Bimodal SLD Ice Accretion on a NACA 0012 Airfoil Model

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Outline

- Objectives
- Approach
- Background
  - Facility
  - Cloud Conditions
  - Model
  - Test Procedures
  - Test Matrix
- Results
- Concluding Remarks
- Acknowledgements

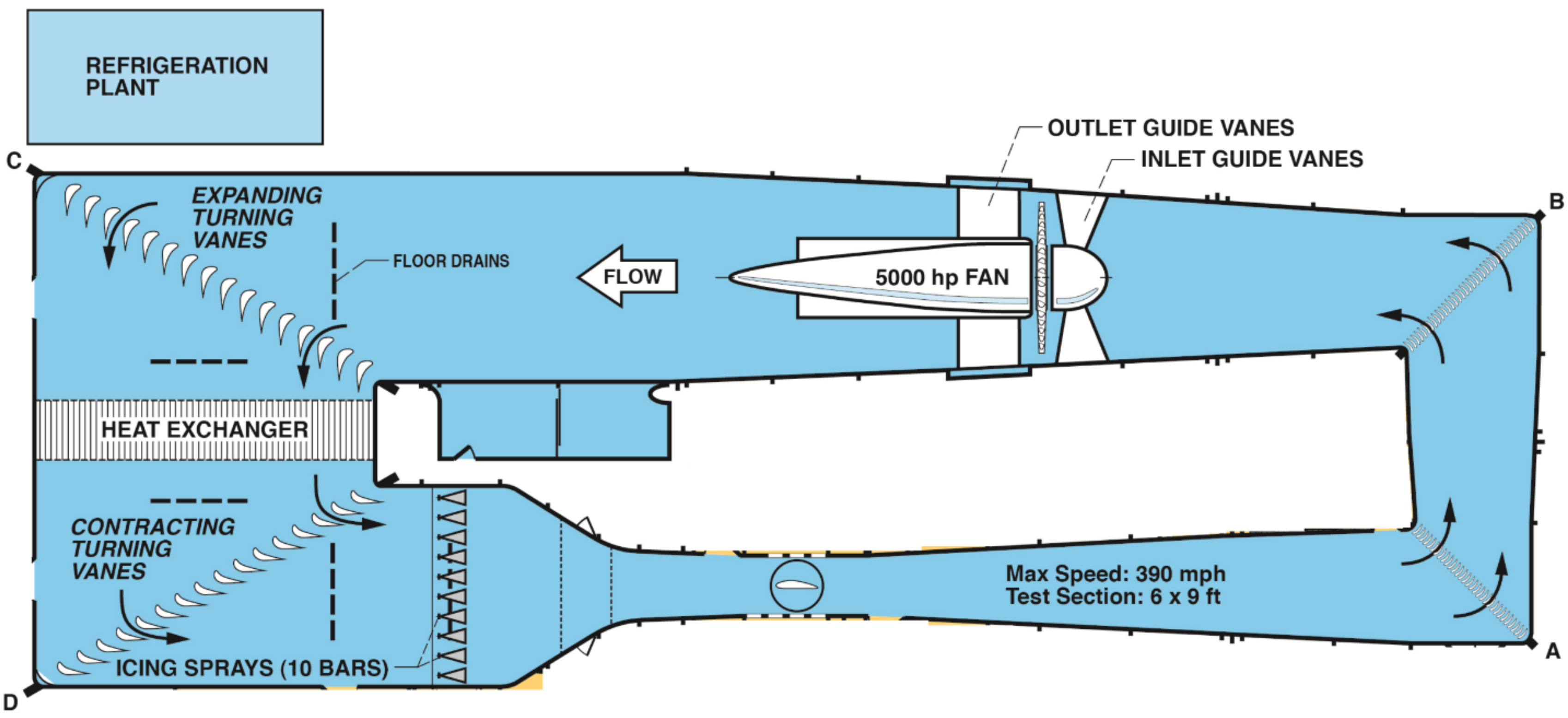
Objectives

1. Document the Ice Shapes Produced using the IRT Bimodal Spray Conditions
2. Compare with Ice Shapes Produced using the Single Nozzle Array (Monomodal) for Equivalent Cloud Conditions
   - Use previously produced ice shapes as reference conditions

Approach

1. Evaluate the IRT Bimodal Spray Ice Shapes
   - At 130, 150, 200 & 250 knots
   - At $\alpha = 0^{\circ}, 4^{\circ}$
2. Compare with Monomodal Spray Ice Shapes at
   - 2 Ice Shape Repeatability Conditions
   - 2 Ice Shape Condition from Scaling Work

NASA Icing Research Tunnel



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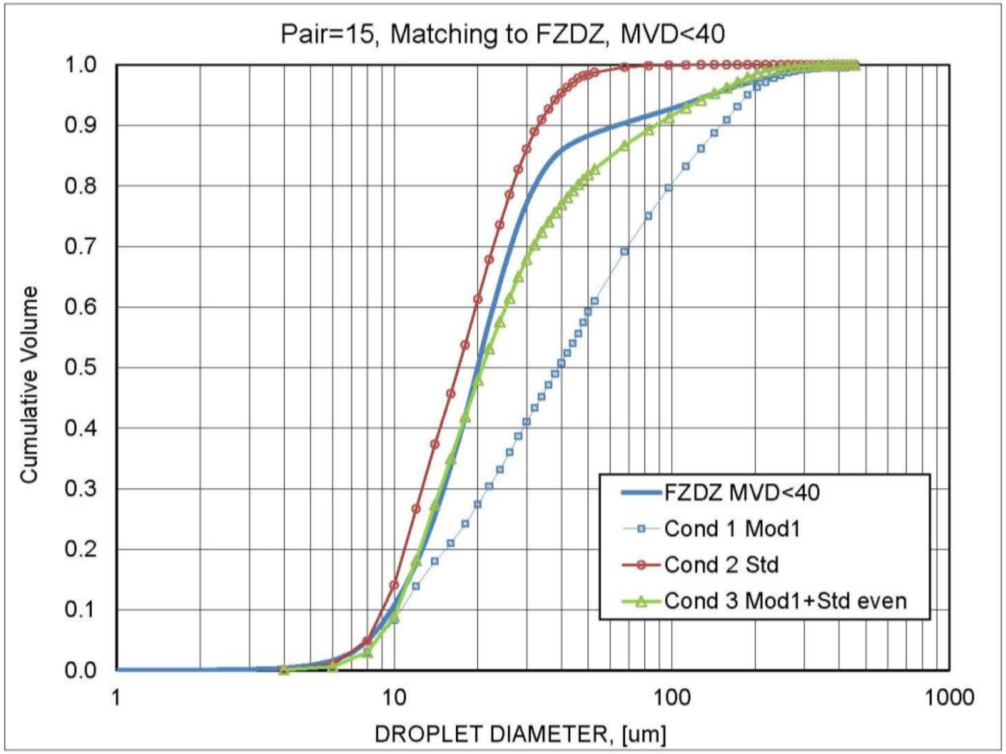
2016 IRT Bimodal Spray



Pair = 15 psig

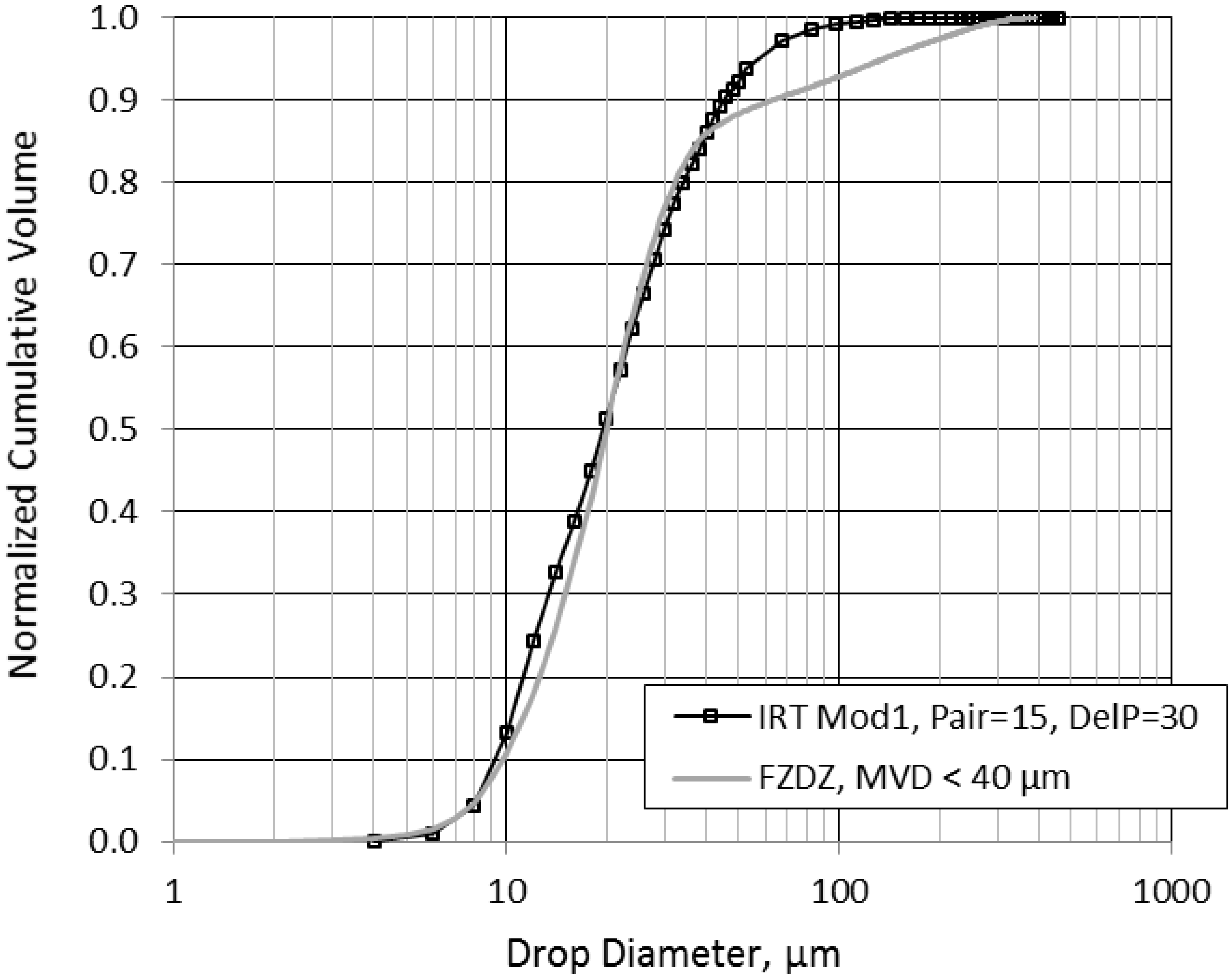
- Man1 (Mod1) deltaP = 80 psid
  - MVD = 39.2 um
  - minLWC (@250 kts)* = 0.67 g/m^3
- Man2 (Std) deltaP = 7 psid
  - MVD = 17.1 um
  - minLWC (@250 kts)*= 0.78 g/m^3
- Combined:
  - MVD = 20.8 um
  - minLWC (@250 kts)* = 1.45 g/m^3

- How good of a match is it to FZDZ, MVD<40?
  - The normalized cumulative LWC in each of the measured bins was within 10% of what the normalized cumulative LWC is for FZDZ, MVD<40 (for each corresponding bin)

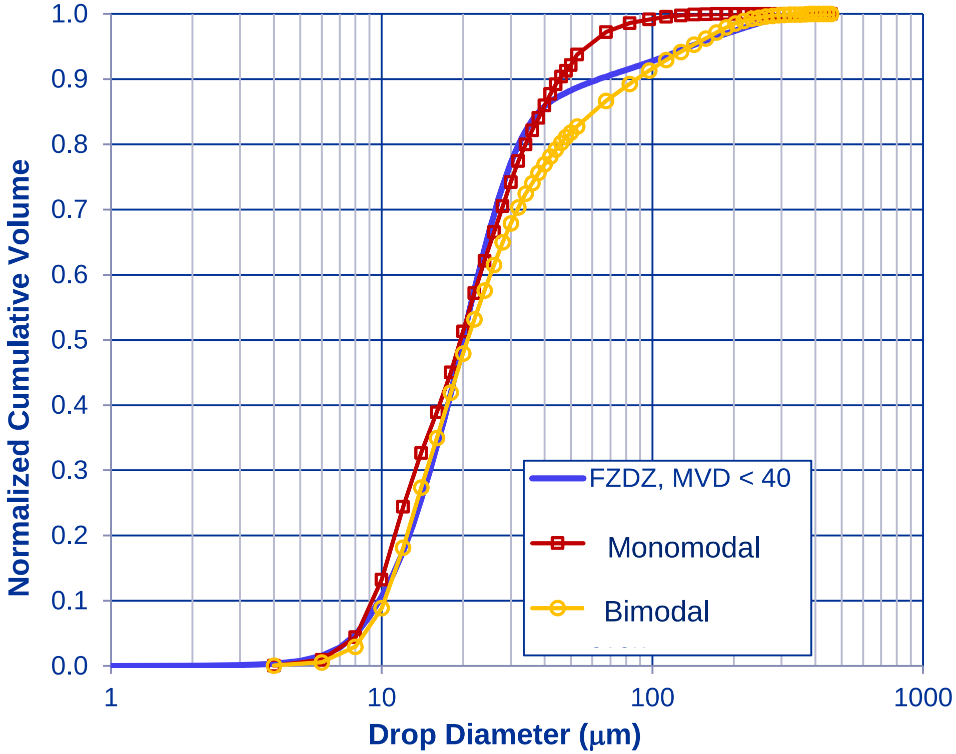
*LWC values based on IRT LWC calibration curves

Selected IRT Mod1 Spray Condition

Monomodal Distribution



2016 IRT Bimodal & Monomodal Distributions



- FZDZ, MVD<40
  - FAA App O distribution
  - MVD=20 µm
  - LWC between 0.29 and 0.44 g/m^3
- Bimodal
  - Mod1 + Std nozzles
  - Pair = 15 psig
  - Mod1 DeltaP = 80 psid
  - Standard DeltaP = 7 psid
  - Combined MVD = 20.8 µm
  - Combined minLWC (@250 kts) = 1.45 g/m^3
- Monomodal
  - Mod1 nozzles
  - Pair=15 psig
  - DelP=30 psid
  - MVD=19.3 µm
  - minLWC (@250 kts) = 0.37 g/m^3

- Both IRT distributions were measured by spraying only even-numbered spray bars, as is typical for drop-sizing calibrations in Appendix C conditions in order to avoid coincidence error
- LWC values are based on IRT calibration curves

Test Model

21-in chord NACA 0012 model, full span

Test Procedures

- The tunnel temperature and velocity conditions were set.
- The spray bar air and water pressures were set.
- The tunnel was run at the set temperature and velocity conditions and the thermocouples on the model were monitored.
- When the model temperature matched the tunnel static air temperature, the model was considered to be sufficiently cold to initiate the spray.
- The spray was initiated and lasted for the prescribed time for the icing condition of that run.
- After the spray was stopped and the tunnel velocity was reduced to idle conditions, personnel entered the test section and performed the following tasks.
- Photographs of the ice on the model were taken from several pre-set locations around the model.
- A laser scanner system was used to obtain geometric data of the ice shape using the method described by Lee, et al.*
- Once the ice shapes were scanned, a 12 inch spanwise section of the ice shape was removed from the surface into a collection tray and weighed in order to obtain the accumulated mass.
- Following the removal of the mass, the model surface was cleaned of all remaining ice and prepared for the next test run.

*Lee, S., Broeren, A.P., Kreeger, R.E., Potapczuk, M., and Utt, L., "Implementation and Validation of 3-D Ice Accretion Measurement Methodology," AIAA 6th Atmospheric and Space Environments Conference, Atlanta, GA, June 16-20, 2014, AIAA Paper 2014-2613.

Test Matrix

5 proposed reference conditions

Test Conditions									
Case	Reference Condition	α	V (kts)	MVD (mm)	LWC (g/m^3)	T_t (°C)	T_s (°C)	Time (min)	n_0
Ice Shape Repeatability Run 3	1	4	200	20	0.55	-5.6	-10.8	7	0.52
Ice Shape Repeatability Run 23	2	4	130	22	1	-5.6	-7.8	6	0.34
5-15-06/Run 14	3	0	150	30	1.34	-12.5	-15.5	5.5	0.49
5-15-06/Run 15	4	0	100	30	1.75	-13.5	-14.8	6.7	0.5
3-28-05/Run 6	5	0	250	26.8	0.56	-5.2	-13.4	8.5	0.46

Note: For scaling, two selected spray clouds are considered

Test Matrix

Monomodal and bimodal test conditions based upon scaling of reference conditions.

Run #	Reference Condition	α	V (kts)	MVD (mm)	LWC (g/m^3)	T_t (°C)	T_s (°C)	Time (min)	n_0	*Mod-1* *p_{air}*, psig	*Mod-1* *Dp*, psid	*Std* *p_{air}*, psig	*Std* *Dp*, psid
AE2716	5.b	0	250	19.3	0.37	-2.3	-10.5	14	0.46	15	30		
AE2717	2.b	4	130	19.3	0.55	-2.8	-5	11.5	0.34	15	30		
AE2718	1.b	4	200	19.3	0.42	-3.9	-9.2	9.3	0.52	15	30		
AE2719	2.a	4	130	20.8	2.15	-9.9	-12.1	2.9	0.34	15	80	15	7
AE2720	5.a	0	250	20.8	1.45	-11.9	-20.2	3.5	0.46	15	80	15	7
AE2721	1.a	4	200	20.8	1.64	-15.2	-20.5	2.3	0.52	15	80	15	7
AE2738	5.b	0	250	19.3	0.37	-2.3	-10.5	14	0.46	15	30		
AE2739	2.b	4	130	19.3	0.55	-2.8	-5	11.5	0.34	15	30		
AE2740	3.b	0	150	19.3	0.5	-4.2	-7.2	17	0.49	15	30		
AE2741	2.a	4	130	20.8	2.15	-9.9	-12.1	2.9	0.34	15	80	15	7
AE2742	3.a	0	150	20.8	1.96	-14.9	-17.9	4.2	0.49	15	80	15	7

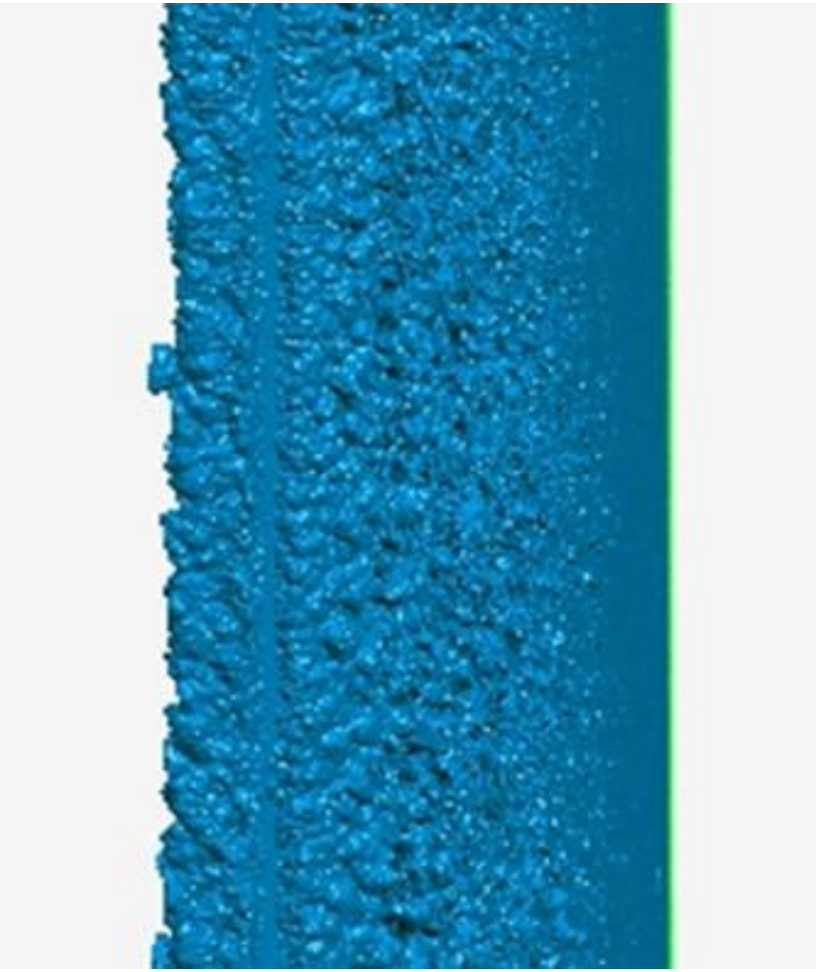
Note: a - Bimodal spray; b - Monomodal spray

Olsen Method for Scaling LWC

1. $c_s = c_r$
2. $V_s = V_r$
3. $MVD_s = MVD_r$
4. Choose a LWC_s
5. Calculate the scale temperature $T_{st,s}$ from $n_{0,s} = n_{0,r}$
6. Calculate the scale total temperature, $T_{tot,s}$. If $T_{tot,s}$ is greater than -2˚C, repeat steps 4, 5, and 6 with a larger LWC_s
7. Calculate the scale accretion time from $A_{c,s} = A_{c,r}$, which leads to $t_s = (LWC_r \times t_r)/LWC_s$

Sample Photograph and Scan

Test Run #AE2741



Test Results

Quantitative Data

Mass and volume measurements for the ice shapes resulting from the scaled monomodal and bimodal distribution icing conditions from this test program.

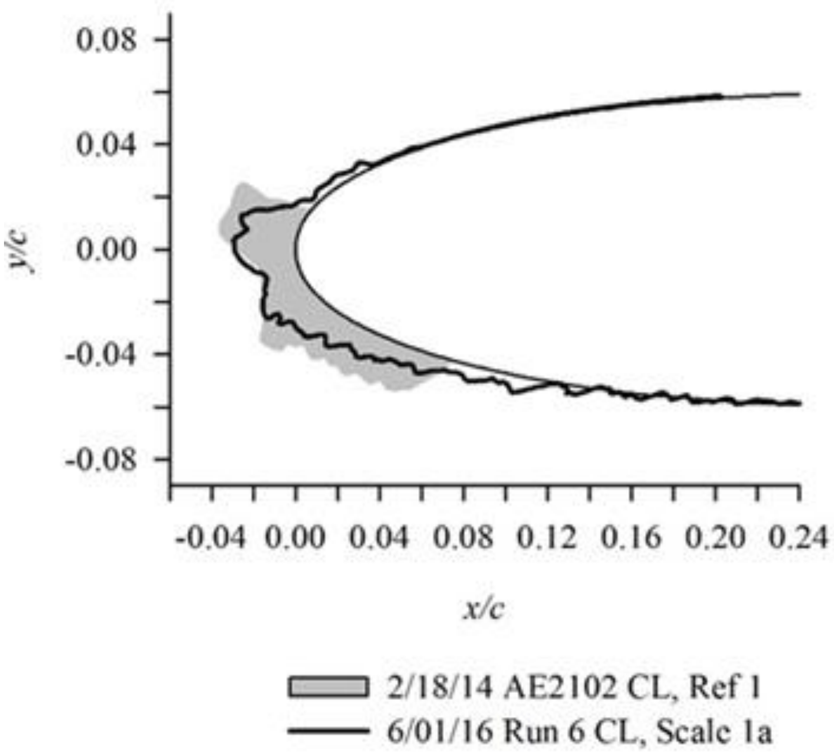
Test Results

Reference Condition	Mass bimodal (g)	Mass monomodal (g)	Δm_i (g)	Δm_i %	Volume bimodal in^3	Volume monomodal in^3	ΔVol. in^3	ΔVol. %	$\rho_{eff,b}$ g/in^3	$\rho_{eff,m}$ g/in^3	$\Delta\rho_{eff}$ %
1	163.1	131.2	31.9	24%	13.67	12.39	1.28	10.3%	11.9	10.6	12.7%
2	151.9	137.9	14	10%	14.3	11.28	3.02	26.8%	10.6	12.2	-13.1%
3	207.1	188	19.1	10%	18.46	15.49	2.97	19.2%	11.2	12.1	-7.6%
5	228.5	157.8	70.7	45%	19.52	13.56	5.96	44.0%	11.7	11.6	0.6%

Note: Density of ice at 0˚C is 0.9167 g/cm^3 = 15.02 g/in^3

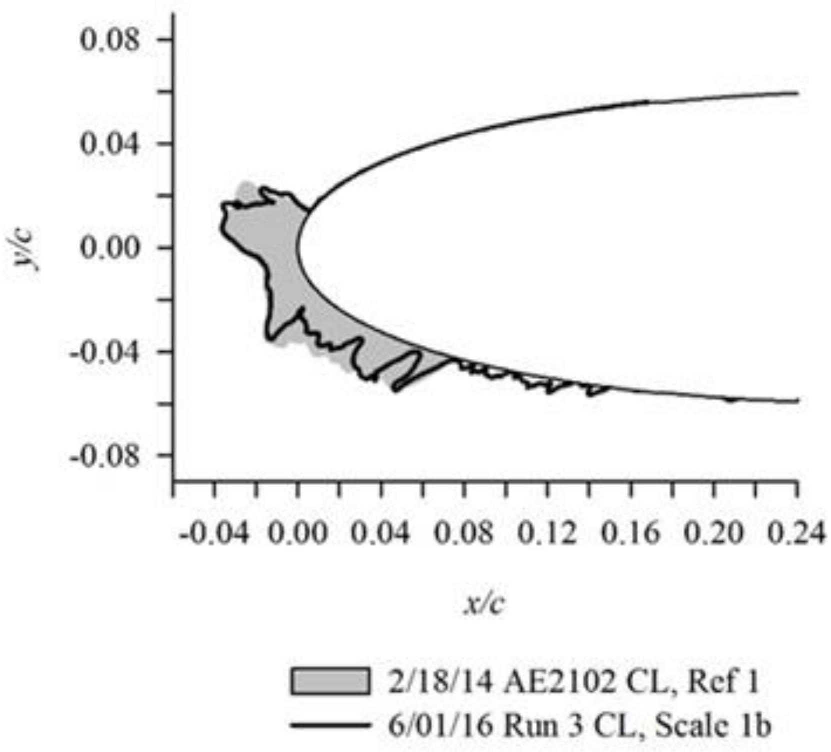
Ice Shape Comparisons to Reference Shapes

Reference Condition 1, V= 200 knots



MVD_1 = 20 μm, LWC_1 = 0.55 g/m^3, t_1 = 7 min
MVD_{1a} = 20.8 μm, LWC_{1a} = 1.64 g/m^3, t_{1a} = 2.3 min

Bimodal Distribution (a)

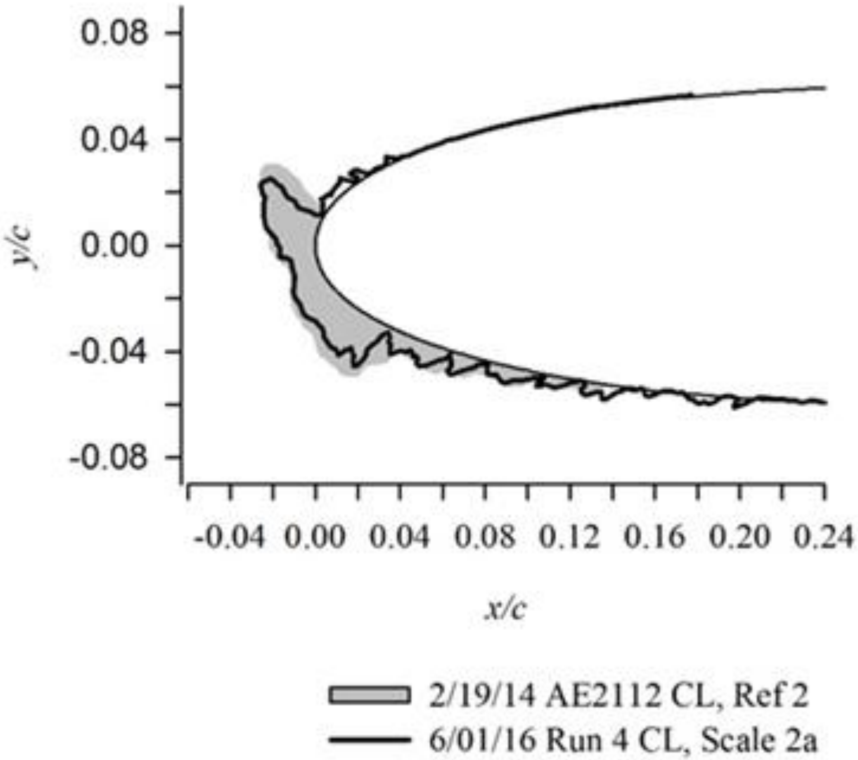


MVD_1 = 20 μm, LWC_1 = 0.55 g/m^3, t_1 = 7 min
MVD_{1b} = 19.3 μm, LWC_{1b} = 0.42 g/m^3, t_{1b} = 9.3 min

Monomodal Distribution (b)

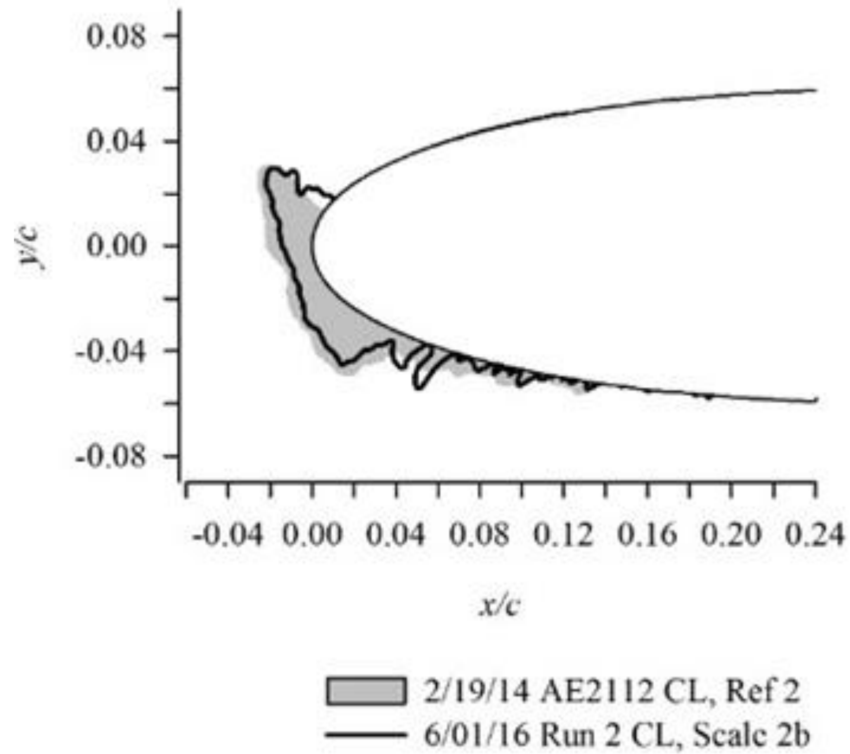
Ice Shape Comparisons to Reference Shapes

Reference Condition 2, V = 130 knots



MVD_2 = 22 μm, LWC_2 = 1.00 g/m^3, t_2 = 6 min
MVD_{2a} = 20.8 μm, LWC_{2a} = 2.15 g/m^3, t_{2a} = 2.9 min

Bimodal Distribution (a)

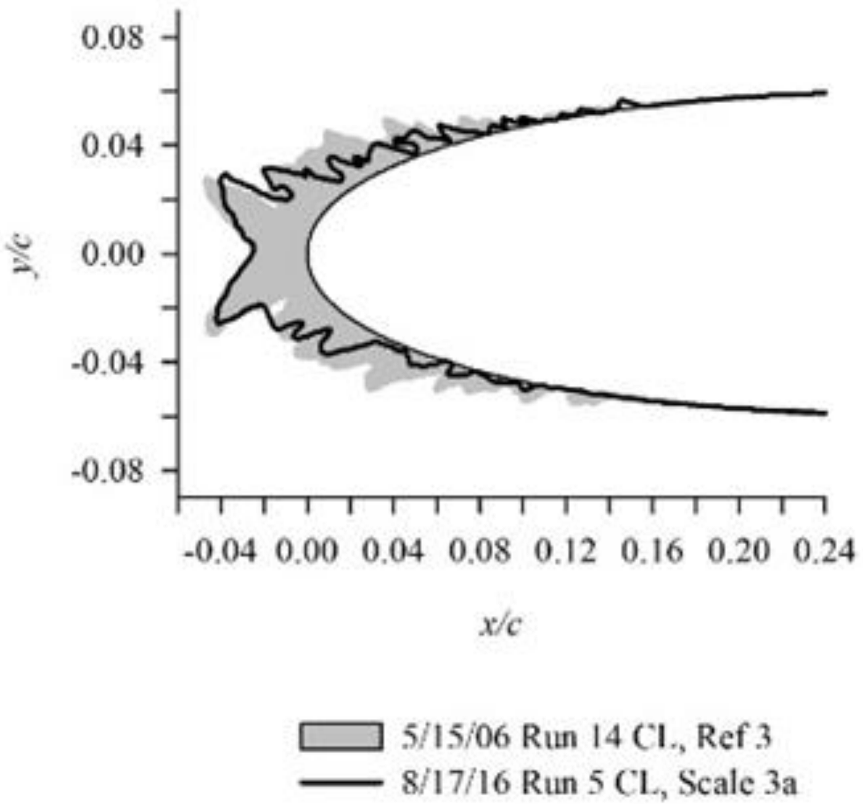


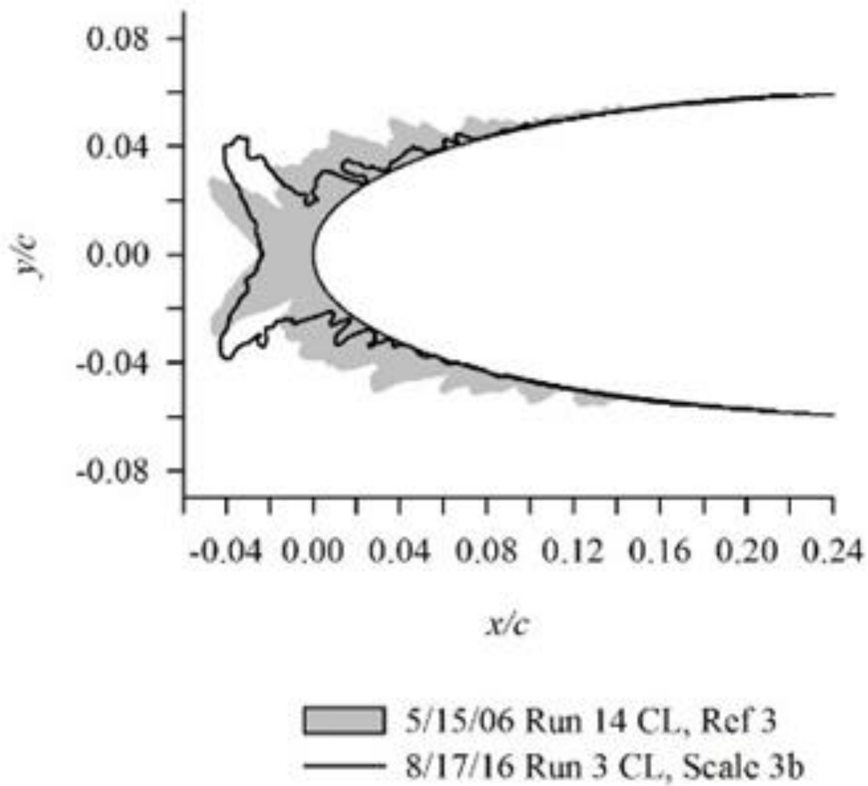
MVD_2 = 22 μm, LWC_2 = 1.00 g/m^3, t_2 = 6 min
MVD_{2b} = 19.3 μm, LWC_{2b} = 0.55 g/m^3, t_{2b} = 11.5 min

Monomodal Distribution (b)

Ice Shape Comparisons to Reference Shapes

Reference Condition 3, V = 150 knots





MVD_3 = 30 μm, LWC_3 = 1.34 g/m^3, t_3 = 5.5 min
MVD_{3a} = 20.8 μm, LWC_{3a} = 1.96 g/m^3, t_{3a} = 4.2 min

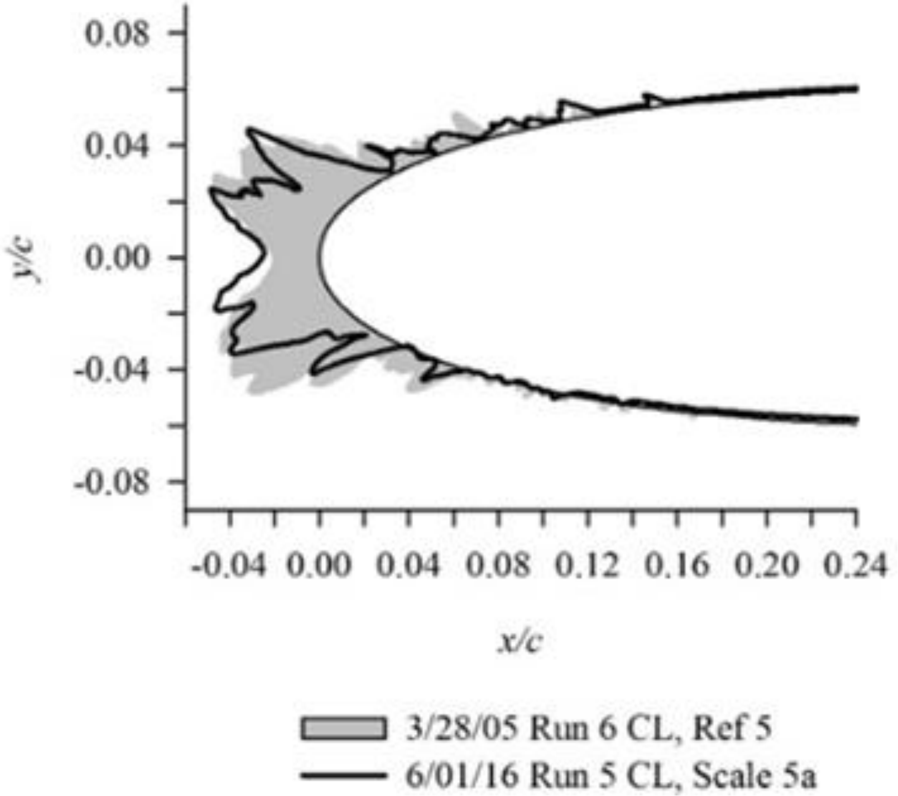
Bimodal Distribution (a)

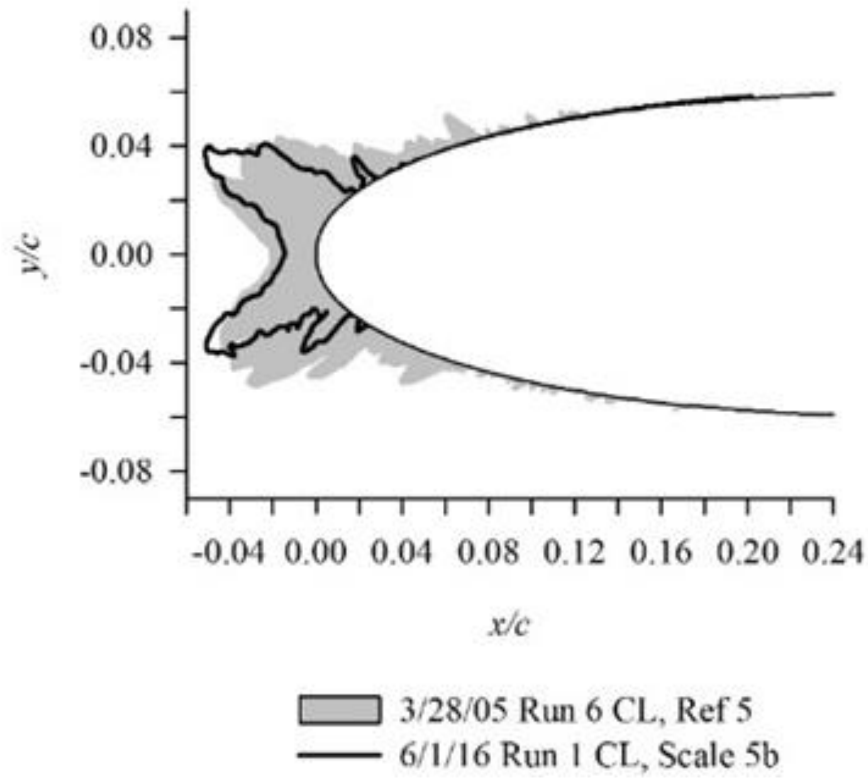
MVD_3 = 30 μm, LWC_3 = 1.34 g/m^3, t_3 = 5.5 min
MVD_{3b} = 19.3 μm, LWC_{3b} = 0.5 g/m^3, t_{3b} = 17 min

Monomodal Distribution (b)

Ice Shape Comparisons to Reference Shapes

Reference Condition 5, V = 250 knots





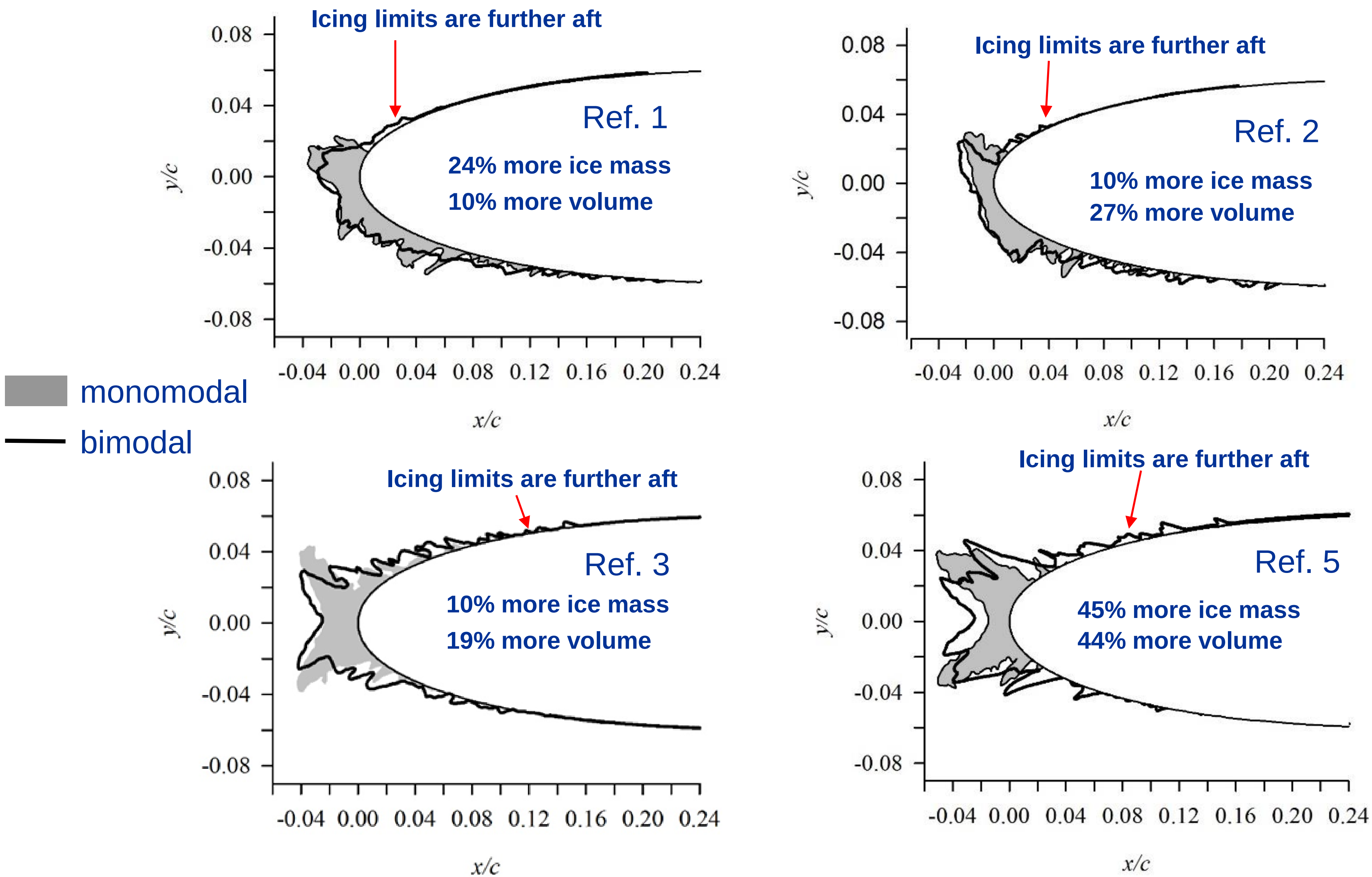
MVD_5 = 26.8 μm, LWC_5 = 0.56 g/m^3, t_5 = 8.5 min
MVD_{5a} = 20.8 μm, LWC_{5a} = 1.45 g/m^3, t_{5a} = 3.5 min

Bimodal Distribution (a)

MVD_5 = 26.8 μm, LWC_5 = 0.56 g/m^3, t_5 = 8.5 min
MVD_{5b} = 19.3 μm, LWC_{5b} = 0.37 g/m^3, t_{5b} = 14 min

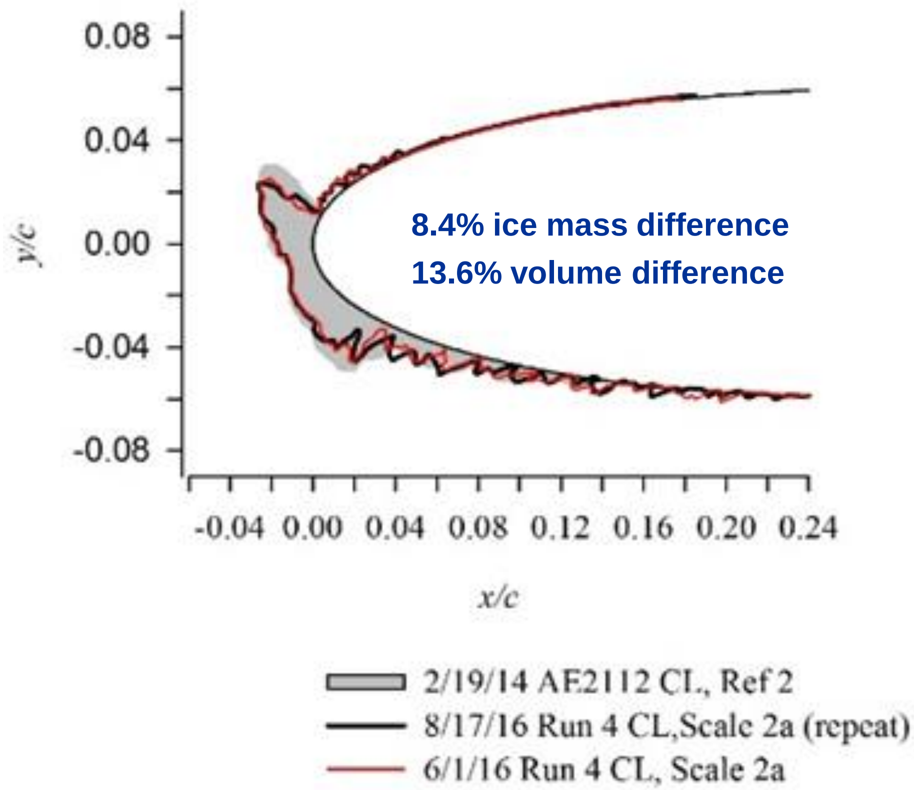
Monomodal Distribution (b)

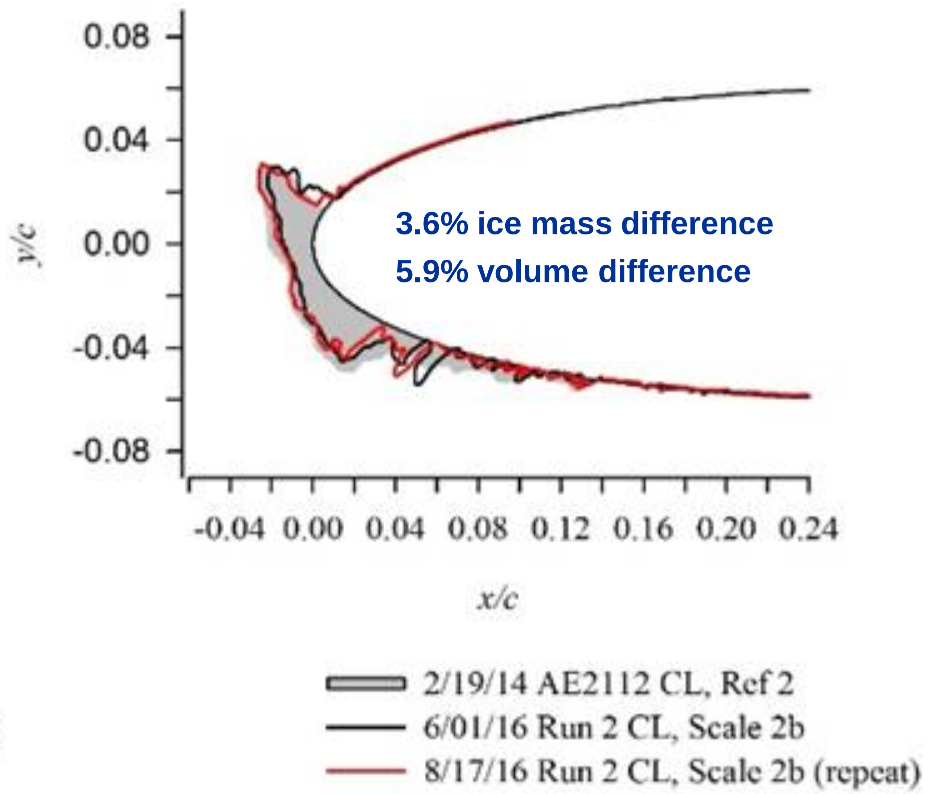
Bimodal Cloud Effects on Ice Shapes



Ice Shape Repeatability

Reference Condition 2

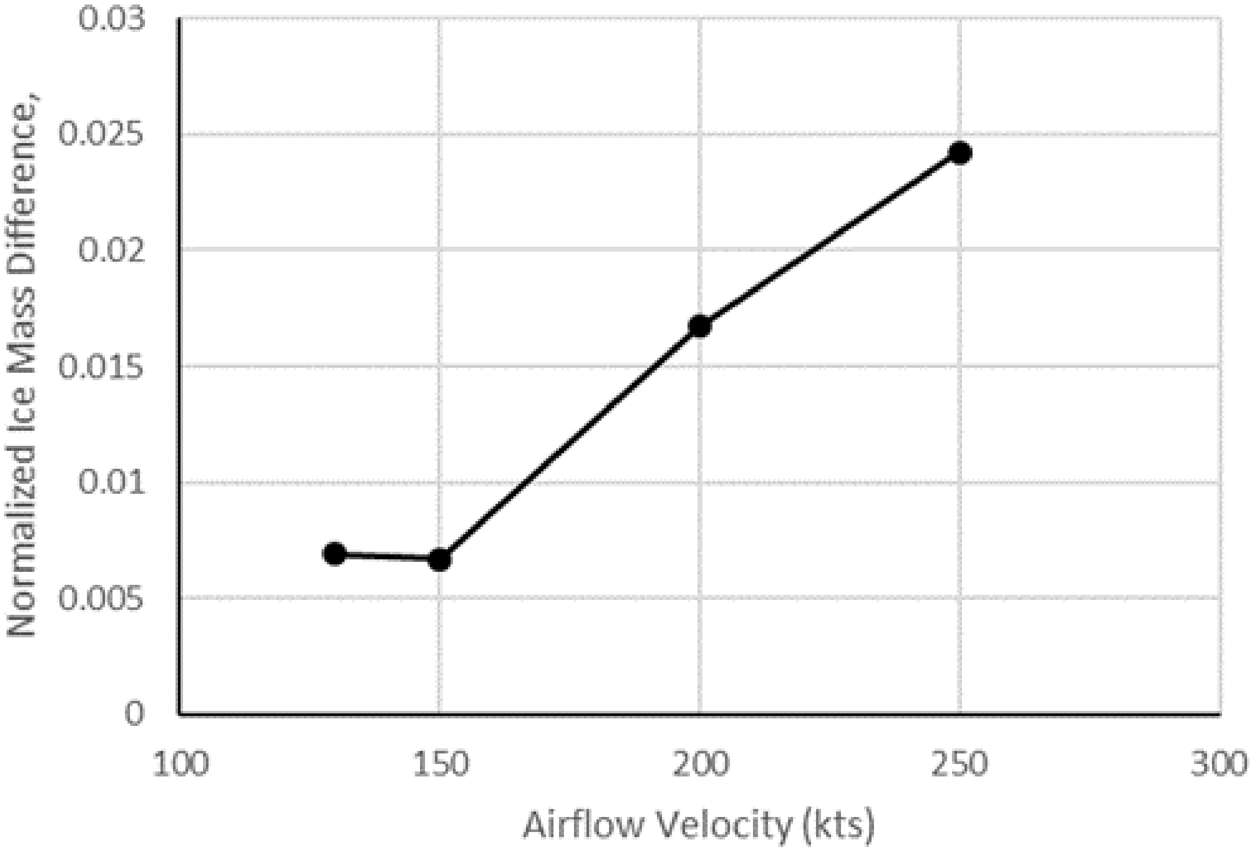




Bimodal Distribution (a)

Monomodal Distribution (b)

Normalized Ice Mass Difference



$$M_w = LWC \cdot V \cdot t \cdot A_p$$

$$\Delta\widetilde{m}_i = \Delta m_i / \overline{M_w}$$

A_p = projected area

Δm_i = measured mass difference

Concluding Remarks

- Bimodal spray ice shapes were created based upon the simultaneous spray process of Steen and Ide
- Test conditions, using monomodal and bimodal spray distributions, were developed for comparison to previously tested and recorded conditions
- For conditions that were the nominally the same, using the Olsen scaling method, the bimodal ice shapes:
  - ✓ Had a larger mass
  - ✓ Had a greater volume
  - ✓ Had icing limits further aft on the airfoil
- The ice mass difference seemed to increase with increasing velocity
- These differences seemed to be somewhat larger than repeatability
- More Evaluation Tests Recommended

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