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**

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

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

\[
\frac{\dot{m}_{\text{shed}}}{\dot{m}_{\text{runback,in}}} = \frac{W_e - W_{e_c}}{W_e}, \quad W_e = \frac{\rho_a V_a^2 x_k}{\sigma}, \quad W_{e_c} = 200 + 5 \times 10^5 x_k
\]

- **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
    \[ Nu = 0.004 \text{Re} \text{Pr}^{1/3} \left( \frac{z_n}{d_h} \right)^{-0.22} \left( \frac{x}{d_h} \right)^{-0.38} \]

- **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**
<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>
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<td>Warm Hold(Ref)</td>
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<td>92.7</td>
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Warm Hold (Ref) - Dry
Warm Hold (ref) - Wet
Warm Hold (Ref) Ice Shape Comparison
Warm Hold (Re Scale) - Wet
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
Cold Hold (Ref)
Cold Hold (Re Scale) - wet
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)**

\[
\frac{m_b}{m_o} = \left(1 - \xi \cos(\alpha_{imp})\right)\left(0.57 + 7.5 \times 10^{-4}\left[V_{imp} \cos(\alpha_{imp})\right]^{0.5}\right)
\]

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

- 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>
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<td>0</td>
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</table>
Ice Shape Prediction for Scan 996
Ice Shape Prediction for Scan 1003
Sticking Efficiency on Wedge at Various Particle Sizes

![Graph showing sticking efficiency on a wedge at various particle sizes. The graph plots sticking factor against s/c ratio, with different colors representing different particle sizes.](image-url)
Ice Thickness Prediction for Scan 796 (NACA0012)

![Graph showing ice thickness prediction over time.](image)

Glenn Research Center
Icing Branch

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at Lewis Field
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