An Assessment of
the SEA Multi-Element Sensor
for Liquid Water Content Calibration
of the NASA GRC Icing Research Tunnel

Laura E. Steen – Sierra Lobo, Inc.
Robert F. Ide – Sierra Lobo, Inc.
Judith F. Van Zante – NASA Glenn Research Center
Cleveland, Ohio

International Icing Conference 2015, Prague
June 25, 2015
Introduction:

• The NASA Glenn Icing Research Tunnel (IRT) is a facility that is heavily utilized for development/certification of aircraft ice protection systems and icing research.
  • Data from the IRT has been accepted by the FAA, EASA, CAA, and JAA in support of manufacturers’ icing certification programs.

• The IRT had been using an Icing Blade technique to measure cloud liquid water content since 1980.

• The IRT conducted testing with Multi-Element sensors from 2009 to 2011 to assess performance. These tests revealed that the Multi-Element sensors showed some significant advantages over the Icing Blade.

• Results of these and other tests are presented here.
Outline:

• Facility Description (IRT)
• Description of the Multi-Element Sensor
  • Components
  • Physics (theory of operation)
  • Processing Multi-Element data
• Description of the Blade
  • Measurement Principles
  • Ludlam Limit
• Comparisons of Multi-Element Sensor to Blade
  • Varying water content
  • Varying speed
  • Varying drop size (Large drops, SLD)
• Conclusions:
  • Strengths of Blade
  • Limitations of Blade
  • Strengths of Multi-Element
  • Limitations of Multi-Element
• Test section size: 6 ft. x 9 ft. (1.8 m x 2.7 m)
  • All LWC & MVD calibration measurements are made in the center of the test section
  • LWC uniformity is ±10% for the central 4 ft x 6 ft
• Calibrated test section airspeed range: 50 – 325 kts
• Air temperature: -40 degC static to +20 degC total
• Calibrated MVD range: 14 – 270 µm
• Calibrated LWC range: 0.15 – 4.0 g/m³ (function of airspeed)
• Two types of spray nozzles:
  • Standards = higher flow rate
  • Mod1 = lower flow rate
The Multi-Element Sensor
From Science Engineering Associates, Inc.

• Commonly known as “the Multi-Wire”

• Typical Multi-Wire shrouds contain 3 sensing elements of various sizes
  • Different element types are designed for better response to different conditions
  • Elements vary in diameter and in shape
  • IRT typically uses just the TWC element for LWC calibration

• A compensation wire is located behind central element
  • Shielded from impinging liquid/ice water
  • measures changes coming only from airspeed, air temperature, air pressure, and relative humidity
Multi-Element Sensor
Theory of Operation

- A voltage is applied across each of the elements to maintain them at a temperature of 140 degC
  - Elements are cooled by convection and impinging water
- Data system records the power required to maintain each element at constant temperature.
- The compensation wire is shielded to stay dry
  - Changes in the comp wire during a spray are reflected in the calculated water content
- The recorded powers are used to calculate liquid water content:

  \[
  LWC = \frac{P_{\text{elem,wet}}(\text{watts}) \times 2.389 \times 10^5}{L_{\text{evap}} \frac{\text{cal}}{g} + 1.0 \frac{\text{cal}}{g} \cdot s \cdot C (T_{\text{evap}} - T_{\text{ambient}})} \times TAS \frac{m}{s} \times l_{\text{elem}} mm \cdot w_{\text{elem}} mm
  \]

  \[P_{\text{elem,wet}} = P_{\text{elem,tot}} - (\text{offset} + \text{slope} \cdot P_{\text{comp,dry}})\]

  Subtract off cooling from dry air, correlated to comp wire

  Conversion factor

Source: the SEA User’s Manual
Multi-Wire Data Processing

Multi-Wire data trace, showing all 4 sensing elements

Multi-Wire Data processing:

- IRT uses only the water content values from the TWC element
  - *A comparison of the different elements is beyond the scope of this presentation*

- In-house MATLAB code averages and tares the recorded values
  - Code also flags data irregularities

- Measured TWC is corrected for collection efficiency*

The Icing Blade

- Simple piece of stainless steel: 1/8” x 6” x 3/4”
  - 3.175 mm x 154.2 mm x 19.05 mm
- Was the standard measurement for all LWC calibrations in the IRT from 1980 to 2011
- Ice Accretion: Requires Rime Ice
  - Tunnel total air temp of -18 to -20 degC
  - Adjust spray time to collect approx. 0.15 in. (3.8 mm) of ice.
    \((12 \leq t \leq 200 \text{ sec})\)
  - Width of ice is measured (< 0.200 in., or 5mm) to make sure changes in collection efficiency are minimal
- 3 measurements (1 in. apart)—use the median value

\[
LWC = \frac{1710 \times d}{V \times t \times E_b}
\]

\(d\) = ice thickness (mm)
\(V\) = tunnel airspeed (kts)
\(t\) = spray time (sec)
\(E_b\) = Collection efficiency (calculated, function of airspeed, air density, & drop size)
\(1710\) = constant—contains unit conversions and an assumed ice density of 0.88
The Ludlam Limit (for the blade)

• **Ludlam Limit**: the supercooled water impingement rate above which not all impinging water will freeze for a given air temperature and airspeed (impingement rate above which the measured LWC is reduced)
  - Water impingement rate is a function of the airspeed, LWC, & Collection Efficiency

• Stallabrass applied Ludlam’s work to derive the Ludlam limit for a 1/10\(^{th}\) inch diam. rotating cylinder. We used his data to calculate the limit at -20 degC

Consider: We have a 1/8\(^{th}\) in. Blade, not a 1/10\(^{th}\) in. rotating cylinder.

• **Collection Efficiency**:
  - We have data that shows the collection efficiency of the 1/8\(^{th}\) inch blade is within 2\% of that of the 1/10\(^{th}\) inch cylinder

• **Temperature**: Stallabrass used static air temperature.
  - In the IRT, icing blade tests are conducted at a total temperature between -18 and -20 degC.
  - The blade temp is somewhere between static and total

Comparing Multi-Wire vs. Blade

• Thorough comparison had to be done before we could switch LWC calibration instruments.

• The Multi-Wire has obvious advantages over the Blade in terms of:
  • Temperature → the Blade requires hard rime conditions
  • Test efficiency → can collect 30 conditions/day with Blade, vs. 50 conditions/day with Multi-Wire
  • Spray time → not restricted, can capture real-time trends

• We want to see how the two instruments compare, varying:
  • Liquid water content (LWC)
  • Airspeed
  • Drop size (MVD)
Multi-Wire vs. Blade, with respect to Liquid Water Content

- For these points:
  - Airspeed = 150 kts
  - MVD = 20 µm
  - $T_{\text{tot}} = -20 \text{ degC (blade)}$
  - $T_{\text{tot}} = -10 \text{ degC (multi-wire)}$

- For these conditions, the Ludlam limit is 1.8 g/m$^3$ if we use the total temp, and 2.2 if we use the static temp.

- This plot shows the water contents match until the LWC approaches or surpasses the Ludlam Limit.
Multi-Wire vs. Blade, with respect to **Airspeed**

- Airspeed sweeps for two nozzle sets, MVD=20µm
  - Standard nozzles are higher water flow, Blade testing requires shorter spray time.
- Plotted alongside Ludlam limit curve fit shown on previous slide
  - Limit for a temperature of -20 degC
- The Mod1 nozzles show good agreement between the MW and the blade, even at high airspeeds
- But at higher impingement rates (LWC x airspeed x Collection Efficiency), the blade measures lower than the MW

Blade & Multi-wire LWC vs. Airspeed (MVD = 20µm)

- Standard nozzles, Multi-wire
- Standard nozzles, Blade
- Mod1 nozzles, Multi-wire
- Mod1 nozzles, Blade
- Ludlam Limit, assuming Blade at Tstat
- Ludlam Limit, assuming Blade at Ttot
Multi-Wire vs. Blade, with respect to **Drop Size (MVD)**

Multi-wire vs Blade LWC, at 100, 150, and 250 kts

- As drop size increases, Blade measures lower than Multi-Wire. But is this an effect of increasing drop size or of increasing LWC?
- We will try plotting this a different way...
Multi-Wire vs. Blade, with respect to Drop Size (MVD) (part 2)

- For smaller drop sizes at all velocities, there is an LWC limit at which the Blade measures lower than the Multi-Wire, even for MVD’s below 50 µm.

- For larger drop sizes, the Ludlam limit can no longer account for the roll-off we see from the Blade. We suspect that we have an added problem due to mass-loss (splashing?) at larger drop sizes.
Conclusions:

Strengths of Blade
- Simplicity
- Reliability
- Researcher can see the physical ice characteristics

Limitations of Blade
- Does not respond well at higher impingement rates (Ludlam limit)
- Does not respond well at larger drop sizes (suspect mass-loss)

Strengths of Multi-Wire
- Compares well to Blade for most Appendix C conditions
  - MVD ≤ 30 µm
  - Moderate impingement rates
  - Some MW results validated by icing scaling tests in the IRT
- Temperature independent
- Test efficiency
- Spray time independent
- Ability to measure ice crystals (not addressed in this presentation)

Limitations of the Multi-Wire
- No limitations of the multi-wire were found from these tests
Questions?