Bimodal SLD Ice Accretion on a NACA 0012 Airfoil Model

Mark Potapczuk
NASA John H. Glenn Research Center, Cleveland, Ohio, 44135 USA

Jen-Ching Tsao
Ohio Aerospace Institute, Cleveland, Ohio, 44135 USA

Laura King-Steen
HX5 Sierra, Cleveland, Ohio, 44135 USA

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Outline

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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
2016 IRT Bimodal Spray

Pair = 15 psig
- **Man1 (Mod1) deltaP = 80 psid**
  - MVD = 39.2 um
  - minLWC (@250 kts)* = 0.67 g/m³
- **Man2 (Std) deltaP = 7 psid**
  - MVD = 17.1 um
  - minLWC (@250 kts)* = 0.78 g/m³
- **Combined:**
  - MVD = 20.8 um
  - minLWC (@250 kts)* = 1.45 g/m³

**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

Normalized Cumulative Volume

Drop Diameter, μm

IRT Mod1, Pair=15, DelP=30
FZDZ, MVD < 40 μm
2016 IRT Bimodal & Monomodal Distributions

- **FZDZ, MVD<40**
  - FAA App O distribution
  - MVD=20 µm
  - LWC between 0.29 and 0.44 g/m³

- **Bimodal**
  - Mod1 + Std nozzles
  - Pair = 15 psig
  - Mod1 ΔP = 80 psid
  - Standard ΔP = 7 psid
  - Combined MVD = 20.8 µm
  - Combined minLWC (@250 kts) = 1.45 g/m³

- **Monomodal**
  - Mod1 nozzles
  - Pair=15 psig
  - ΔP=30 psid
  - MVD=19.3 µm
  - minLWC (@250 kts) = 0.37 g/m³

- 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.

# Test Matrix

5 proposed reference conditions

## Test Conditions

<table>
<thead>
<tr>
<th>Case</th>
<th>Reference Condition</th>
<th>α</th>
<th>V (kts)</th>
<th>MVD (m)</th>
<th>LWC (g/m³)</th>
<th>T&lt;sub&gt;t&lt;/sub&gt; (°C)</th>
<th>T&lt;sub&gt;s&lt;/sub&gt; (°C)</th>
<th>Time (min)</th>
<th>n&lt;sub&gt;0&lt;/sub&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ice Shape Repeatability Run 3</td>
<td>1</td>
<td>4</td>
<td>200</td>
<td>20</td>
<td>0.55</td>
<td>-5.6</td>
<td>-10.8</td>
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<td>0.52</td>
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<td>Ice Shape Repeatability Run 23</td>
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<td>4</td>
<td>130</td>
<td>22</td>
<td>1</td>
<td>-5.6</td>
<td>-7.8</td>
<td>6</td>
<td>0.34</td>
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<td>5-15-06/Run 14</td>
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<td>0</td>
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<td>0.49</td>
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<td>3-28-05/Run 6</td>
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<td>-13.4</td>
<td>8.5</td>
<td>0.46</td>
</tr>
</tbody>
</table>

Note: For scaling, two selected spray clouds are considered.
Test Matrix

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

<table>
<thead>
<tr>
<th>Run #</th>
<th>Reference Condition</th>
<th>α</th>
<th>V (kts)</th>
<th>MVD (m)</th>
<th>LWC (g/m³)</th>
<th>Tₜ (°C)</th>
<th>Tₛ (°C)</th>
<th>Time (min)</th>
<th>n₀</th>
<th>Mod-1 pₐᵢᵣ, psig</th>
<th>Mod-1 Dₚ, psid</th>
<th>Std pₐᵢᵣ, psig</th>
<th>Std Dₚ, psid</th>
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<tbody>
<tr>
<td>AE2716</td>
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<td>250</td>
<td>19.3</td>
<td>0.37</td>
<td>-2.3</td>
<td>-10.5</td>
<td>14</td>
<td>0.46</td>
<td>15</td>
<td>30</td>
<td>15</td>
<td>30</td>
</tr>
<tr>
<td>AE2717</td>
<td>2.b</td>
<td>4</td>
<td>130</td>
<td>19.3</td>
<td>0.55</td>
<td>-2.8</td>
<td>-5</td>
<td>11.5</td>
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<td>30</td>
<td>15</td>
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<td>AE2719</td>
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<td>130</td>
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<td>2.9</td>
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<td>80</td>
<td>15</td>
<td>7</td>
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<td>-20.2</td>
<td>3.5</td>
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<td>80</td>
<td>15</td>
<td>7</td>
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<td>-20.5</td>
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<td>80</td>
<td>15</td>
<td>7</td>
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<td>-10.5</td>
<td>14</td>
<td>0.46</td>
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<td>30</td>
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<td>-2.8</td>
<td>-5</td>
<td>11.5</td>
<td>0.34</td>
<td>15</td>
<td>30</td>
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<td>AE2740</td>
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<td>150</td>
<td>19.3</td>
<td>0.5</td>
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<td>-7.2</td>
<td>17</td>
<td>0.49</td>
<td>15</td>
<td>30</td>
<td></td>
<td></td>
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<td>20.8</td>
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<td>-12.1</td>
<td>2.9</td>
<td>0.34</td>
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<td>80</td>
<td>15</td>
<td>7</td>
</tr>
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<td>AE2742</td>
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<td>150</td>
<td>20.8</td>
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<td>-17.9</td>
<td>4.2</td>
<td>0.49</td>
<td>15</td>
<td>80</td>
<td>15</td>
<td>7</td>
</tr>
</tbody>
</table>

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.

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

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

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

Bimodal Distribution (a)  Monomodal Distribution (b)
Ice Shape Comparisons to Reference Shapes
Reference Condition 2, \( V = 130 \) knots

MVD\(_2\) = 22 \( \mu \)m, LWC\(_2\) = 1.00 g/m\(^3\), \( t_2 \) = 6 min
MVD\(_{2a}\) = 20.8 \( \mu \)m, LWC\(_{2a}\) = 2.15 g/m\(^3\), \( t_{2a} \) = 2.9 min

MVD\(_{2b}\) = 19.3 \( \mu \)m, LWC\(_{2b}\) = 0.55 g/m\(^3\), \( t_{2b} \) = 11.5 min

Bimodal Distribution (a)  
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

MVD$_{5b}$ = 19.3 μm, LWC$_{5b}$ = 0.37 g/m$^3$, $t_{5b}$ = 14 min

Bimodal Distribution (a)  Monomodal Distribution (b)
Bimodal Cloud Effects on Ice Shapes

- Icing limits are further aft

Ref. 1
- 24% more ice mass
- 10% more volume

Ref. 2
- 10% more ice mass
- 27% more volume

Ref. 3
- 10% more ice mass
- 19% more volume

Ref. 5
- 45% more ice mass
- 44% more volume

monomodal

bimodal
Ice Shape Repeatability
Reference Condition 2

Bimodal Distribution (a)  Monomodal Distribution (b)

8.4% ice mass difference
13.6% volume difference

3.6% ice mass difference
5.9% volume difference
Normalized Ice Mass Difference

\[ M_w = LWC \cdot V \cdot t \cdot A_p \]

\[ \Delta \tilde{m}_i = \Delta m_i / M_w \]

\[ A_p = \text{projected area} \]

\[ \Delta m_i = \text{measured mass difference} \]
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
Acknowledgements

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