Update on the NASA Glenn PSL Ice Crystal Cloud Characterization (2016)

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HAIC Forum, Toulouse, France, 2016-09.
**PSL Goal:** to simulate the ice crystal icing physics inside the engine core flow path.

**Outline**

- Facility Description (very briefly)
- Cloud Characterization Parameter Space
- Aspects Characterized
- Conclusions

PSL Facility

Crystals from spray nozzle freeze-out

Aero-Thermal Duct  Tomography & Raman  Cloud Calibration Duct

Sta 1

Configuration 1:
• Engine
• 27:1 CR

2016 HAIC Forum – Toulouse, France
Two regions of conditions simulated

- Engine Fan Face (Honeywell Engine Tests LF01 & LF11)

- Aft of Fan / Inside Booster (Fundamental Ice Crystal Icing Study, Struk et. al)
PSL Parameter Space

Airflow Conditions
• (Duct Geometry)
• Pressure Altitude, $P_0$
• Temperature, $TPL$
• Mach, Air Mass Flow Rate, $Wa$
• Relative Humidity, $RHPL$

Spray Conditions
• Nozzle Type & #: Mod1, Std
• Water Pressure, $P_{wat}$
• Air Pressure, $Pair$
• Air/Water Temp, $Tair$, $Twat$
• Water Source: City, DI
• Spraybar Cooling Air Temp and Pressure

PSL is Isentropic & Adiabatic

Physics of the Process:
• Liquid water issues from the spraybars.
• Water particles immediately start to evaporate.
• Particles start to chill/freeze as they travel through the plenum and into the contraction.
• The vapor …
PSL Cloud Characterization Elements

- Cloud Uniformity
- Total Water Content
  - Measurements in Center
  - Bulk average in Cross-Section
- Particle Size
- Particle Phase and Temperature

Also investigating
- Water vapor radial profile
- Temperature radial profile
Tomography – near real-time monitoring

Procedure:
- Measure light extinction with cloud OFF (baseline)
- Measure light extinction with cloud ON (extinction due to size and number of particles)
- Intensity Ratio, $I_{ij}$, output at every ‘pixel’ (i, j)
- Calculate avg Intensity Ratio over 1x1-in Center, $I_{00}$
- Calculate Concentration Factor, CF, $I_{00}/\sum I_{ij}$
Total Water Content Measurements

Multi-Wire (MW)  Robust Probe (RP)  Iso-Kinetic Probe (IKP2)

All measurements at Duct Center, TWC$_{00}$
TWC Measurement Notes

IKP2 (Standard):
• Importance of accurate background RH measurement

Heated Elements:
• Correct for Collection (Collision) Efficiency. No account for particle bouncing, splashing.
• Minimize flow angularity into MW head.
• Calculate both TWC (100% liquid) and iWC (100% ice).
  \[ \text{iWC} / \text{TWC} \approx 0.88 \]
• Particle Phase indicated by MW. Future investigations with SEA’s Ice Crystal Detector.
Bulk Total Water Content: Calculated

TWC\_Wf: Simple calculation assuming uniform distribution over entire duct based on measurands

- Water Flow Rate ($Wf$)
- Air Mass Flow Rate
- Sta 1 Static Pressure and Temperature

TWC\_Wf\_BL: Add a cloud boundary layer thickness

TWC\_Wf is the \textit{basis function} for TWC measurements
Bulk Total Water Content: Measured

- Combine Measured $TWC_{00}$ and Tomography CF.

$$TWC_{Bulk\_Meas} (g/m^3) = \frac{\sum (I_{ij} \times (TWC_{00}/I_{00}) \times A_{ij})}{\sum A_{ij}}$$

- Created a CF curve fit based upon Pair and TWC_Wf, TWC_Bulk_Fit
TWC Bulk Comparison

IKP + Tomography ≈ Water Flow + Boundary Layer

With the same boundary layer thickness assumption, and same basis formulation, TWC_Wf
Particle Size Measurements

Both PDI and HSI are non-intrusive.

Have taken data in two most recent efforts at center and off-center. Will be reported in future.

Phase Doppler Interferometer (PDI)
- Particle size (liquid only)
- Particle velocity
- Number density

High Speed Imager (HSI)
- Particle size (ice & liquid)
- Shape
- Number density
Particle Size Measurements (liquid)

Cloud Droplet Probe (CDP)

Cloud Imaging Probe (CIP-GS)

All measurements at Duct Center.
Future ability to shift off-center
Sample HSI Images

Liquid

Crystal
Particle Phase & Temperature Meas.

- “Point” measurement at beam waist
- Benchtop success and some success in PSL, with particles moving at 0.5 Mach
- Development continues
Radial Temperature & Humidity Profiles at Station 1 Change, $\Delta = (\text{Station 1} - \text{Plenum}^+)$ with Cloud On

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Preliminary Data

Temperature

Mass Mixing Ratio

Translating Temperature and Humidity Probe
Conclusions & Future Work

• Cloud Cal Space is 12-parameters with complex interactions

• TWC Measurements
  - Best measured with IKP2.
  - Bulk Measured (IKP + tomography) matches Bulk Calculated.

• PSD Measurements (least confidence)
  - HSI for ice crystals, but misses smallest particles (< 9 um).
  - Investigate off-center measurements.

• Particle Phase and Temperature Measurements
  - Phase indicated with MW. Ice Crystal Detector in future?
  - Progress on measuring with Raman / Fluorescence spectra.

• Investigate and document Cloud On radial RH and Temperature profiles
TWC & radial distribution of particle size

- Scatter in data due to radial MVD effect. CFD predicts larger particles concentrated at center, while smaller particles more uniformly distributed.
- This radial MVD profile is *not* currently incorporated into the tomography intensity ratios.
Particle Phase and Temperature

- Raman Spectra can evaluate bonded structure of water in both liquid and solid phases, as well as temperature.
- Benchtop success