An Initial Study of the Fundamentals of Ice Crystal Icing Physics in the NASA Propulsion Systems Laboratory

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Peter Struk
NASA Glenn Research Center

Tadas Bartkus, Jen-Ching Tsao
Ohio Aerospace Institute

Timothy Bencic, Michael King, Thomas Ratvasky, Judy Van Zante
NASA Glenn Research Center
Outline

• Introduction & background

• NASA Fundamental Ice Crystal Icing Research Goals
  – Concepts using the NASA Propulsion System Laboratory (PSL)

• Experimental Description

• Results
  – Freeze-out characteristics of cloud
  – Changes in aero-thermal conditions at the test section
  – Accreted ice characteristics observed

• Summary
Introduction

• NASA investigating the fundamental physics of ice crystal icing (ICI)

• Challenging to study ice-accretion physics directly inside the engine
  – Trying to simulate local ICI environment without using an engine

• This paper presents an initial study of the fundamental physics of ICI using PSL
  – Test occurred in March 2016
  – Select results presented
    • Last year, presented preliminary work in preparation for this test
  – Complementary papers to follow

Advance Air Transport Technology Project (AATT; 2015 +)
Advanced Aircraft Icing (AAI) Subproject

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 Research Goals

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

• Generate & characterize (i.e. measure) those conditions

• Gather data and develop models on ice-crystal icing factors

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

Link actual conditions in an engine to fundamental work

Engine Tests

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
Fundamental Test #1

• **Eight (8) days of testing occurred in March 2016**

• **Objectives**
  – Examine spray bar and plenum parameters and how they affect the mixed-phase at the exit of the free jet

  – Cloud characterization at the test section:
    • Melt ratio (fraction of freeze out)
    • Total water content
    • Temperature & humidity measurements at test section (cloud on vs. cloud off)
    • Particle size distributions
    • Uniformity

  – Observe ice accretion
PSL Configuration

Inlet plane

Transition Ducts

Constant Area Ducts

PLENUM

Free Jet

Spray Bars

Multi-wire probe

Exit plane (test section)

8.84 m
29.0 ft

6.68 m
21.92 ft

2.16 m
7.08 ft

0.91 m
3.0 ft
Test Configurations

A. Configuration 0
Open duct with traverse

B. Configuration 1
Multiwire

C. Configuration 2
Airfoil

D. Configuration 3a
Cloud Droplet Probe

E. Configuration 3b
Cloud Imaging Probe

F. Configuration 4
Isokinetic Probe

Humidity Inlet “A”
Humidity Inlet “B”
Commercial TAT
RFTP

Humidity Inlet “A”
Humidity Inlet “B”
Commercial TAT
RFTP

Humidity Inlet “A”
Humidity Inlet “B”
IKP Background Humidity
Commercial TAT
RFTP

Humidity Inlet “B”
Humidity Inlet “B”
IKP Background Humidity
Commercial TAT
RFTP
Mixed-Phase Investigation
Plenum Relative Humidity Sweep Approach

Parameters

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

Nomenclature

- $TWC_e = \frac{(\text{Nozzles}) \ m_{noz}}{U_e A}$
- $TW C_{m}$
- $P_{s,e}$
- $U_e$
- Exit plane (test section)
Mixed-Phase Investigation
Plenum Relative Humidity Sweep Results

Water Content Measurement Results

\[ P_{0,i,T} = 44.8 \text{ kPa (6.5 psia)} \text{ and } 42.8 \text{ kPa (6.21 psia)} \]
\[ T_{0,i,T} = 7.2^\circ \text{C} \]
\[ \text{TWC}_{e,T} = 6.5 \text{ g/m}^3 \text{ (^* Estimated)} \]

\[ U_{e,T} = 85 \text{ m/s} \]
\[ \text{MVD}_i = 15 \mu \text{m} \]

Ice accretion cases → a *

Liquid

Glaciated

Liquid

\[ U_{e,T} = 85 \text{ m/s} \]
\[ \text{MVD}_i = 50 \mu \text{m} \]
Test Section $T_{wb}$ (static) and Melt Ratio

$P_{0,i,T} = 44.8$ kPa (6.5 psia) and 42.8 kPa (6.21 psia)
$T_{0,i,T} = 7.2^\circ C$
$T_{WC,e,T} = 6.5$ g/m$^3$ (\* Estimated)

Ice accretion cases → a \* Accretions shown on next slides

$U_{c,T} = 85$ m/s
$MVD_i = 15\mu m$

$U_{c,T} = 85$ m/s
$MVD_i = 50\mu m$
Ice Accretion Examples

Accretion “b”
Low melt ratio

8x actual speed
(10 minute spray time)
Ice Accretion Examples

Accretion “e”
High melt ratio

8x actual speed
(10 minute spray time)
Surface TC measurements

Accretion “b”
Low melt ratio

Accretion “e”
High melt ratio
Summary

• NASA conducting research on fundamentals of ICI:
  – Identify and bound the conditions at the (local) accretion site
  – Generate & characterize conditions
  – Develop models & gather data on ice-crystal icing factors

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

• Presented data from an 8-day test effort in March 2016, examining:
  – Freeze-out characteristics of cloud
  – Changes in aero-thermal conditions at the test section
  – Ice characteristics observed

• These result offer modelers a dataset to help develop and validate ice-crystal, mixed-phase accretion models.
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Questions
Backup Slides
Measurements

• Temperature
  – Rearward Facing Temperature Probe
  – Commercial TAT Sensor
• Humidity
  – Spectra sensor WVSS-II
• Pressure / velocity / Mach
• Uniformity
  – Traverse RTFP
    • Temperature
    • Humidity
  – Condensed phase water
    • PSL Tomography
• Total water content
  – Isokinetic Probe – version 2
• Liquid water content
  – SEA Multi-Element Probe
• Particle size distributions
  – Cloud Droplet Probe (CDP)
  – Cloud Imaging Probe (CIP)
  – High Speed Imager (HSI)
  – Phase Doppler Interferometer (PDI)
• Video cameras recorded ice accretion
Test Section Changes is T and $\omega$ when cloud activated

$P_{0,i,T} = 44.8$ kPa (6.5 psia) and 42.8 kPa (6.21 psia)
$T_{0,i,T} = 7.2^\circ$C
$TWC_{e,T} = 6.5\, \text{g/m}^3$ (* Estimated)