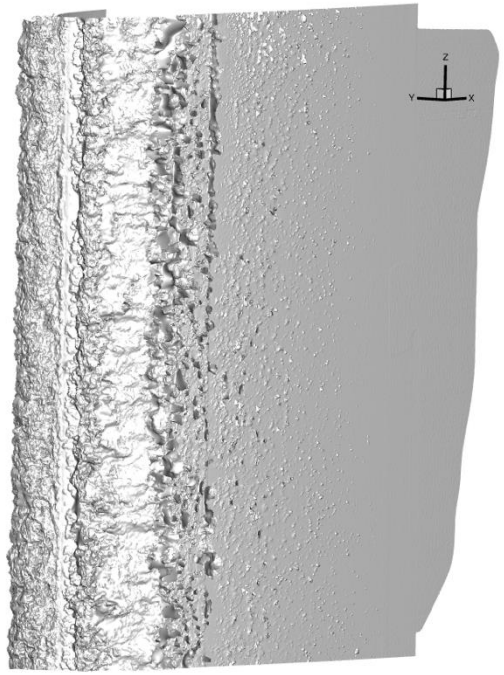


AE3933

Experimental Data



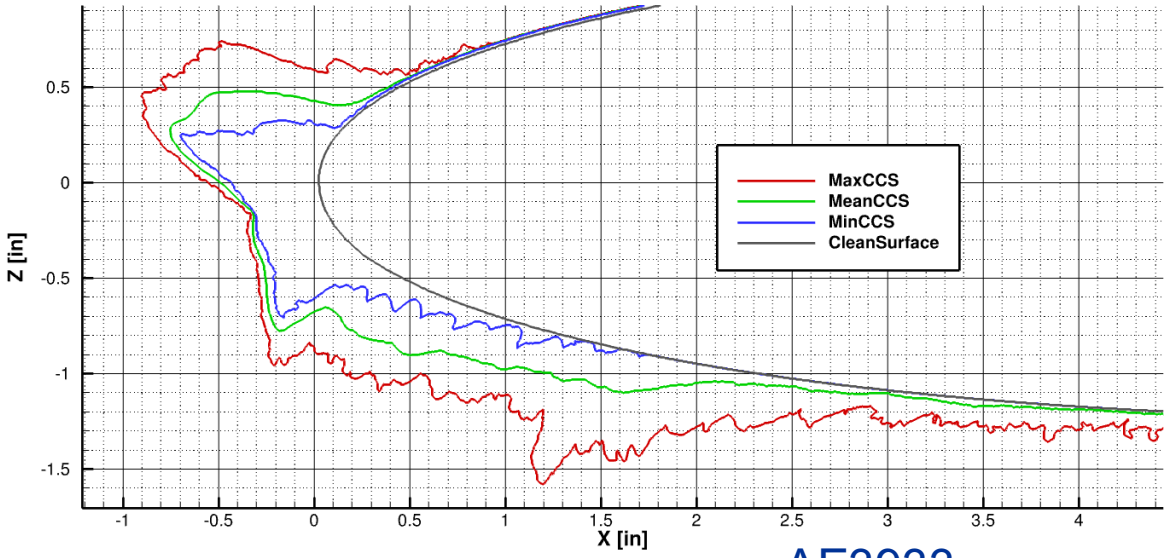
AE3932



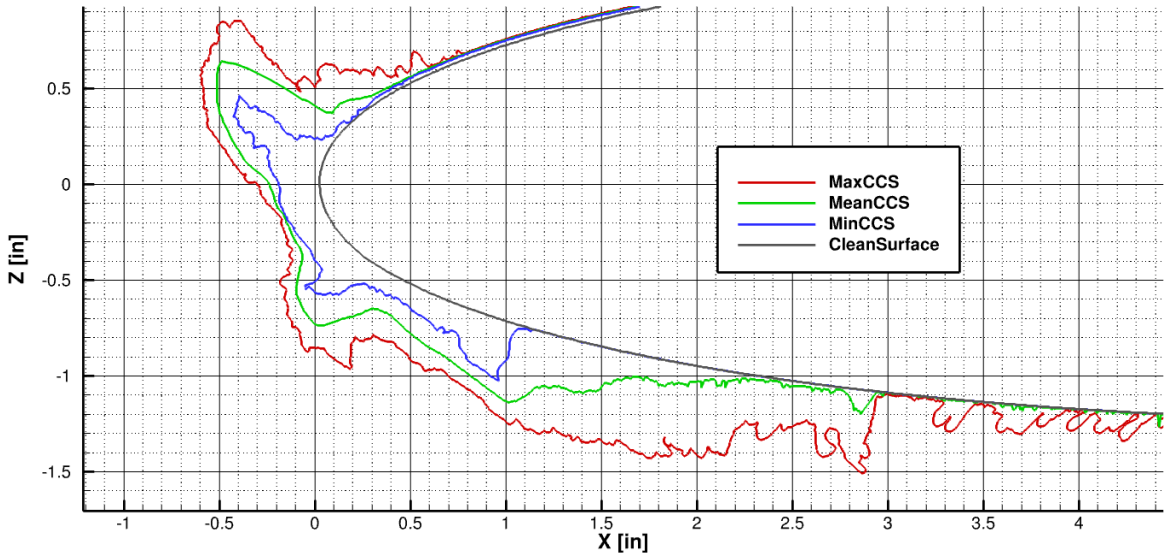
AE3933

	Run	AE3932	AE3933
Laser Scanned Based	Scaned Ice Volume (in^3)	10.12	7.58
2D CCS Profile Area * Extraction Width (8-inches)	MaxCCS Bulk Volume (in^3)	20.79360	17.01280
	MeanCCS Bulk Volume (in^3)	10.49296	8.51664
	MinCCS Bulk Volume (in^3)	5.02496	3.66856
	Ice Mass (g)	101.0	85.9
Considered a Bulk Density not a 'true' density	Scanned Bulk Density (kg/m3)	609	692
	MaxCCS Bulk Density (kg/m^3)	296	308
	MeanCCS Bulk Density (kg/m^3)	587	615
	MinCCS Bulk Density (kg/m^3)	1226	1429

AE3932

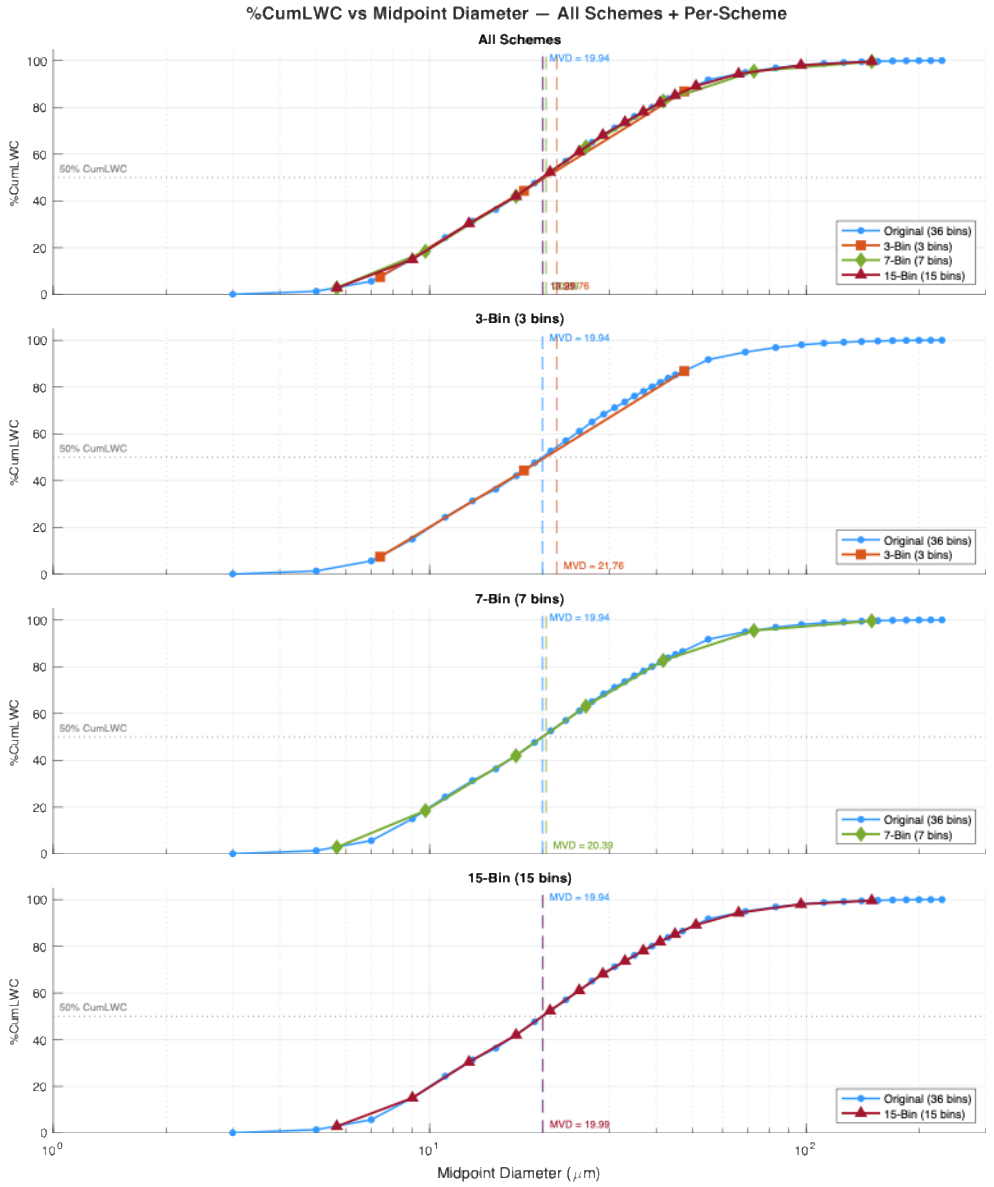


AE3933



Drop Size Distributions

- Bins are generated by unequal weighting of concurrent bins
- Interpolation is done to determine where that cumulative LWC exists on the continuous diameter curve
- Total LWC [g/m^3] is preserved
- MVD is not preserved due to resolution of DV50 region
- I believe this to be a numerically sound and computationally consistent representation of the continuous tunnel distribution



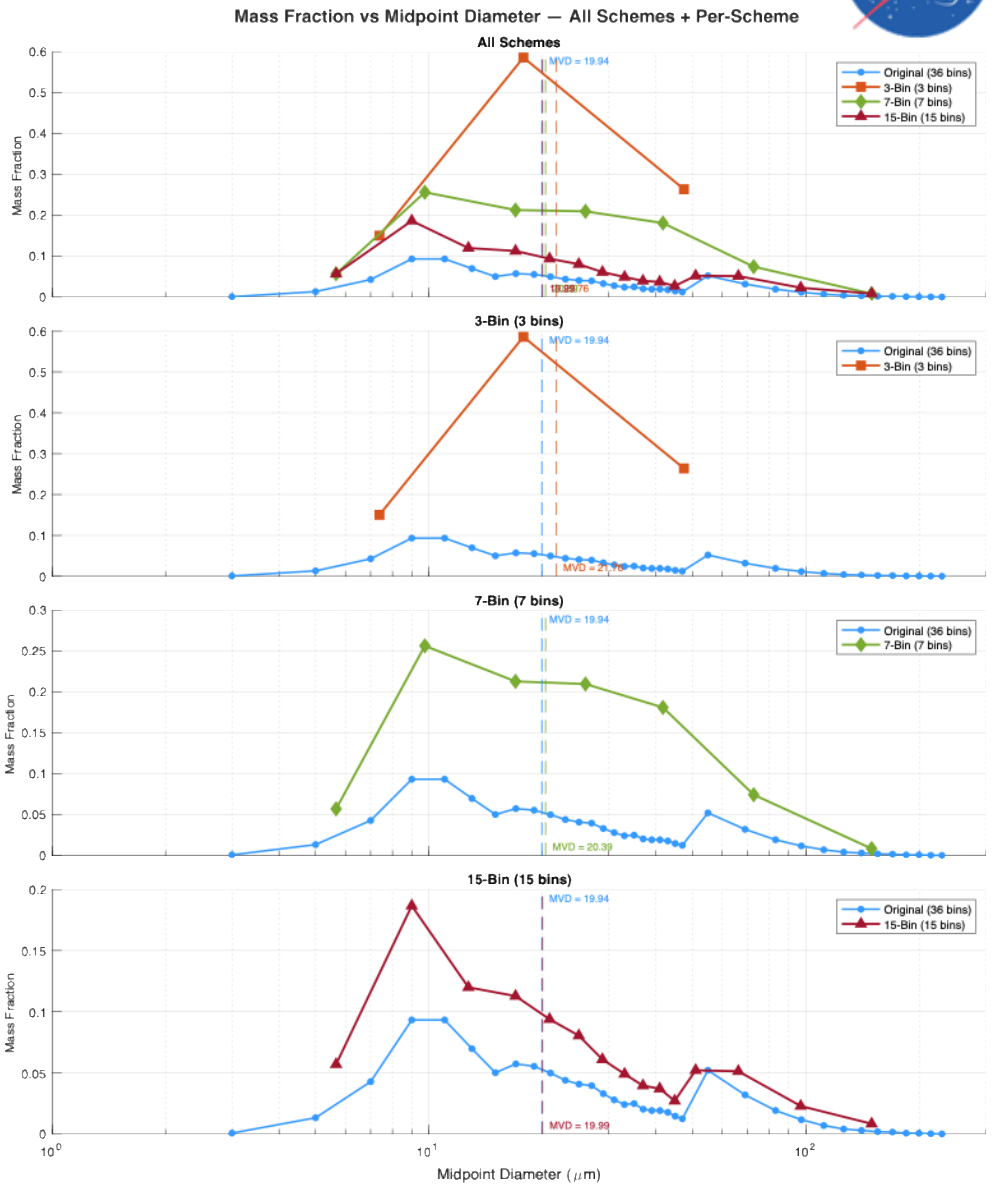


Table Breakdown of Bin Data

3-Bin			
Bin	Diameter [µm]	LWC [g/m^3]	Mass Fraction
1	7.389	0.083	0.150
2	17.801	0.322	0.586
3	47.458	0.145	0.264

7-Bin			
Bin	Diameter [µm]	LWC [g/m^3]	Mass Fraction
1	5.669	0.031	0.057
2	9.748	0.141	0.256
3	16.962	0.117	0.213
4	26.009	0.115	0.210
5	41.750	0.100	0.181
6	72.683	0.041	0.075
7	149.391	0.005	0.008

*Added 0.001 to Bin 6 Mass Fraction to ensure it's equal to 1.00

15-Bin			
Bin	Diameter [µm]	LWC [g/m^3]	Mass Fraction
1	5.669	0.031	0.057
2	9.000	0.103	0.187
3	12.719	0.066	0.120
4	16.966	0.062	0.113
5	20.881	0.052	0.094
6	24.969	0.044	0.081
7	28.848	0.034	0.061
8	33.030	0.027	0.049
9	36.945	0.022	0.040
10	40.929	0.020	0.037
11	44.855	0.015	0.027
12	50.978	0.029	0.052
13	66.175	0.028	0.051
14	96.876	0.013	0.023
15	149.391	0.004	0.008

* Subtracted 0.001 [g/m^3] from Bin 15 LWC to ensure it's equal to 0.55

Included on the workshop website in excel form as IPW3-NACA0012-IRT-Distributions.xlsx

AE3933 Icing Conditions

- M_{ref} = 0.3127
- U_{ref} [m/s] = 102.19
- AOA [deg] = 4
- $T_{s,ref}$ [K] = 265.8
- $T_{0,ref}$ [K] = 271.0
- ρ_{ref} [kg/m^3] = 1.2000
- P_{ref} [Pa] = 91554
- $P_{0,ref}$ [Pa] = 97974
- a_{ref} [m/s] = 326.83
- μ_{ref} [kg/m-sec] = 1.6794E-05
- $Re_{L,ref}$ [/m] = 7.3016E6
- $Re_{c,ref}$ = 3.8947E6
- LWC = 0.55
- MVD = 20μm
- Time = 7 minutes

Setting Tunnel Conditions:

- **Recommended condition to be run if temperature can be changed in your icing code. Assumes changes to impingement are small. Cp agreement should be good.**
- These values should be used to match the test section conditions
- This would be done by sampling upstream to get close to the necessary value for Mach number
- For simplicity, the sampling can be done at: (X, Y, Z) [in] = (-139, 45.58, 0)
- It is recommended that participants try a purely isentropic analysis first and then adjust from there if outside of a +/- 0.5 m/s difference in U_{ref} or +/- 0.01 difference in M_{ref}
- It should be noted that all conditions (Cp, AE3932, AE3933) fall within these uncertainty bounds. It is up to the participants discretion whether they take into account the changes in Reyolds number, Density, and Pressure. Be sure to track temperature changes accordingly.

AE3932 Icing Conditions

- M_{ref} = 0.3151
- U_{ref} [m/s] = 102.31
- AOA [deg] = 4
- $T_{s,ref}$ [K] = 262.305
- $T_{0,ref}$ [K] = 267.51
- ρ_{ref} [kg/m^3] = 1.2119
- P_{ref} [Pa] = 91249
- $P_{0,ref}$ [Pa] = 97750
- a_{ref} [m/s] = 324.67
- μ_{ref} [kg/m-sec] = 1.6618E-05
- $Re_{L,ref}$ [/m] = 7.4607E6
- $Re_{c,ref}$ = 3.9795E6
- LWC = 0.55
- MVD = 20μm
- Time = 7 minutes

Setting Tunnel Conditions:

- These values should be used to match the test section conditions
- This would be done by sampling upstream to get close to the necessary value for Mach number
- For simplicity, the sampling can be done at:
  (X, Y, Z) [in] = (-139, 45.58, 0)
- It is recommended that participants try a purely isentropic analysis first and then adjust from there if outside of a +/- 0.5 m/s difference in U_{ref} or +/- 0.01 difference in M_{ref}
- It should be noted that all conditions (Cp, AE3932, AE3933) fall within these uncertainty bounds. It is up to the participants discretion whether they take into account the changes in Reyolds number, Density, and Pressure. Be sure to track temperature changes accordingly.

Running Cases

- Please record relevant values like C_l, C_d, C_m along with mean flow and turbulent working residuals
  - Please compute these over the entire airfoil (floor to ceiling)
- We will be comparing the convergence of these integrated values, residual convergence, and C_p
- We will compare collection profiles at Y = 36 in along with volume and mass values over the Y = 32 in to Y = 40 in extraction region
- Run the NACA 0012 case with your roughness model of choice turned on for this case
  - This will result in a shift to your impingement behavior which is fine if documented
- Please run with any void fraction/ice density model of your choice – please note it
- Please record icing outputs such as convergence, collection, total collection, total ice mass, total evaporation, ice shape, etc.
- Which tunnel condition you use is up to you.
  - If you do not believe the tunnel temperature to be independent of your droplet solution, run each at the different tunnel conditions.
  - If you are okay with this assumption, then move forward with running the AE3933 condition for everything
- Run each drop size distribution for each grid level
  - If you have time issues, please start with the 15-bin
- The C_p, C_l, C_d, and C_m data can be provided for any of the tunnel conditions run
- This is more like a typical IPW case, just with multiple grid levels

Verification Test Case

TEST CASE 2 – IN-FLIGHT ONERA-M6

CFD Conditions

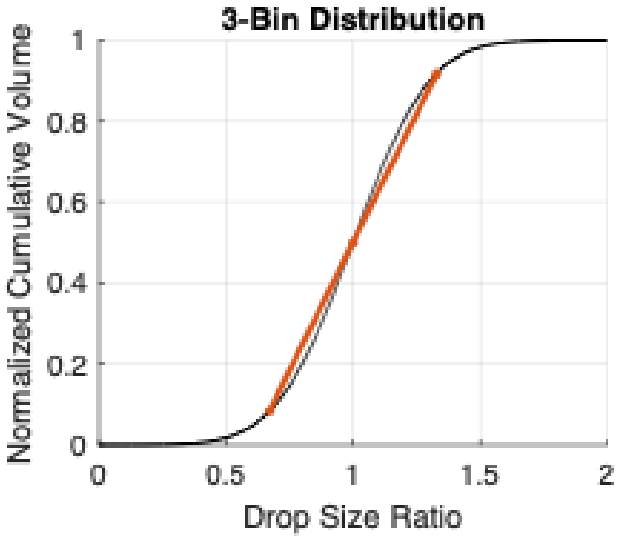
- M_∞ = 0.40
- U_∞ [m/s] = 131.064
- AOA [deg] = 2
- $T_{s,\infty}$ [K] = 267.15
- $T_{0,\infty}$ [K] = 275.7
- ρ_∞ [kg/m^3] = 0.68301
- P_∞ [Pa] = 52377.824
- a_∞ [m/s] = 327.66
- μ_∞ [kg/m-sec] = 1.68626E-05
- Re_L [/m] = 5.3087E6
- Re_c = 4.2558E6

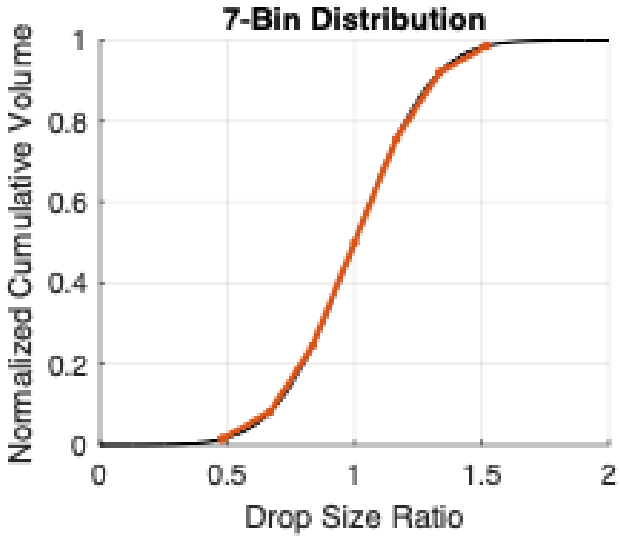
Geometry Properties from Grid Construction

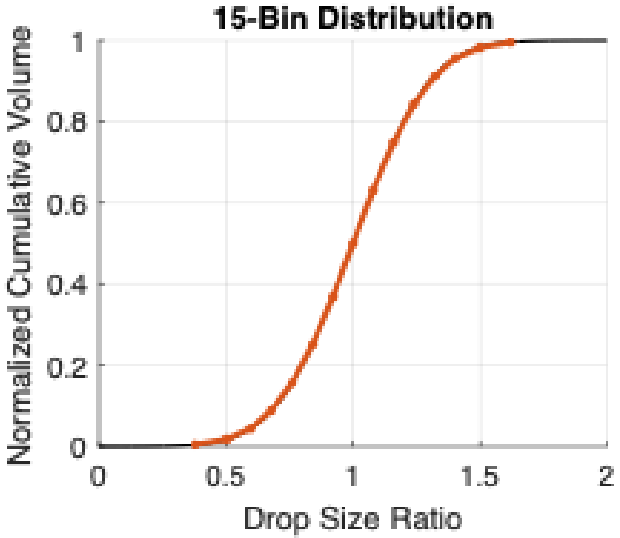
- Root chord = 1.00000 m
- Semi span = 1.476018 m
- Reference area = 1.1532 m^2
- Aspect ratio (span^2/area) = 3.778567
- Mean aerodynamic chord (M.A.C.) = 0.801673 m
- X, Y, Z moment center [m] = 0.25m, 0, 0

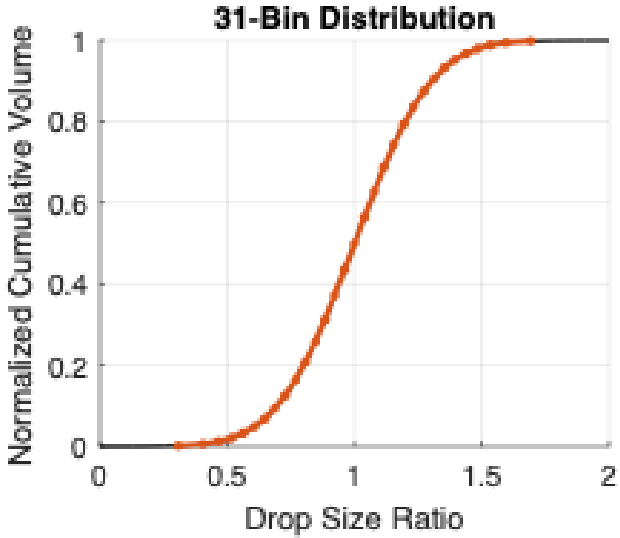
- Use these for any non-dimensionalization of integrated properties

Drop Size Ratio Compared to Ideal Continuous

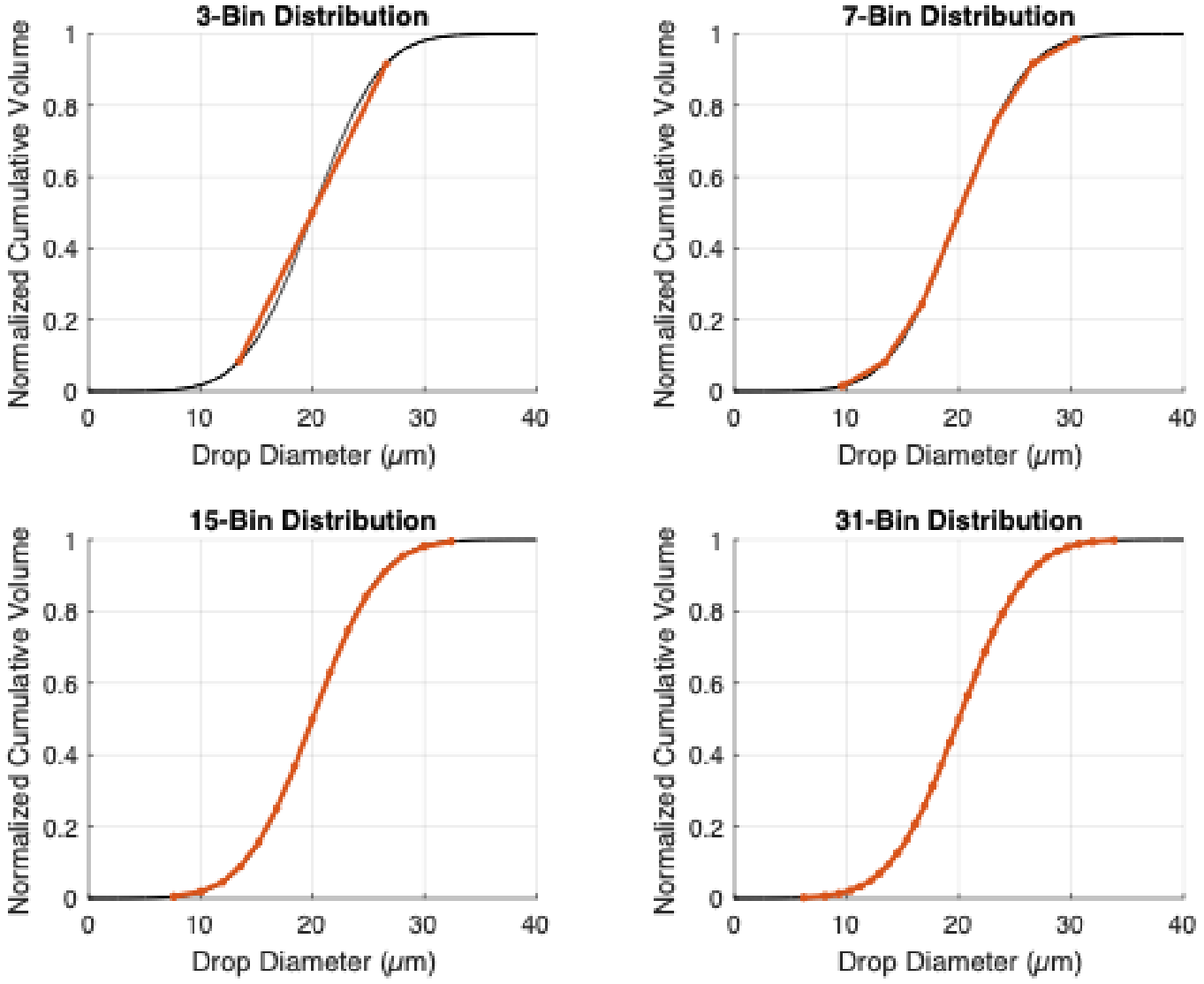




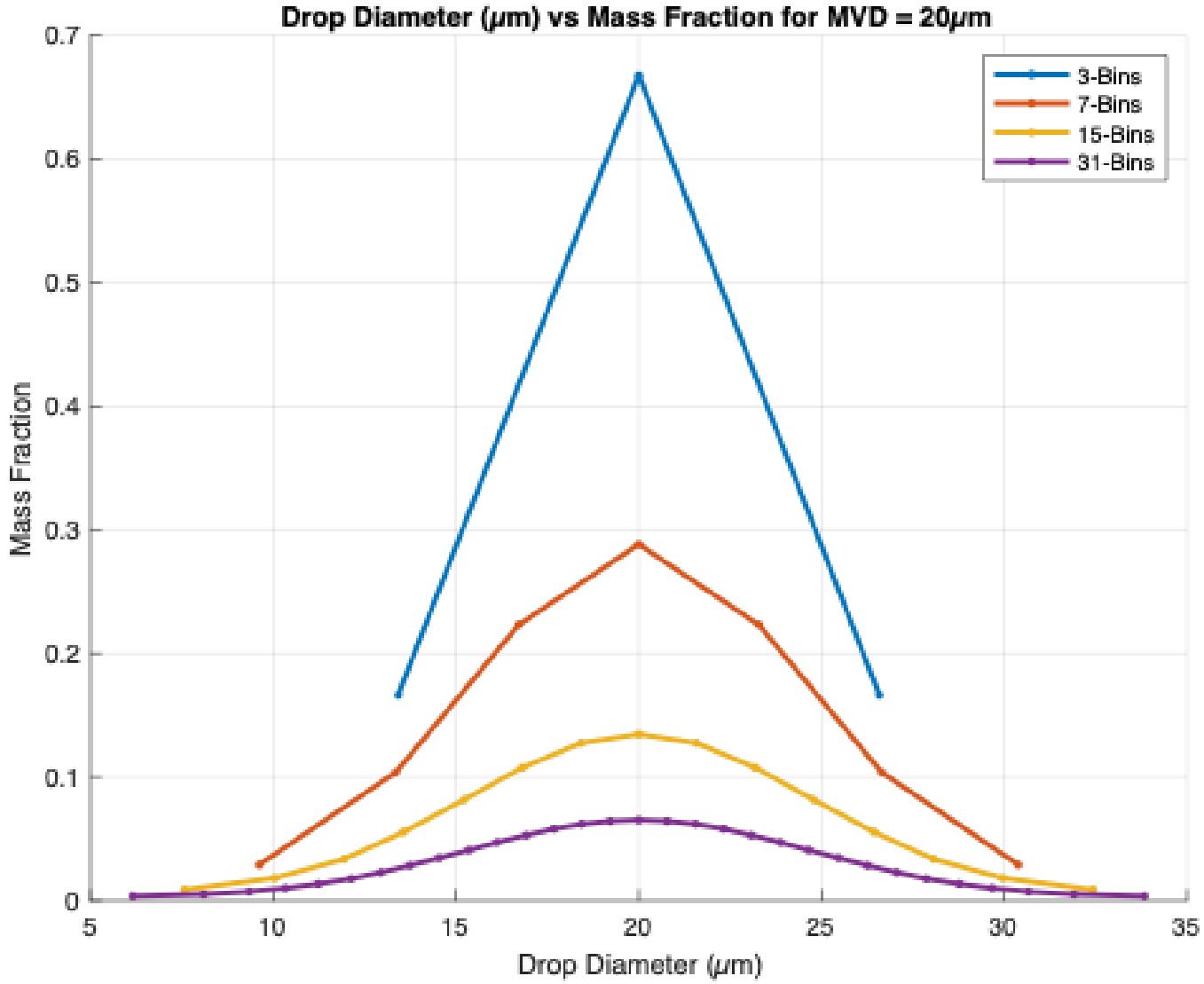




MVD = 20μm Drop Size Distributions Compared to Ideal Continuous



MVD = 20μm Drop Size vs Mass Fraction



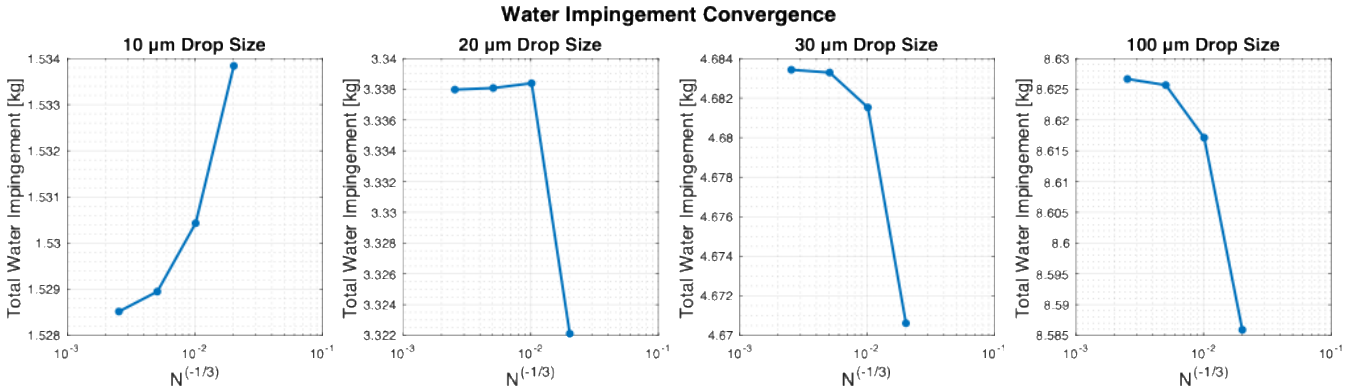
Icing Conditions

MVD (μm): 20

For completeness only. Do Not Run.

1-Bin				3-Bin				7-Bin				15-Bin				31-Bin			
Mass fraction	LWC (g/m^3)	Diameter Ratio	Diameter	Mass fraction	LWC (g/m^3)	Diameter Ratio	Diameter (μm)	Mass fraction	LWC (g/m^3)	Diameter Ratio	Diameter (μm)	Mass fraction	LWC (g/m^3)	Diameter Ratio	Diameter (μm)	Mass fraction	LWC (g/m^3)	Diameter Ratio	Diameter (μm)
1.0000	0.5100	1.0000	20.0000	0.1663	0.0848	0.6710	13.4200	0.0290	0.0148	0.4810	9.6200	0.0088	0.0045	0.3790	7.5800	0.0035	0.0018	0.3080	6.1600
				0.6674	0.3404	1.0000	20.0000	0.1039	0.0530	0.6680	13.3600	0.0182	0.0093	0.5020	10.0400	0.0051	0.0026	0.4050	8.1000
				0.1663	0.0848	1.3290	26.5800	0.2232	0.1138	0.8360	16.7200	0.0336	0.0171	0.5970	11.9400	0.0072	0.0037	0.4670	9.3400
								0.2882	0.1470	1.0000	20.0000	0.0553	0.0282	0.6780	13.5600	0.0100	0.0051	0.5170	10.3400
								0.2232	0.1138	1.1640	23.2800	0.0816	0.0416	0.7610	15.2200	0.0135	0.0069	0.5620	11.2400
								0.1039	0.0530	1.3320	26.6400	0.1077	0.0549	0.8410	16.8200	0.0178	0.0091	0.6070	12.1400
								0.0290	0.0148	1.5190	30.3800	0.1274	0.0650	0.9210	18.4200	0.0228	0.0116	0.6470	12.9400
												0.1345	0.0686	1.0000	20.0000	0.0284	0.0145	0.6870	13.7400
												0.1274	0.0650	1.0790	21.5800	0.0345	0.0176	0.7270	14.5400
												0.1077	0.0549	1.1590	23.1800	0.0409	0.0208	0.7680	15.3600
												0.0816	0.0416	1.2390	24.7800	0.0471	0.0240	0.8060	16.1200
												0.0553	0.0282	1.3220	26.4400	0.0528	0.0269	0.8460	16.9200
												0.0336	0.0171	1.4030	28.0600	0.0581	0.0296	0.8840	17.6800
												0.0182	0.0093	1.4980	29.9600	0.0619	0.0315	0.9220	18.4400
												0.0088	0.0045	1.6210	32.4200	0.0643	0.0328	0.9610	19.2200
																0.0652	0.0332	1.0000	20.0000
																0.0643	0.0328	1.0390	20.7800
																0.0619	0.0315	1.0780	21.5600
																0.0581	0.0296	1.1160	22.3200
																0.0528	0.0269	1.1540	23.0800
																0.0471	0.0240	1.1940	23.8800
																0.0409	0.0208	1.2320	24.6400
																0.0345	0.0176	1.2730	25.4600
																0.0284	0.0145	1.3130	26.2600
																0.0228	0.0116	1.3530	27.0600
																0.0178	0.0091	1.3930	27.8600
																0.0135	0.0069	1.4380	28.7600
																0.0100	0.0051	1.4830	29.6600
																0.0072	0.0037	1.5330	30.6600
																0.0051	0.0026	1.5950	31.9000
																0.0035	0.0018	1.6920	33.8400

Example plots of the convergence we are going after:

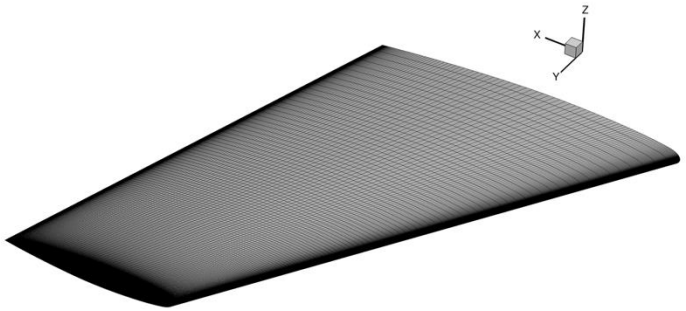


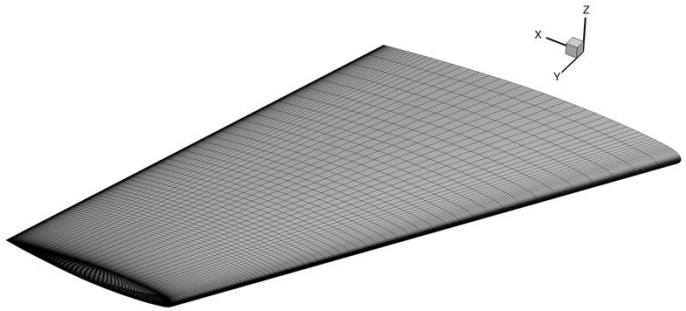
Icing Temperature (T_S) = 267.15K
Accretion Time (t) = 1350 s
LWC (g/m^3) = 0.51
MVD = 20μm
Ice Density = 680 kg/m^3

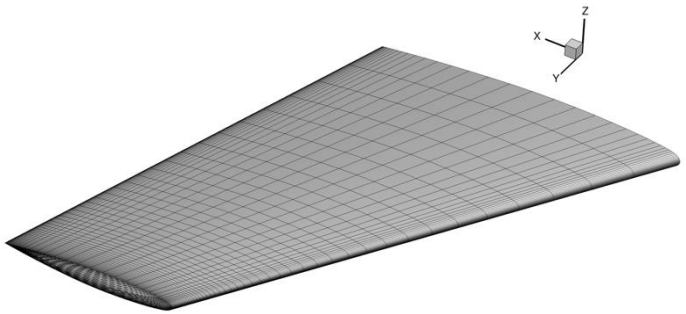
- Utilizing the 1-Bin, 3-Bin, 7-Bin, and 15-Bin distributions only for IPW-3
- The 31-Bin distribution was included for completeness

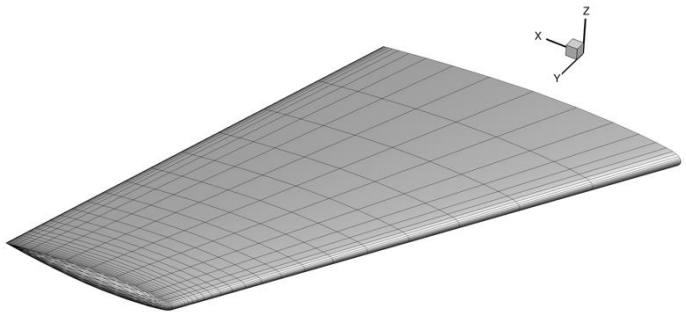
Grid Levels

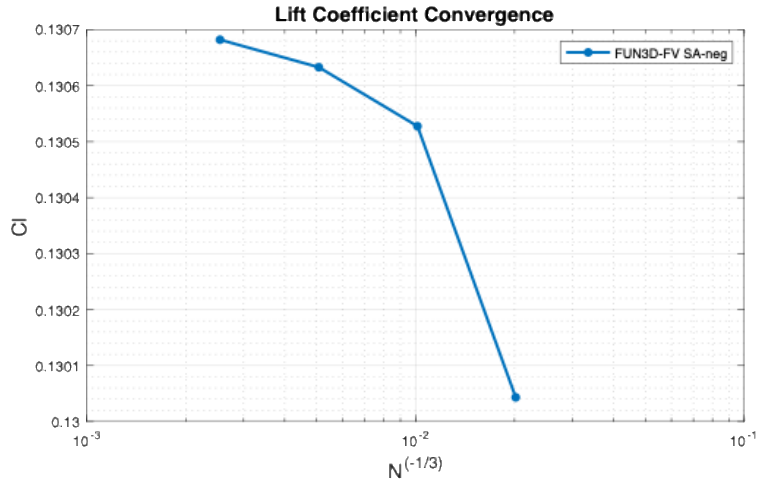
Level	1	2	3	4
Nodes	60,777,345	7,625,153	960,225	121,841

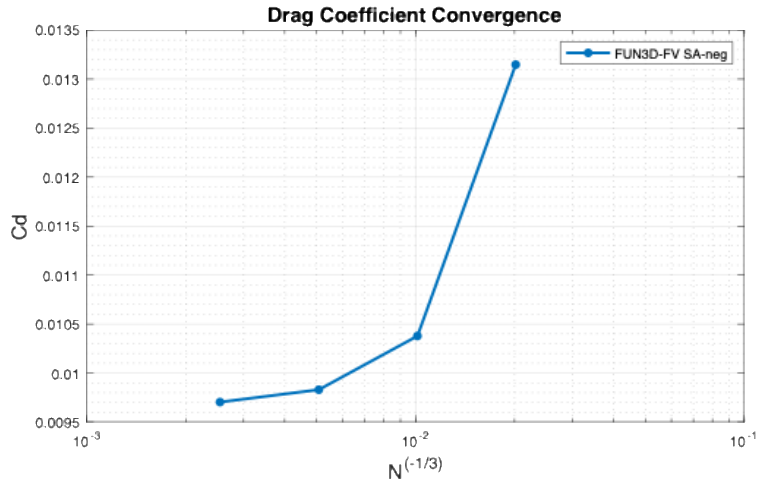












Boundary Conditions

Boundary 1:

- Name: Wing
- Type: Fully Viscous Wall
- Conditions: u, v, w (wall) = 0.0 m/s, explicitly set a no-slip condition

Boundary 2:

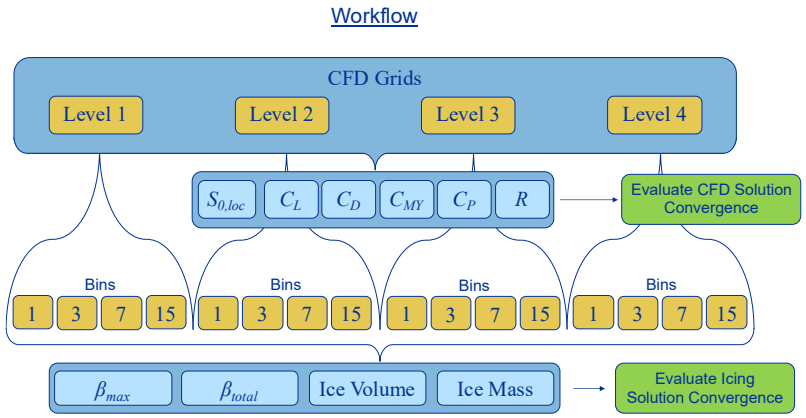
- Name: Symmetry
- Type: Y-Symmetry Plane
- Conditions: Enforce symmetry for *y* Cartesian plane

Boundary 3:

- Name: Farfield
- Type: a) Farfield or b) Freestream
- Conditions: a) Riemann invariants or b) External freestream specified by fluxes

Running Cases

- Please set up your cases using the values/conditions provided
- Please record relevant values like C_l, C_d, C_m along with mean flow and turbulent working residuals
  - Using the 1.0 mm roughness as the baseline condition, not smooth
- We will be comparing the convergence of these integrated values, residual convergence, and C_p
- Please record icing outputs such as convergence, collection, total collection, total ice mass, total evaporation, ice shape, etc.
  - **Perform simulations for all bins over all grid levels**
- Please use a rough-wall turbulence model with a dimensional value of 1.0 mm as the baseline setup on the entire surface
  - If you have the capability, attempt a value of 0.5 mm and 1.5 mm on the entire surface for parametric evaluation of HTC augmentation
    - Perform this only for the 7-bin cases across all grid levels
  - If you can run a smooth and rough wall for evaluating aerodynamic properties, that would be valuable, but not needed
  - If you have the capability, record your computed/predicted roughness value on the surface
    - Perform this only for the 7-bin cases across all grid levels
- Please use an ice density of 680 kg/m^3



Conclusions

- Generating baseline verification cases that can be used by the larger community of practice
- Showing convergence of the solutions can lead to more informed conclusions on impactful inputs and outputs
- Develop a process for demonstrating convergence of icing solutions that can inform best practices

QUESTIONS?