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

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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 Facility

Icing Research Wind Tunnel

- 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:

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

  - \( P_{elem,wet} \) is the power required to maintain each element at constant temperature.
  - \( L_{evap} \) is the amount of energy required to raise the drop temp to evaporative temperature and then evaporate it (cal/g).
  - \( TAS \) is the air speed at which the sensor is operating (m/s).
  - \( l_{elem} \) and \( w_{elem} \) are the length and width of the sensing element (mm).
Multi-Wire Data Processing

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 ≤ t ≤ 200 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

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

- \( d \) = 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 1/10th inch diam. rotating cylinder. We used his data to calculate the limit at -20 degC

**Consider**: We have a 1/8th in. Blade, not a 1/10th in. rotating cylinder.

- **Collection Efficiency**:
  - We have data that shows the collection efficiency of the 1/8th inch blade is within 2% of that of the 1/10th 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

**Figure**: Ludlam limit as a function of airspeed for a 1/10th inch (2.49 mm) diam. cylinder and two temperature constraints [data from Stallabrass]

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
  - $T_{tot} = -20$ degC (blade)
  - $T_{tot} = -10$ degC (multi-wire)
- For these conditions, the Ludlam limit is $1.8 \text{ g/m}^3$ 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
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?