Particle Size Measurements from the first Fundamentals of Ice Crystal Icing Physics Test in the NASA Propulsion Systems Laboratory

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Outline

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Introduction

• NASA is studying ice crystal icing (ICI) conditions to advance the understanding behind this aviation safety hazard

• The unique nature of ICI conditions has slowed cloud characterization in PSL, but it has also stimulated the development of instrumentation

• This work presents select cases of particle measurements acquired using the PDI and HSI in PSL during a March 2016 test
Objective and Approach

- **Objective:** Evaluate capabilities of Phase Doppler Interferometer (PDI) and High Speed Imaging (HSI) instruments to measure and discriminate glaciated conditions.

- **Approach:** Measure the icing cloud through a series of controlled conditions, varying only the Wet-Bulb Temperature, \( T_{WB} \), thereby increasing the presence of glaciated particles in the cloud to examine instrument response.
Instrumentation: 
*Phase Doppler Interferometer*

- PDI is a single particle counter using a flux sampling technique that can size spherical and quasi-spherical particles

- Two coherent beams create an interrogation volume and a local interference fringe pattern

- Particles scatter light, create a Doppler burst signal, which is measured by 3 detectors at separate locations, resulting in a phase shift used to size

- Phase shift from 3 detectors provides a means of shape discrimination (spherical, quasi-spherical or irregular-shaped)
Instrumentation:  
*Phase Doppler Interferometer*

Superimposed Signals at Detectors A and B

simplified example showing only 2 detectors--PDI had 3

Interference Fringes

Detector A

Detector B

Particle Trajectory

Scattered Light

\[ \theta_{AB} \]
Instrumentation: High Speed Imaging

- HSI uses a spatial sampling technique that can size spherical to irregular-shaped particles.
- Acquires high-resolution images of particles passing through the interrogation volume created by several pulsed laser beams with a CMOS camera.
- 1.8 μm/pixel resolution during March 2016 test.
- Parameters measured in images provide means of quantitative shape discrimination of particles.
Instrumentation: High Speed Imaging

Sample Image Capture

Direction of Increasing Aspect Ratio

AR = 1
AR = 2
AR = 3

representation only to help interpret data
Experimental Methodology

• Tests were conducted in March 2016 in PSL

• Modular versions of the PDI and the HSI were focused approximately 152 mm above the centerline of the approximately 1 m diameter exit duct

• Simulated icing conditions were generated with either a Large $MVD_i$ or a Small $MVD_i$
  – $Large MVD_i = 50 \mu m$, $Small MVD_i = 15 \mu m$
  – Spray bar conditions based on the Icing Research Tunnel PSD Calibration and $MVD_i$ does not necessarily represent PSD at duct exit

• The plenum $T_{WB}$ was driven down incrementally for each test condition in the Large $MVD_i$ Series and the Small $MVD_i$ Series by varying plenum humidity
  – Large $MVD_i$ Series: $T_{WB} = 2.4^\circ C$ to $-6.0^\circ C$, $u = 85 \, m/s$
  – Small $MVD_i$ Series: $T_{WB} = 2.4^\circ C$ to $-3.3^\circ C$, $u = 85 \, m/s$

• Data was acquired with the PDI and the HSI simultaneously during each test condition
Results:

PDI Raw Signal Phase Difference Trend

$T_{WB}$

<table>
<thead>
<tr>
<th>Temperature</th>
<th>Large Series</th>
<th>Small Series</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.4°C</td>
<td>0.6°C</td>
<td>0.6°C</td>
</tr>
<tr>
<td>-0.4°C</td>
<td>-0.5°C</td>
<td>-0.5°C</td>
</tr>
<tr>
<td>-2.6°C</td>
<td>-2.6°C</td>
<td>-2.6°C</td>
</tr>
<tr>
<td>-3.3°C</td>
<td>-3.3°C</td>
<td>-3.3°C</td>
</tr>
<tr>
<td>-6.0°C</td>
<td>-6.0°C</td>
<td>-6.0°C</td>
</tr>
</tbody>
</table>

Large Series

Small Series

Scatter indicates presence of irregular shape particles.

Decreasing $T_{WB}$
Results:

**HSI Area-Perimeter Correlation Trend**

**Large Series**

- **$T_{WB} = 2.4^\circ C$**
- **$T_{WB} = -2.6^\circ C$**

**Small Series**

- **$T_{WB} = 0.6^\circ C$**
- **$T_{WB} = -0.5^\circ C$**
- **$T_{WB} = -3.3^\circ C$**

Increasing Aspect Ratio
Results:
HSI Sample Images Trend

Large Series

\[ T_{WB} = 2.4^\circ C \]

Random selection of particles

all images are same scale

Small Series

\[ T_{WB} = 2.4^\circ C \]

\[ T_{WB} = -6.0^\circ C \]

\[ T_{WB} = -3.3^\circ C \]
Results:
Size Distribution Trend

Large Series

\[ T_{WB} = 2.4^\circ C \]

Small Series

\[ T_{WB} = 2.4^\circ C \]

\[ T_{WB} = -2.6^\circ C \]

\[ T_{WB} = -0.5^\circ C \]

\[ T_{WB} = -6.0^\circ C \]

\[ T_{WB} = -3.3^\circ C \]

Decreasing \( T_{WB} \)

all distribution values are provided in paper
Results:

Number Density Trend

Large Series

$T_{WB} = 2.4\, ^\circ C$

$-2.6\, ^\circ C$

$-6.0\, ^\circ C$

Small Series

$T_{WB} = 2.4\, ^\circ C$

$-0.5\, ^\circ C$

$-3.3\, ^\circ C$
Summary

• NASA has completed the first Fundamentals of Ice Crystal Icing Physics test in PSL

• The Artium Technologies, Inc. PDI and HSI instruments were successfully used to measure the icing cloud during the test

• The PDI and HSI demonstrated good agreement during the Large $MVD_i$ Series through a range of $T_{WB}$

• Due to minimum measurable range of the HSI, there was not good agreement between the PDI and HSI during the Small $MVD_i$ Series

• Further development of the PDI and HSI towards measuring the lower end of the irregular-shape particle spectrum is necessary

• The PDI raw signal phase difference and HSI area-perimeter correlation demonstrated the current capability to examine particle morphology, and consequently discriminate glaciated conditions
  – Further evaluation is required
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