Air Probes Tests in Icing Tunnels

A Heat and Mass Transfer Effects Review

SAE Aerospace
An SAE International Group

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Introduction

Review

Testing

Conclusions

Acknowledgments

Objectives

- ✓ *Perform a bibliographic research;*
- ✓ *Present an overview about heat and mass transfer effects during icing tests of heated pitot probes.*

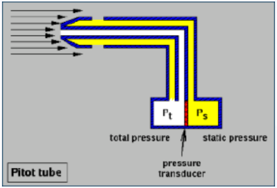
Presentation focus

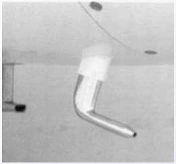
- ✓ *Heat and mass transfer aspects of thermal ice protection of pitot probes;*
- ✓ *Aspects of similitude tunnel-flight when testing heated pitot type probes;*
- ✓ *Main reason → Knowledge and experience of authors.*

Review

Air Data Probes Ice Protection:

- ✓ *High water droplets collection efficiency (by definition)*
- ✓ *Usually fuselage mounted*
- ✓ *Local AOA differs from aircraft AOA because installation*
- ✓ *Local LWC may differ from freestream LWC cloud value due installation*
- ✓ *Typically electrical anti-icing and de-icing heaters installed*
- ✓ *Certification based on FAA TSO-C16a and FAA FAR 25 sections and Ap. C*
- ✓ *New rules and standards under discussions at ARAC, IPHWG and SAE*
- ✓ *EASA CRI with additional conditions*





Source: Duvivier, E. (EASA) "Flight Instrument External Probes", 1st SAE Aircraft & Engine Icing International Conference, Seville, 2007

Current Probe Qualification Documents

- ✓ *FAA - TSO C16a (refs. AS8006, BS2G.135 and FAR 25 AP. C)*
- ✓ *SAE - AS390, AS393, AS403A, AS8006*
- ✓ *British Standard Institution - BSI 2G.135*
- ✓ *MIL - MIL-T-5421B, MIL-T-5421A, MIL_P-83206, MIL-P-25632B*

Coverage

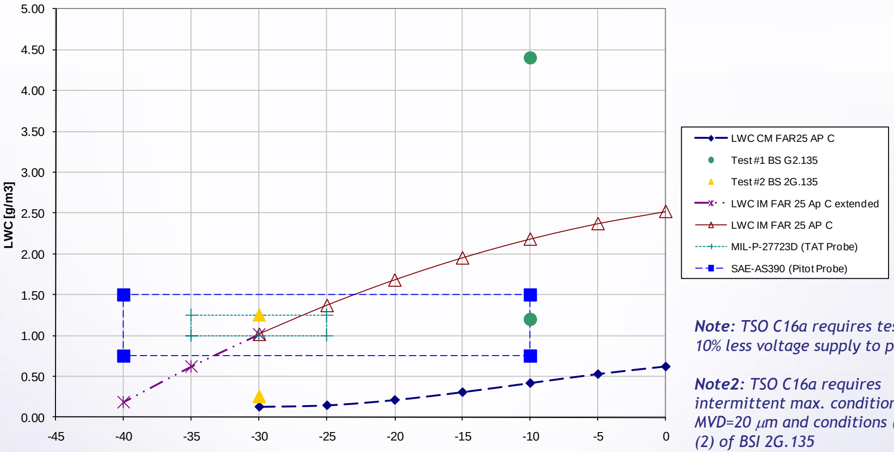
Environmental Conditions: Temperature, Altitude, Vibration, Radio Interference, Magnetic Effect

Detail Requirements: Drainage, Marking, Power Variation, **Anti-Icing / De-Icing**

Individual Performance Tests: Leakage, Dielectric, Heater Operation, Insulation Resistance, Aerodynamic Tests

Qualification Tests: Vibration, Endurance, Scale Error @ 0 deg AoA, Scale Error @ various AoA, Scale Error @ various angles of Yaw, Magnetic Effect, **Anti-Icing / De-Icing**, Cold soak, Shock, Salt Spray, Sand and Dust, Humidity, Power Consumption, Heat Conductivity, Status, Weight, Repeatability

LWC vs. Static Air Temperature (SAT) Chart



***Note:** TSO C16a requires tests with 10% less voltage supply to probe*

***Note2:** TSO C16a requires intermittent max. conditions with MVD=20 μm and conditions (1) and (2) of BSI 2G.135*

SAE AS5562 (Draft) - Ice and Rain Qualification Standards for Airdata Probes

- ✓ *Not yet released, under development by SAE AC-9C Committee*
- ✓ *Types of Probes:*
  - Pitot, Static Pressure, Angle of Attack and Temperature Probes
- ✓ *Conditions*
  - Liquid, Mixed and Solid Phase Icing
  - Rain
  - Super Large Droplets (SLD)*
    - Freezing Rain
    - Freezing Drizzle
- ✓ *Aircraft installation effects, including concentration factor*
- ✓ *Testing*
  - Setup Effects
  - Operational limitations
  - Test Procedure

(*) SLD envelope also under discussions by FAA and EASA at IPHWG Task 2.

Testing

Some Typical Icing Tunnel Limitations

- ✓ *Maximum true air speed (TAS) lower than in-service*
- ✓ *Operational pressure is usually higher (lower altitude) than in-service*
- ✓ *Cloud characteristiscs (LWC and MVD) may differ from flight*
- ✓ *Tunnel minimum temperature may be higher than in flight*

Tunnel Condition Adjustment (as per AS5562 draft) :

- ✓ *Mass air flow at the probe be equiv. or greater than at the in-service*
- ✓ *Water drop mass flux be no less than at the in-service condition*
- ✓ *Total air temperature be no greater than at the in-service condition*
- ✓ *To compensate higher temperatures, increase mass airflow to realize a desired lower probe surface temp. and/or decrease probe power.*
- ✓ *Rules related to MVD and LWC under discussion*

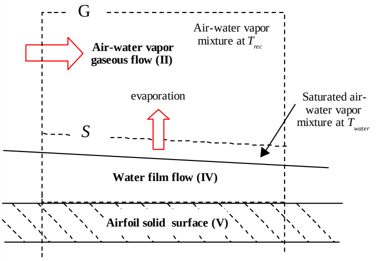
Typical Similitude Parameters

- ✓ *Flow*
  - ➢ Reynolds number (Re)
  - ➢ Mach or True Air Speed (TAS)
- ✓ *Water Droplets Impingement and Trajectories*
  - ➢ Water catch
  - ➢ Droplets inertia parameter
- ✓ *Heat and Mass Transfer*
  - ➢ Water evaporation rate (runback=impinged-evaporated)
  - ➢ Heat and mass transfer rate (heat load)
  - ➢ Skin Temperature
  - ➢ Total Air Temperature (TAT)

- ✓ *Parameters depends on test objectives and installation*
- ✓ *When is impossible to keep the important parameters fixed, choose parameter values to have a conservative tunnel condition*

Coupled Heat and Mass Transfer*

- ✓ *Heat transfer coefficient (or* **St***) depends on* **Re** *and* **Pr***;*
- ✓ *Higher the* **Re***, higher* **St***, higher the mass transfer coefficient (by analogy);*
- ✓ *Mass transfer driven force depends on surface temperature (saturation pressure) and ambient pressure (water vapor partial pressure);*
- ✓ *But higher the mass transfer, thicker the thermal boundary layer, lower the* **St** *(important for surface temperature > 40 C) …*
- ✓ *Higher the ambient pressure, higher the* **Re** *and* **St** *but lower the driven force …*
- ✓ *Higher the lost by evaporation, lower the temperature but lower the evaporation, higher the temperature…*
- ✓ *Solution by 1st Law ! Only thermal analysis will determine what effect is more important.*



(*) Only liquid water considered

Coupled Heat and Mass Transfer (Spalding, 1962)

Evap. mass flux and mass transfer conv. coefficient: $\dot{m}''_{evap} = g_m \cdot B_m$ &

$$g_m = g_h \cdot Le^{2/3} = \frac{h_{conv}}{c_p} \cdot Le^{2/3}$$

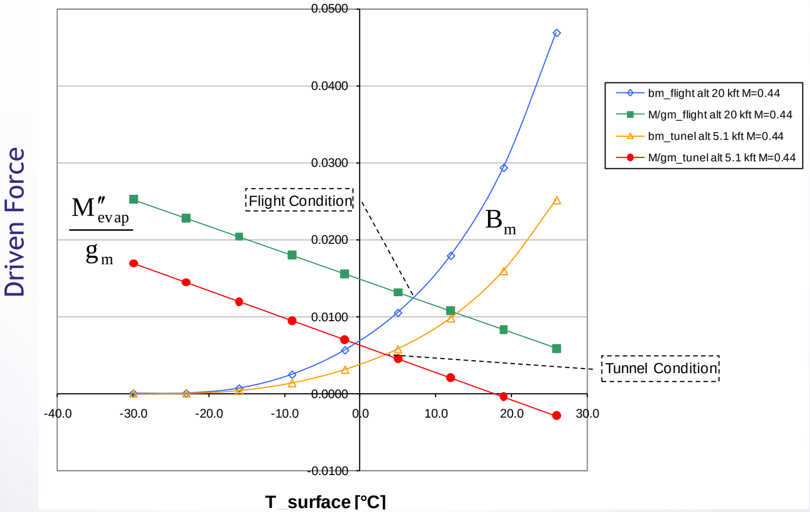
Mass transfer driven force: $$B_m = \frac{m_{H2O,S} - m_{H2O,G}}{m_{H2O,S} - 1}$$

Mass fraction close to water film surface: $$m_{H2O,S} = \frac{p_{vap}}{1.61 \cdot p_{amb} - 0.61 \cdot p_{vap}}$$

Mass fraction in compressible flow near B.L. edge: $$m_{H2O,G} = \frac{p_{vap}}{1.61 \cdot p_{amb} - 0.61 \cdot p_{vap}}$$

The evaporative mass flux by First Law of Thermodynamics: $$\frac{\dot{m}''_{evap}}{g_h} = B_h = \frac{1}{h_{lv}} \cdot \left[c_{mix} \cdot (T_{rec} - T_{surf}) + \frac{\dot{q}''_{surf}}{g_h} \right]$$

Coupled Heat and Mass Transfer Effects*



(*) Only liquid phase considered. Sample calculation.

Conclusions

Conclusions on Testing Pitot Tubes

- ✓ *Icing tunnels are important and necessary tools*
- ✓ *Literature of calibration, operation and selection of tunnels is rich*
- ✓ *Tunnel tests must be always conservative*
- ✓ *Current tools for similitude:*
  - SAE recommendations;
  - Analytical 1st Law analysis;
  - Ice protection code.
- ✓ *More research required about similitude flight vs. tunnel*

Presentation References

- ✓ *Certification/Qualification Documents*
  - ➢ Regulations – FAR 25 and **TSO C16a**
  - ➢ Standards – SAE AS390, SAE AS393, SAE AS403A, SAE AS8006, BSI 2G.135, MIL-T-5421B, MIL-T-5421A, MIL_P-83206, MIL-P-25632B
- ✓ *SAE Standard in preparation*
  - ➢ **SAE AS5562 (Draft)** - Ice and Rain Qualification Standards for Airdata Probes
  - ➢ AC-9C, Air Data Probe Standards Panel, SAE, 2006 (presentation)
  - ➢ AC-9C, Design Requirement Cross Reference List Rev6, SAE (excel spreadsheet)
- ✓ *SAE , SAE Aerospace Applied Thermodynamics Manual, **"Ice, Rain, Fog, and Frost Protection"**, SAE AIR1168/4, Proposed Draft, 2006*
- ✓ *Spalding, D. B., **"Convective Mass Transfer, an Introduction"**, McGraw-Hill, New York, 1963.*
- ✓ *Duvivier, E. (EASA) **"Flight Instrument External Probes"**, 1st SAE Aircraft & Engine Icing International Conference, Seville, 2007 (conference presentation)*

Further Reading

- ✓ *Mason, J., "**The Physics of Clouds**", 2nd Ed., Claredon Press, Oxford, 1971 (book)*
- ✓ *Johns, D. (TC Canada), "**Future Rulemaking - Ice Protection Harmonization Working Group - Update**", 1st SAE Aircraft & Engine Icing International Conference, Seville, 2007 (conference presentation)*
- ✓ *Bernstein, B., Ratvasky , T. P., Miller, D.R., "**Freezing Rain as an in-Flight Icing Hazard**", NASA TM--2000-210058, NCAR, Colorado, June (NASA Report)*
- ✓ *Jeck, R. K., "**Representative Values of Icing-Related Variables Aloft in Freezing Rain and Freezing Drizzle**", DOT/FAA/AR-TN95/119, Federal Aviation Administration, U.S. Department of Transportation,1996 (FAA Technical Note)*
- ✓ *Jeck, R. K., "**Advances in the Characterization of Supercooled Clouds for Aircraft Icing Applications**", DOT/FAA/AR-07/4, Federal Aviation Administration, U.S. Department of Transportation,2008 (FAA Report)*
- ✓ *European Aviation Safety Agency (EASA), **ETSO C16 update** , Terms of Reference, ToR Task number ETSO.009, Issue 1, August 31, 2009 (EASA document)*
- ✓ *Ice Protection Harmonization Working Group (IPHWG), **Tasks 5 & 6 Working Group Report**, October 2006, Rev A March 2007 (IPHWG report)*
- ✓ *Ice Protection Harmonization Working Group (IPHWG), "**Task 2 Working Group Report on Supercooled Large Droplet Rulemaking**", December 2005 (IPHWG report)*

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Thank you !