Recent Advances in the LEWICE Icing Model

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Outline

- Thermal Model Modifications
- Thermal Model Validation
  - Comparison with Thermal Scaling Data
- Conclusions from Thermal Analysis
- Mixed Phase Additions
- Mixed Phase Calibration
  - Comparison with RatFac Data
- Conclusions From Ice Crystal Analysis
Thermal Model Additions

- **Myers Water Film Model**

\[
\frac{\partial h}{\partial t} + \frac{\partial}{\partial x} \left( \frac{h^3}{3\mu_w} \left( \frac{\partial^3 h}{\partial x^3} + G_3 \frac{\partial h}{\partial x} - G_1 \right) + \tau_w \frac{h^2}{2\mu_w} \right) = \frac{\rho_a}{\rho_w} \beta V_\infty
\]

- **Surface Water Shedding Model (calibrated)**

\[
\frac{\dot{m}_{shed}}{\dot{m}_{runback,in}} = \frac{We - We_c}{We} \quad We = \frac{\rho_a V_a^2 x_k}{\sigma} \quad We_c = 200 + 5\times10^5 x_k
\]

- **Enhanced Evaporation**
  - Chilton-Colburn analogy underestimates evaporation rate by 30%
Process for Comparison

• Determine Internal Heat Transfer Coefficient from Dry Cases
  – All Cases Use Same Coefficients
    \[ Nu = 0.004 \text{RePr}^{\frac{1}{3}} \left( \frac{z_n}{d_h} \right)^{-0.22} \left( \frac{x}{d_h} \right)^{-0.38} \]

• External Heat Transfer Coefficient is Forced Laminar Where There is No Ice

• Run All Dry Cases To Ensure Correlation Matches

• Run Wet Cases for Validation
## Conditions Used For Thermal Comparison

<table>
<thead>
<tr>
<th>Case</th>
<th>P(Pa)</th>
<th>V(m/s)</th>
<th>T(K)</th>
<th>LWC</th>
<th>MVD</th>
<th>AOA</th>
<th>t(min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Warm Hold(Ref)</td>
<td>57295</td>
<td>92.7</td>
<td>264.5</td>
<td>0.5</td>
<td>20</td>
<td>0</td>
<td>7</td>
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<tr>
<td>Warm Hold(Scale)</td>
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<td>0.85</td>
<td>27.8</td>
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<td>Descent(Ref)</td>
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<td>253.1</td>
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<td>0</td>
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<td>10</td>
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</tbody>
</table>
Warm Hold (Ref) - Dry

![Graph showing Warm Hold (ref) dry with data points and a line graph.](image-url)
Warm Hold (ref) - Wet
Warm Hold (Ref) Ice Shape Comparison
Warm Hold (Re Scale) - Dry

Temperature (K)

s/c

exp

LEWICE
Warm Hold (Re Scale) Ice Shape

- No Ice from Experiment nor from LEWICE
Descent (Ref)
Descent (Ref)

Ice Growth Normal to Surface (Default)

Ice Growth in Impingement Direction
Descent (Re Scale)
Descent (Re Scale)
Cold Hold (Ref) - wet

![Graph showing Cold Hold (ref) - wet with data points and curves.](image-url)
Cold Hold (Ref)
Cold Hold (Re Scale) - wet

![Graph showing temperature (K) vs. s/c with data points and a line representing LEWICE comparison.]
Cold Hold (Re Scale)
Observations from Thermal Analysis

• Temperature Prediction is Very Good to Excellent for Most Cases
• Warm Hold Cases Show Predicted Runback Ice Forward of Experiment
  – Peak Ice Thickness Higher for LEWICE
• Descent and Cold Show Predicted Runback Ice Forms Slightly Behind Experiment
  – Peak Thickness Higher for LEWICE, Especially Upper Surface
• Ice in Experiment Grows Toward Leading Edge While LEWICE always grows Ice Normal to Surface
• Further Refinement of Runback Model May Be Necessary
• External Heat Transfer Coefficients for Residual Ice Shapes Need to Be Separately Validated
Ice Breakup Model

- **Breakup Threshold (Hauk)**

\[ V_{imp} \geq \frac{0.45}{\sin \alpha \sqrt{d}} \]

- **Sticking Efficiency (Currie)**

\[
\frac{m_b}{m_o} = \left(1 - \xi \cos(\alpha_{imp})\right) \left(0.57 + 7.5 \times 10^{-4} \left[V_{imp} \cos(\alpha_{imp})\right]^{1.5}\right)
\]

\[
\xi = -0.1425 + 47.292TWC - 1979.167TWC^2
\]

- For TWC < 0.12 kg/m³ and \(\xi = 0.14\) for TWC > 0.12
### Conditions for Ice Crystal Comparison

<table>
<thead>
<tr>
<th>Airfoil</th>
<th>Scan#</th>
<th>P</th>
<th>V</th>
<th>T</th>
<th>Sh</th>
<th>LWC</th>
<th>IWC</th>
<th>AOA</th>
<th>t(m)</th>
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<tbody>
<tr>
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<td>86.2</td>
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<td>5.9</td>
<td>0.6</td>
<td>4.9</td>
<td>0</td>
<td>3</td>
</tr>
</tbody>
</table>
Ice Shape Prediction for Scan 996
Ice Shape Prediction for Scan 1003
Sticking Efficiency on Wedge at Various Particle Sizes
Ice Thickness Prediction for Scan 796 (NACA0012)
Observations from Ice Crystal Comparison

• Peak Thickness is Over Predicted by LEWICE while Extent is Under Predicted
  – Additional Erosion Effects may be Needed
  – Improved Model for Reimpingement of Ice Crystals
• Additional Data is Needed to Complete Model