Plans & Preliminary Results of Fundamental Studies of Ice Crystal Icing Physics in the NASA PSL

June 15, 2016

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Outline

• Introduction & background

• NASA Fundamental Ice Crystal Icing Research Goals
  – Concepts using PSL

• Experimental Description – Preliminary 2-day test May 2015

• Results
  – Review one case in detail
  – Look at general trends from sweeping
    • Total Water Content
    • Humidity
    • Spray Bar Water Temperature

• Conclusions
Introduction

• NASA investigating the fundamental physics of ice crystal icing (ICI)
  – AEST → AATT

• Challenging to study ice-accretion physics directly inside the engine
  – Trying to simulating that environment without using engine

• Evaluating whether the NASA Propulsion Systems Lab (PSL), in addition to full-engine and motor-driven-rig tests, can be used for more fundamental ice-accretion studies
  – Paper presents concept & some preliminary experimental test results
  – Subsequent paper present complementary modelling work

Technical Challenge:
Expand engine aero-thermodynamic modeling capability to predictively assess the onset of icing in current and N+2/N+3 aircraft during flight operation (FY21).

The simulation tools are well anchored in results from both fundamental physics studies and full engine tests.
NASA Fundamental ICI Goals

1. Identify and bound the conditions affecting ice-crystal ice accretion at the (local) accretion site

2. Generate & characterize (i.e. measure) those conditions including uniformity

3. Gather data and develop models on ice-crystal icing factors

4. Scaling: develop & test scaling relations for ice-crystal icing

Local region requires more information than full-scale test (e.g. melt ratio)

Graphic: NASA (www.ueet.nasa.gov)
Concept Using PSL

**Goal**: Ability to generate a prescribed mixed-phase condition at the test section for fundamental ice-crystal icing research

**Match**:
1. wet-bulb temperature
2. particle size distribution
3. melted portion of incoming ice
Preliminary Testing

• **2 days of testing occurred in May 2015**

• **Objectives**
  – Preparation for more extensive test scheduled for 2016
  – Examine spray bar and plenum parameters and how they affect the mixed-phase at the exit of the free jet
  – Cloud characterization:
    • Melt ratio using SEA multiwire
    • Temperature & humidity measurements at test section (cloud on vs. cloud off) using custom probe
  – Observe ice accretion
PSL Configuration

Inlet plane

Transition Ducts

Constant Area Ducts

PLENUM

Spray Bars

Free Jet

0.91 m
3.0 ft

Exit plane (test section)

8.84 m
29.0 ft

6.68 m
21.92 ft

2.16 m
7.08 ft
PSL Configuration (cont.)

Flow splitter plate

Multi-wire probe

245 mm 9.65"

Rearward-facing temperature and humidity probe
Temperature and Humidity Measurement

- **Reward facing probe**
  - **Temperature**
    - Resistance Temperature Device (RTD) placed inside probe inlet to prevent water / ice contamination
    - Small suction induced in probe
    - Calibrated to read total temperature given Mach

- **Humidity**
  - Flow extracted via same probe inlet
  - Using Spectra Sensor Model WVSS-II
    - Tunable Diode Laser Absorption Spectroscopy (TDLAS)

- Cameras imaged probe to observe any ice accretion
Mixed-Phase Investigation

Parameters

- **Plenum / test section**
  - Total pressure, \( P_{0,i} \) (kPa)
  - Static pressure, \( P_{s,e} \) (kPa)
  - Velocity, \( v_e \) (m/s)
  - Total temperature, \( T_{0,i} \) (°C)
  - Humidity, \( \omega_i \) (g / kg dry)

- **Spray bar**
  - TWC
    - \( P_{\text{air}} \) & \( P_{\text{water}} \rightarrow m_{\text{noz}} \)
    - Nozzle #
  - Particle Size
    - MVD\( i \) (IRT calibrated values)
  - Water / air temperatures, \( T_{\text{water}} \)

Nomenclature

\[
TW C_{\text{bulk}} = \frac{(\text{Nozzle } \#) \cdot m_{\text{noz}}}{v_e A}
\]

Where:
- \( m_{\text{noz}} \): Mass flow rate of the nozzle
- \( v_e \): Velocity
- \( A \): Area
- \( P_{s,e} \): Static pressure
- \( T_{\text{water}} \): Temperature of water
- \( T_{0,i} \): Temperature at inlet plane
- \( \omega_i \): Humidity
- \( P_{0,i} \): Total pressure
- \( TW C_{m} \): Mass concentration

Inlet plane (test section)

Exit plane
Sample Test Data

- **Plenum / Test Section (targets)**
  - $P_{0,i} = 87.3$ kPa
  - $P_{s,e} = 83.6$ kPa (1.6 km)
  - $v_e = 85$ m/s
  - $T_{0,i} = 1.8^\circ$C
  - $\omega_i = 0.5$ g/kg dry (RH$_{PL} = 10\%$)

- **Spray bar**
  - $TW_{C_{bulk}} = 1.4$ g/m$^3$
  - MVD$i = 40$ µm

- **Reported data**
  - Temperature measurement lag likely due to thermal inertia of inlet
  - 30 second averages
    - Cloud off (0.52 g/kg, 1.2 °C)
    - Cloud on (1.37 g/kg, -0.9 °C)
  - $\Delta T_{0,e} = T_{0,e,\text{on}} - T_{0,e,\text{off}}$
Wet-bulb temperature

**INPUT**

- Mass Moire Ratio, g H₂O/kg dry air
- Temperature, °C
- Pressure (psia)

**OUTPUT**

- Test 676
- Wet bulb slightly increased...typical result
Multiwire Results

- $TWC_{bulk} = 0.78 \text{ g/m}^3$
  - $MVD_i = 40 \mu\text{m}$

- Multiwire data
  - 30 second averages
  - $TWC_m = 1.50 \text{ g/m}^3$
  - $LWC_{m,2.1} = 1.06 \text{ g/m}^3$
  - $LWC_{m,0.5} = 0.83 \text{ g/m}^3$

- Melt ratio, $\eta_e$

$$\eta_e = \frac{\max(LWC_m)}{TWC_m} = \frac{1.06}{1.50} = 0.70^*$$

* more detailed analysis anticipated to be applied later
Ice Accretion Examples

Case 677 ($\eta_e = 0.70$)

Case 663 ($\eta_e = 0.20$)

8X actual speed
Parameter Sweeps

• Paper presents parameter sweeps for the following variables:
  – \( TWC_{\text{bulk}} \) (0.5 – 5 g/m\(^3\))
  – Plenum RH (10 – 50%)
  – Spray bar temperature (7°C, 43°C, and 82°C)

• Within each sweep, additional variations on:
  – MVD\(_i\)
  – Wet-bulb temperature

<table>
<thead>
<tr>
<th>Table 2. Facility target conditions and select measurements during two TWC sweeps</th>
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</thead>
<tbody>
<tr>
<td>( \text{Test Series} \rightarrow )</td>
</tr>
<tr>
<td>( P_{0,i} ) (kPa)</td>
</tr>
<tr>
<td>( P_{s,e} ) (kPa)</td>
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<tr>
<td>( v_e ) (m/s)</td>
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<tr>
<td>Altitude (km)</td>
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<td>( T_{0,i} ) (°C)</td>
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<td>( T_{{s,e},\text{off}} ) (°C)</td>
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<tr>
<td>RH(_{0,i} ) (%)</td>
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<tr>
<td>( \omega_i ) (g/kg)</td>
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<tr>
<td>( T_{\text{wb},0,e,\text{off}} ) (°C)</td>
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<tr>
<td>( T_{\text{wb},s,e,\text{off}} ) (°C)</td>
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<tr>
<td>( T_{\text{water},i} ) (°C)</td>
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<tr>
<td>( TWC_{\text{bulk}} ) (g/m(^3))</td>
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<tr>
<td>MVD(_i) (µm)</td>
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<table>
<thead>
<tr>
<th>Measurements</th>
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<tr>
<td>Test #</td>
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<tr>
<td>( TWC_{m} ) (g/m(^3))</td>
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<tr>
<td>( \eta_e ) (-)</td>
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<tr>
<td>( \Delta \omega_e ) (g/kg)</td>
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<td>( \Delta T_{0,e} ) (°C)</td>
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<td>( T_{\text{wb},0,e,\text{on}} ) (°C)</td>
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<tr>
<td>Ice Accr. (Y/N)</td>
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Conclusions

• NASA conducting research on fundamentals of ICI with following goals:
  – Identify and bound the conditions at the (local) accretion site
  – Generate & characterize conditions
  – Develop models & gather data on ice-crystal icing factors
  – Scaling: develop & test scaling relations for ice-crystal icing

• Generate environment outside of an engine to facilitate study
  – Evaluating PSL as potential test bed

• Presented data from an initial 2-day test effort in May 2015
  – Parameter sweeps on TWC, Plenum RH, and $T_{\text{water}}$
    • More limited variation on initial particle size and $T_{\text{wb}}$
  – Saw both expected trends; harder-to-explain trends; new insights
    • Measurement uncertainties, cloud uniformity, and additional data required
  – Preparatory work for 2016 testing

• 2-week test campaign occurred in March 2016
  – Data analysis beginning
Acknowledgement

• Financial support:
  – NASA's, Advanced Air Vehicle's program
    • Advance Air Transport Technology Project (AATT)
      – Advanced Aircraft Icing (AAI) – Mr. Tony Nerone, Project Manager

• Special thanks to:
  – Staff of the NASA PSL
  – Kyle Zimmerle, Michael Oliver, and Judy Van Zante who provided information presented in this paper.
  – Mr. Chris Lynch for his excellent imaging work.