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

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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

Atmospheric Environments Safety Technologies Project (AEST; 2009–2014)

↓

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.

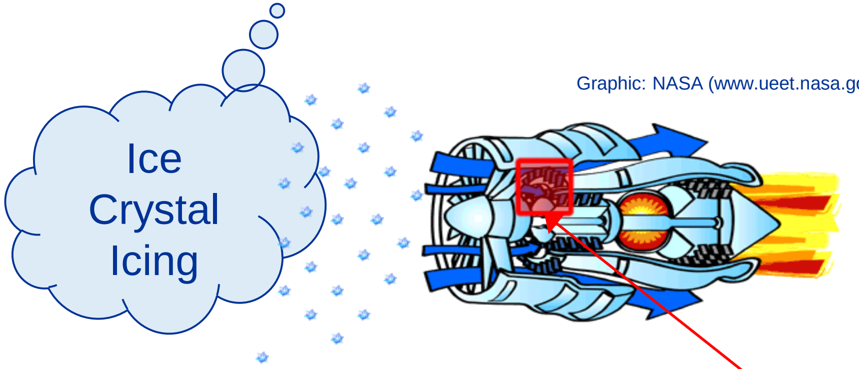
NASA Fundamental ICI Goals

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

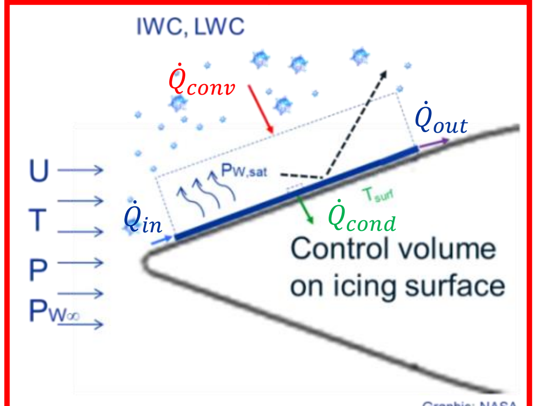


Graphic: NASA (www.ueet.nasa.gov)

PSL Work

Key: Link actual conditions in an engine to fundamental work

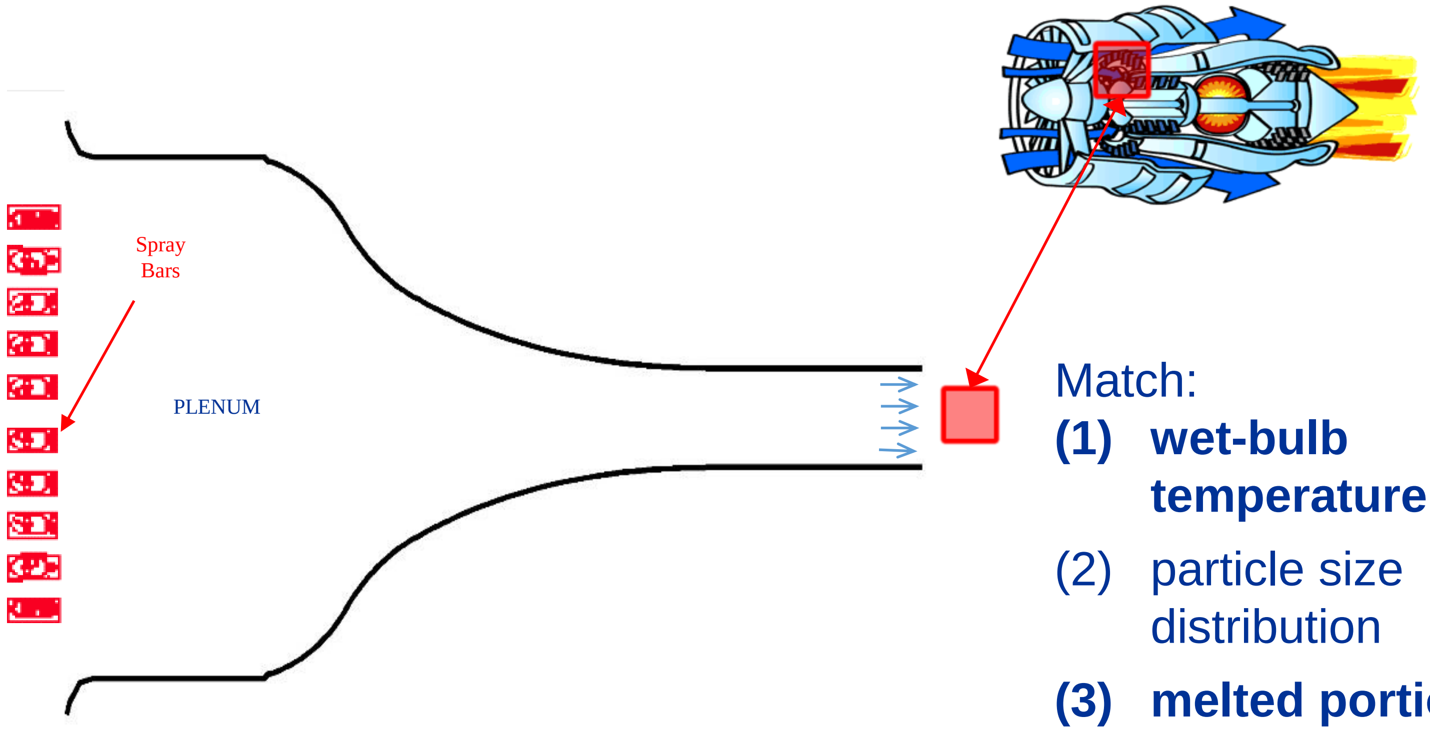
Local Region



Graphic: NASA

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

Concept Using PSL



Match:

(1) wet-bulb temperature

(2) particle size distribution

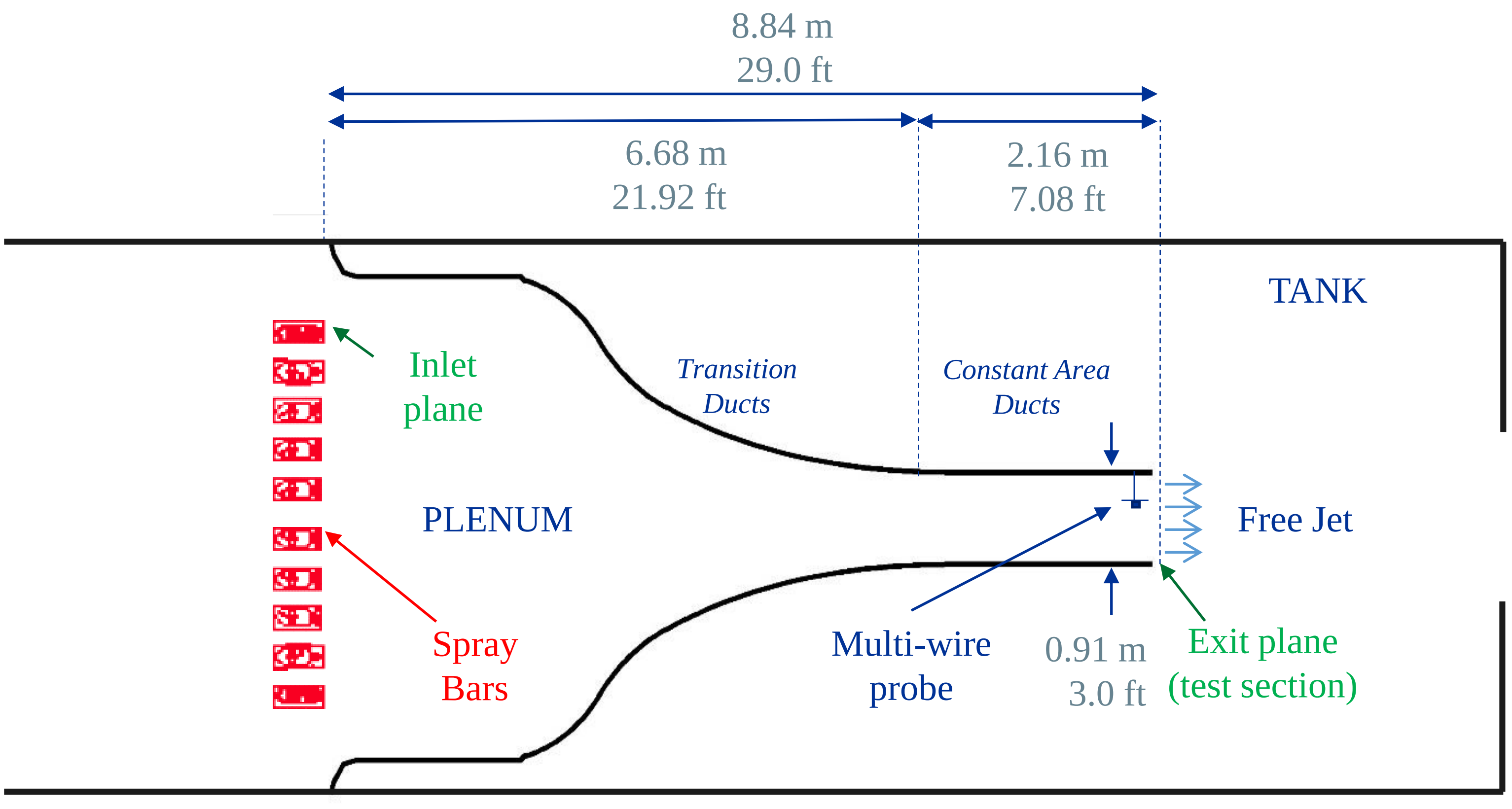
(3) melted portion of incoming ice

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

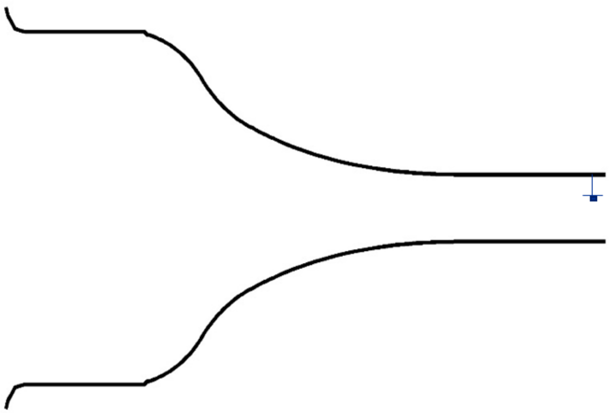
Preliminary Testing

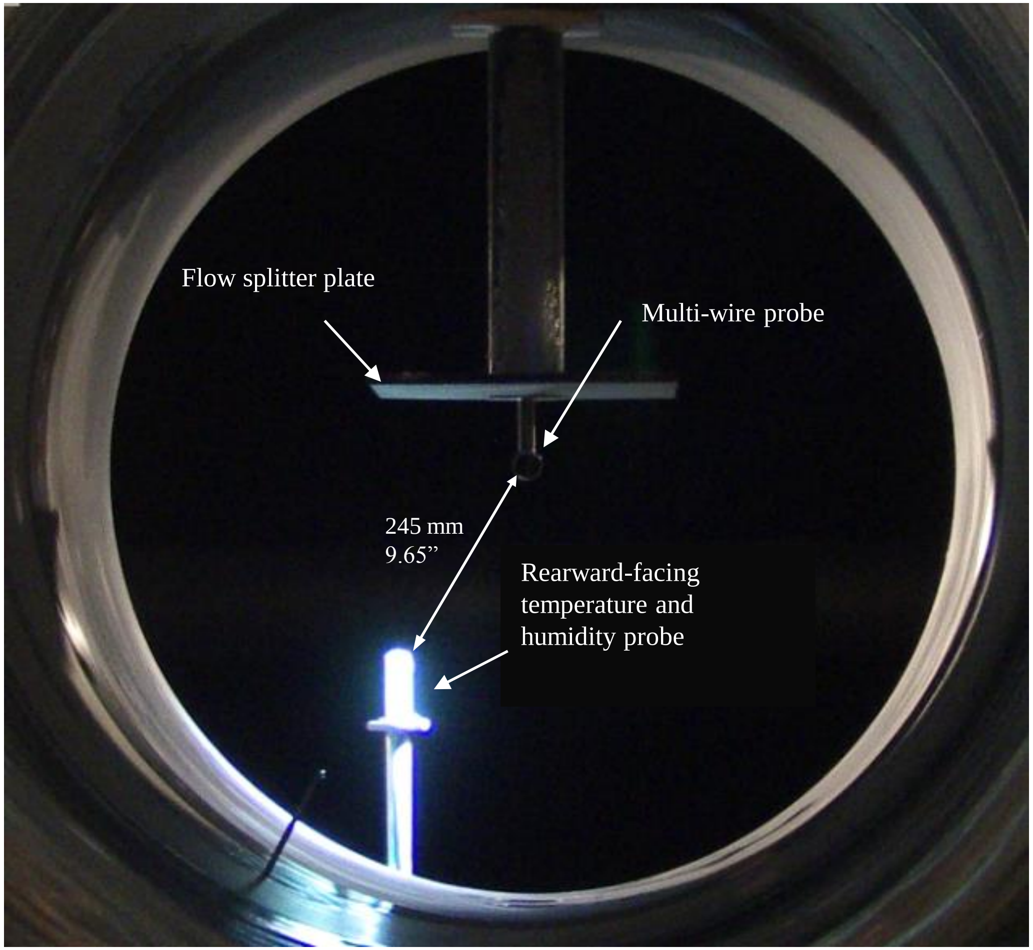
- **2 days of testing occurred in May 2015**
- **Objectives**
  - Preparation for more extensive test scheduled for 2016
  - Examine spray bar and plenum parameters and how they affect the mixed-phase at the exit of the free jet
  - Cloud characterization:
    - Melt ratio using SEA multiwire
    - Temperature & humidity measurements at test section (cloud on vs. cloud off) using custom probe
  - Observe ice accretion

PSL Configuration



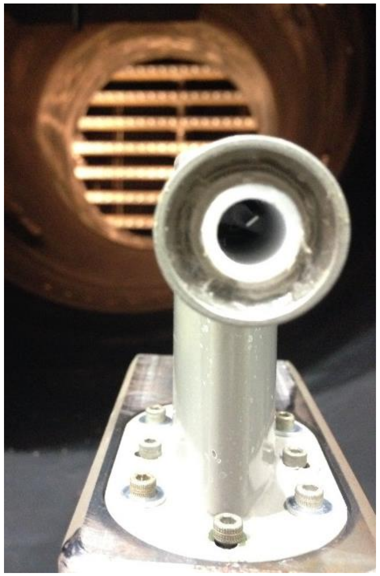
PSL Configuration (cont.)



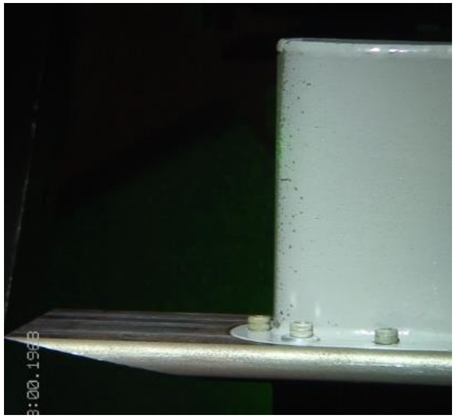


Temperature and Humidity Measurement

Side View



Top View



Tunnel Flow

- 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

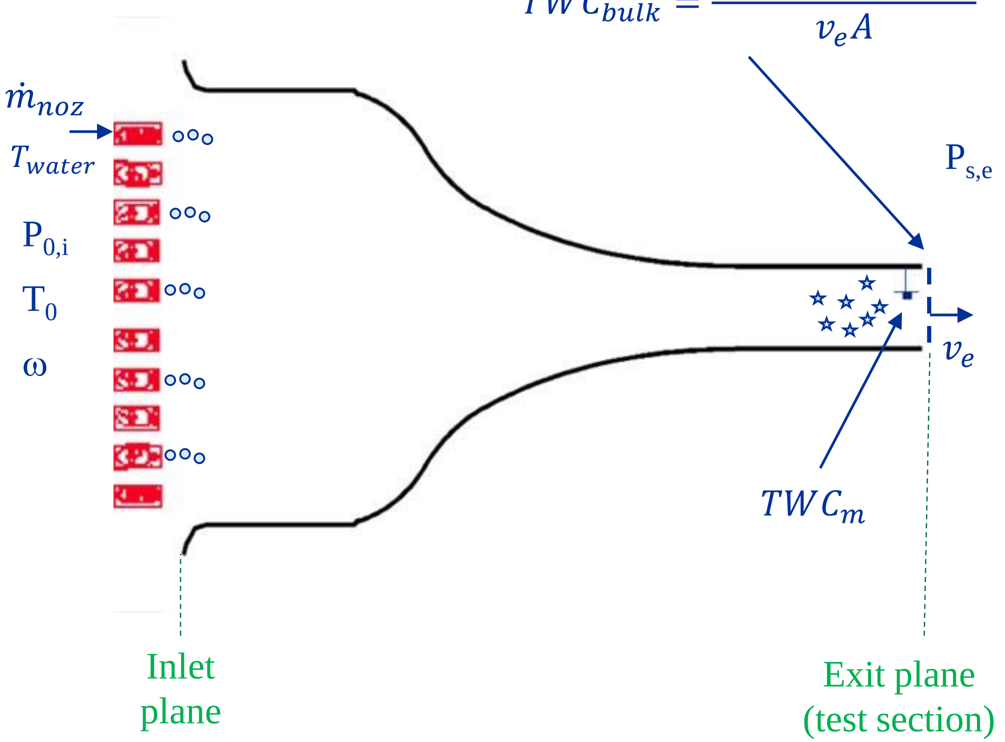
Mixed-Phase Investigation

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, ω_i (g / kg dry)
- Spray bar
  - TWC
    - P_{air} & $P_{water} \rightarrow \dot{m}_{noz}$
    - Nozzle #
  - Particle Size
    - MVDi (IRT calibrated values)
  - Water / air temperatures, T_{water}

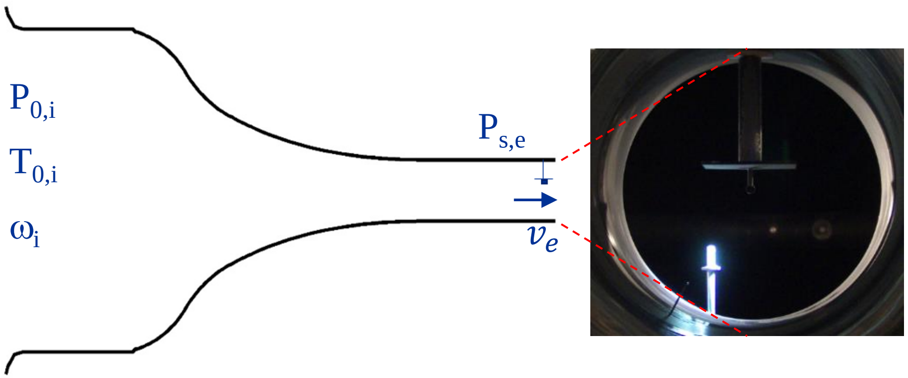
Nomenclature

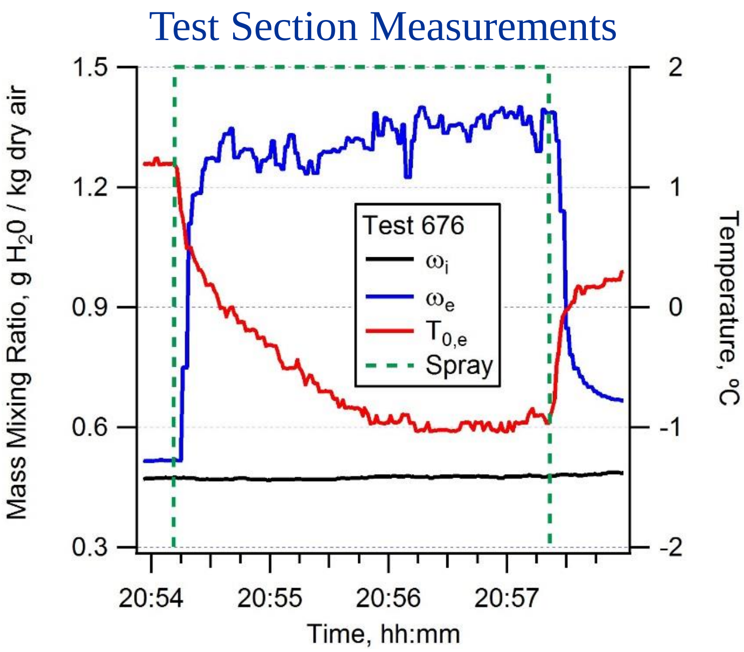
$$TWC_{bulk} = \frac{(\text{Nozzle \#})\, \dot{m}_{noz}}{v_e A}$$



Sample Test Data

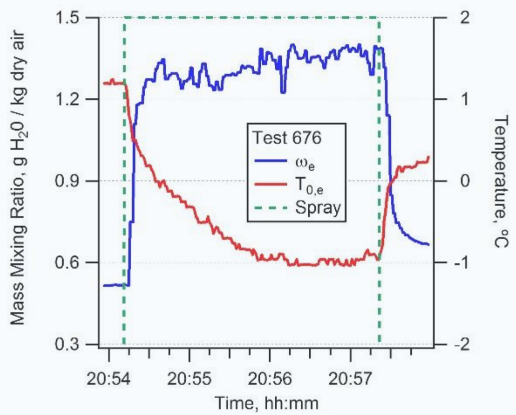
- Plenum / Test Section (targets)
  - $P_{0,i}$ = 87.3 kPa
  - $P_{s,e}$ = 83.6 kPa (1.6 km)
  - v_e = 85 m/s
  - $T_{0,i}$ = 1.8°C
  - ω_i = 0.5 g/kg dry (RH_{PL} = 10%)
- Spray bar
  - TWC_{bulk} = 1.4 g/m³
  - MVDi = 40 µm
- Reported data
  - Temperature measurement lag likely due to thermal inertia of inlet
  - 30 second averages
    - Cloud off (0.52 g/kg, 1.2 °C)
    - Cloud on (1.37 g/kg, -0.9 °C)
  - $\Delta T_{0,e} = T_{0,e,on} - T_{0,e,off}$

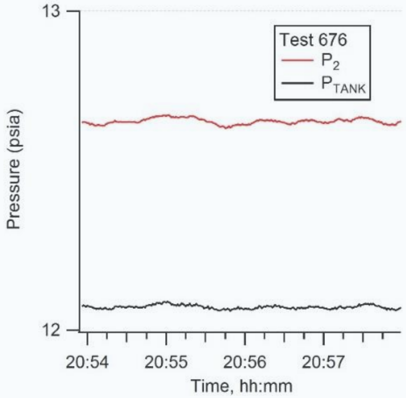




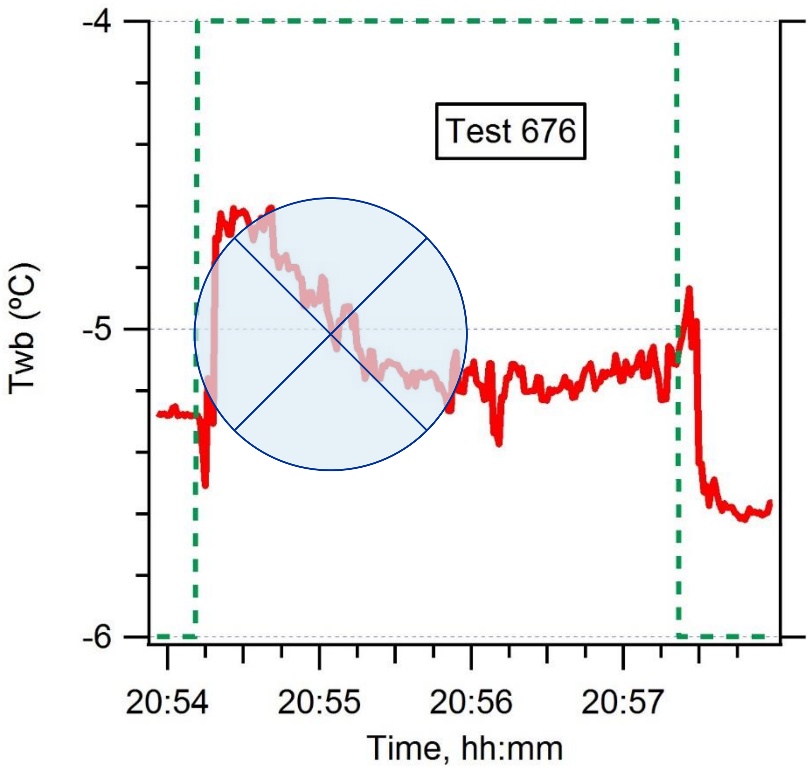
Wet-bulb temperature

INPUT



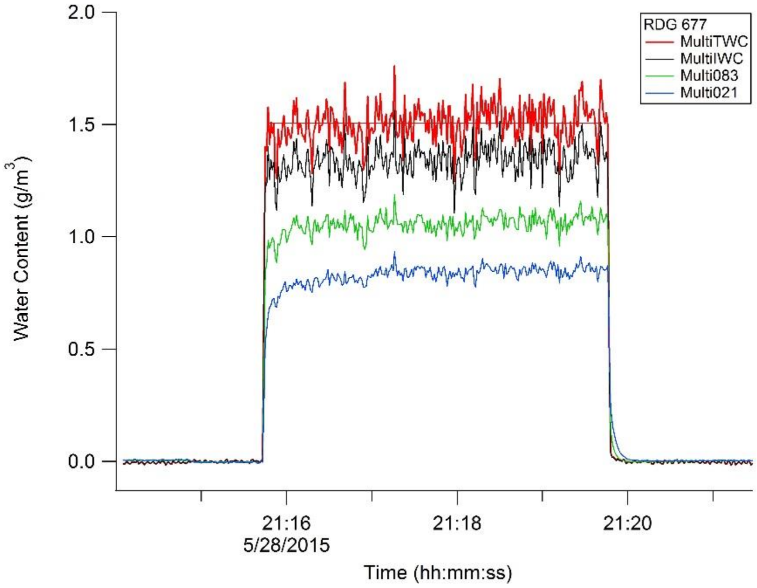


OUTPUT



Wet bulb slightly increased…typical result

Multiwire Results



- TWCbulk = 0.78 g/m^3
  - MVDi = 40 µm

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

  - Melt ratio, η_e

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

* more detailed analysis anticipated to be applied later

Ice Accretion Examples

Case 677 (η_e = 0.70)

Case 663 (η_e = 0.20)

8X actual speed

Parameter Sweeps

- Paper presents parameter sweeps for the following variables:
  - TWC_{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:
  - MVDi
  - Wet-bulb temperature

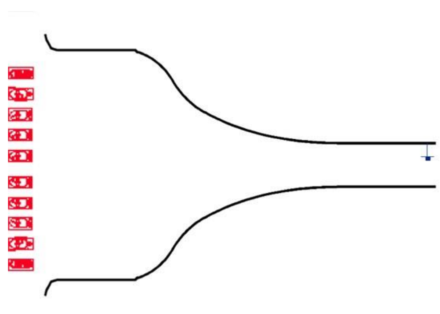


Table 2. Facility target conditions and select measurements during two TW

Test Series ->	TWC Sweep 3			
	Facility Target Condition			
$P_{0,i}$ (kPa)	87.3			
$P_{s,e}$ (kPa)	83.6			
v_e (m/s)	85			
Altitude (km)	1.6			
$T_{0,i}$ (°C)	4.2			
$T_{s,e,off}$ (°C)	0.6			
$RH_{0,i}$ (%)	10			
ω_i (g/kg)	0.6			
$Twb_{0,e,off}$ (°C)	-3			
$Twb_{s,e,off}$ (°C)	-6			
$T_{water,i}$ (°C)	7			
TWC_{bulk}(g/m^3)	0.78	1.4	2.3	5.0
MVD_i (μm)	40			
	Measurements			
Test #	670	671	672	673
TWC_m (g/m^3)	1.4	2.9	4.3	10.0
η_e (-)	0.69	0.66	0.23	0.27
$\Delta\omega_e$(g/kg)	0.55	0.87	1.3	2.3
$\Delta T_{0,e}$ (°C)	-1.7	-2.3	-2.9	-3.7
$Twb_{0,e,on}$ (°C)	-3	-4	-3	-2
$Twb_{s,e,on}$ (°C)	-6	-6	-5	-4
Ice Accr. (Y/N)	Y	Y	Y	Y

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_{water}
    - More limited variation on initial particle size and Twb
  - 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

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