NASA Glenn Propulsion Systems Lab: Update on Calibration Testing

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NASA Glenn Research Center
2015-06 SAE International Icing Conference
Prague, Czech Republic
Agenda

• PSL Icing Configurations and Capabilities
  • Engine
  • Driven Rig
• Icing/Ice Crystal Cloud Characterization
  ▪ Water Content
  ▪ Particle Size
  ▪ Uniformity
  ▪ Particle Temp
Icing Calibration Configurations

- **Aero-Thermal Cal Duct**
  - Pres., Temp., Rel. Humidity

- **Tomography & Raman Duct**

- **Cloud Calibration Duct**
  - Water Content, Particle Sizing

- **Configuration 1**
  - Engine
  - 27:1 CR

- **Configuration 2**
  - Component
  - 11:1 CR
  - 22:1 CR with bullet nose
  - *approx. representation

Modification upstream of spraybars
PSL Operating Range – Icing System

<table>
<thead>
<tr>
<th>Specification</th>
<th>Min</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engine / Rig Dia. (in</td>
<td>cm)</td>
<td>24</td>
</tr>
<tr>
<td>Air Flow Rate (lbm/s</td>
<td>kg/s)</td>
<td>10</td>
</tr>
<tr>
<td>Altitude, pressure (kft</td>
<td>km)</td>
<td>-4</td>
</tr>
<tr>
<td>Total Temp (°F</td>
<td>°C)</td>
<td>-60</td>
</tr>
<tr>
<td>Mach Number</td>
<td>0.15</td>
<td>0.80</td>
</tr>
<tr>
<td>TWC (g/m³)</td>
<td>0.5</td>
<td>8.0 *</td>
</tr>
<tr>
<td>MVD (um)</td>
<td>15</td>
<td>&gt;100 #</td>
</tr>
</tbody>
</table>

* Evidence that probe under-measured
# Particles larger than ≈ 60 um are NOT fully glaciated.
Setting Conditions in PSL

Given the atmospheric environment \( (P_{\text{amb}}, T_{\text{amb}}, \text{Mach}) \) of concern, provide the static conditions \( (P_s, T_s, \text{Mach}) \) at the inlet plane of either:

- Engine (fan face conditions)
- Driven Rig (LPC inlet, etc)

Define target cloud (TWC, MVD)

- Appendix D/P
- Appendix C
- Large Drop

Conduct calibration toward request to see what PSL can cover.

(from Aircraft Engine Design, Mattingly)
PSL-3 Envelope

![Graph of PSL-3 Envelope](image)

**Altitude (kft)**

**Ambient Temperature (°C)**

- Calibration regions to be indicated
PSL Icing Cloud Hardware

Spray Bars – Cloud Generation

- Ten Spray Bars; total of 110 **Standard**
  - nozzles and 112 **Mod1** nozzles.
- Each nozzle is individually controlled.
- Nozzle controls:
  - **Pair**, atomizing air pressure: 5 – 90 psid, Tair temperature: 45 – 180 F.
  - **Pwat**, water pressure: 10 – 300 psid, Twat temperature: 45 – 180 F.
  - **DeltaP** = DP = (Pwat – Pair)
  - SBCA, Spraybar cooling air.
    P: 5 – 40 psid, T: -40 – 40 F.

\[(\text{Pair}, \Delta \text{P}) \Rightarrow (\text{MVD}, \text{TWC})\]

At a given air mass flow rate
Water Content Instruments – IKP

Iso-Kinetic Probe

Ice Catch Tube system not completed for the May 2015 Entry.
Water Content Instruments – Hot wire

Multi-Wire (TWC & LWC) (MW)

Robust Probe (TWC only) SEA Inc.

(MW)

(RP)

2-mm reverse half-pipe (083)
2-mm half-pipe (TWC)
0.5-mm wire (021)
Collection Efficiency Corrected*

3.8-mm half-pipe
No collection efficiency correction, yet.

Water Content – Installation and Analysis

Splitter Plate

Bullet nose
(not recommended)

\[ IWC \left( \frac{g}{m^3} \right) = \frac{C \times P_{\text{sense, wet}}}{[L_{\text{svap}} + c_{\text{liq}}(T_{\text{svap}} - T_{\text{amb}}) + L_{\text{fus}} + c_{\text{ice}}(T_0 - T_{\text{amb}})] \times V \times L_{\text{sense}} \times W_{\text{sense}}} \]
MW Response to Temp. change at Altitude (25 um)

Temperature Effect - Multi-wire (1890 Series)

\[ \text{Twb(C) } = 3 \]

-13 -16 -20 -26

Time (hh:mm:ss)

Static Air Temp, Sta 1 (F)

Water Content (g/m³)

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Sample TWC Measurements

**Effect of Static Pressure (Altitude)**

- **Preliminary**

<table>
<thead>
<tr>
<th>Pstat S1 (psi)</th>
<th>Ice Water Content (g/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>5.0</td>
<td>0.75</td>
</tr>
<tr>
<td>10.0</td>
<td>1.5</td>
</tr>
<tr>
<td>15.0</td>
<td>2.0</td>
</tr>
</tbody>
</table>

**Input Data:**
- IKP
- rRP 3024 IWC Spike
- MW2041 IWC Spike _Em

**Effect of Rel. Humidity**

<table>
<thead>
<tr>
<th>RH_PL Meas %</th>
<th>TWC Spike _Em</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>0.3</td>
</tr>
<tr>
<td>20.0</td>
<td>0.4</td>
</tr>
<tr>
<td>40.0</td>
<td>0.6</td>
</tr>
<tr>
<td>60.0</td>
<td>0.7</td>
</tr>
</tbody>
</table>

**Config 1:** Effects of
- Altitude
- Relative Humidity

**Config 2:** Correlation between Measured and Calculated

Bulk TWC = \( \frac{\text{mass}_{\text{water}}}{\text{time}} \)

Bulk TWC Calculation (g/m³) vs Multi-Wire TWC (g/m³)

- \( y = 0.8077x - 0.4826 \)
- \( R^2 = 0.9691 \)
Water Content Sensor Comparison

IKP-2

\[ y = 3.87x - 0.16 \]
\[ R^2 = 0.84 \]

Robust Probe (raw)

\[ y = 1.95x + 0.33 \]
\[ R^2 = 0.91 \]

Multi-Wire (Em corr)

\[ y = 1.90x + 0.24 \]
\[ R^2 = 0.96 \]

Ribbed Robust Probe (raw)

\[ y = 2.76x - 0.54 \]
\[ R^2 = 0.91 \]
Water Content Sensor Comparison

Sensor Fit Comparison

Sensor/RP v MVD

![Graph showing Sensor Fit Comparison and Sensor/RP v MVD](image_url)
Drop Sizing Instruments

CDP (2 – 50 um)  Forward Scattering

CIP-GS (15 – 930 um)  Shadowing
Sample Combined Distributions
Sample MVD Results

Effect of Relative Humidity

Effect of Altitude (Tank Pressure)
Additional Particle Sizing Techniques

**Phase Doppler Interferometer**
- Particle size
- Particle velocity
- LWC
- Number density

**High Speed Imaging**
- Particle size (ice & liquid)
- Shape
- LWC
- Number density
Cloud Uniformity Diagnostics

- Grid
  - Supercooled liquid only
  - Low speed only
- Laser Sheet *
- Tomography *

*Uniformity is required for Bulk TWC calculation.*

Cloud Uniformity Measurements

Uniformity Grid 3x6 in

Laser Sheet @ duct exit

Tomography in duct

Liquid Water Only
Limited Speed, Time

Long time spray for visualization only.

Light Extinction Measurements
Cloud Uniformity Results

<table>
<thead>
<tr>
<th></th>
<th>TWC_RP (g/m³)</th>
<th>Bulk TWC (g/m³)</th>
<th>Max TWC (g/m³)</th>
<th>Bulk / RP ratio (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser Sheet</td>
<td>3.30</td>
<td>2.44</td>
<td>3.74</td>
<td>74.1</td>
</tr>
<tr>
<td>Tomography</td>
<td>3.30</td>
<td>2.44</td>
<td>3.58</td>
<td>74.0</td>
</tr>
</tbody>
</table>
Particle Temperature

Raman Scattering – Primer

• Measures surface temperature
• Measures average bulk particle phase – ice or water
• Is a very low light technique, signal can be contaminated by light from other techniques or cell lights

Adding a fluorescent dye greatly helps with signal gain.
Raman Scattering – Particle Phase & Temp.

T. Bencic’s bench top results

Raman Spectra of Water & Ice

Raman Area Ratio

Area 1
Area 2

Normalized Intensity

Wavelength (nm)

Temperature °C

Area Ratio (A1/A2)

-25 -20 -15 -10 -5 0 5 10 15 20

Water

Ice

18 C Liq
-8 C Liq
-1 C Ice
-15 C Ice

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Future Tasks

• Continue analysis of May 2015 cloud characterization data
• Implement calibration curves
• Evaluate MVD sensitivity to configuration changes.
• Publish report

With thanks to the PSL Cloud Cal Team:
• Bryan Rosine
• Jonathan Borman
Questions?