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

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Outline

• Introduction
• Objective and Approach
• Instrumentation
• Experimental Methodology
• Results
• Summary
• Acknowledgements
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

Detector A
Detector B
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>2.4°C</th>
<th>Large Series</th>
<th>Small Series</th>
<th>$T_{WB}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>2.4°C</td>
<td>2.4°C</td>
</tr>
<tr>
<td>-0.4°C</td>
<td></td>
<td>0.6°C</td>
<td></td>
</tr>
<tr>
<td>-2.6°C</td>
<td></td>
<td>-0.5°C</td>
<td>-2.6°C</td>
</tr>
<tr>
<td>-3.3°C</td>
<td></td>
<td>-2.6°C</td>
<td>-3.3°C</td>
</tr>
<tr>
<td>-6.0°C</td>
<td></td>
<td>-3.3°C</td>
<td></td>
</tr>
</tbody>
</table>

scatter indicates presence of irregular shape particles
Results:

**HSI Area-Perimeter Correlation Trend**

**Large Series**

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

**Small Series**

- $T_{WB} = 0.6^\circ C$
- Decreasing $T_{WB}$

Increasing Aspect Ratio
Results:

**HSI Sample Images Trend**

**Large Series**

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

**Small Series**

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

**random selection of particles**

All images are same scale

- $T_{WB} = -6.0^\circ C$

- $T_{WB} = -3.3^\circ C$
Results:
Size Distribution 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$^\circ C$

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**

- $T_{WB} = 2.4^\circ C$
- $-0.5^\circ C$
- $-3.3^\circ C$

Decreasing $T_{WB}$
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
Acknowledgements

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