Analysis of Experiments and Simulations for the Certification of Aeronautical Structures and Sensors in Icing Conditions.

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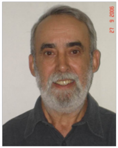
Organization COPPE/UFRJ

Our Technical Leaders



Principal Engineer

Francisco Domingues Alves de Sousa,

- *1970-80 CGreco Consulting - Consultant in Industrial Combustion*
- *1980-2010 Institute for Technological Research - Thermal Engineering Division where leaded laboratories and research teams and projects with industry*
- *Petrobras and IPT Innovation Awards*
- *Since 2010 at ATS4i as associate*

Director Aerospace

Guilherme Araujo Lima da Silva, PhD

- *1997-2007 Embraer - Air Managements Systems, Environmental Control Systems, Bleed Air Systems, Ice Protection, Avionics Cooling at AMX, F-5 BR, Embraer 120, ERJ 145/140/135, Embraer 170/190, Phenoms*
- *PhD 2008 - Heat and Mass Transfer in Two-Phase Flow in Anti-ice Systems*
- *Since 2007 at ATS4i as associate*

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- *1998-2007 Institute for Technological Research (IPT) - Thermal Engineering Division where leaded researches and managed several consulting works*
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ATS4i Selected Customers

EMBRAER

GOODRICH

Braskem

UTC Aerospace Systems

ALUMAR

PETROBRAS

VALE

SIEMENS

AMT

BRASCOPTER

MEGGITT

ZODIAC AEROSPACE

AcousticFab LLC

AngloAmerican

HARTZELL aerospace

IAE

OGRAMAC Engenharia de Superfície

Votorantim Metais

Marinha do Brasil

SAMARCO Desenvolvimento com Envolvimento

AVIBRAS

INPE

COPEBRÁS Uma empresa do grupo Anglo American plc

ULTRAGAZ especialista no que faz

TECSIS Tecnologia e Sistemas Avançados

ERM

AECOM

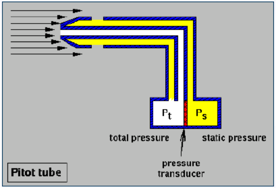
ipt Instituto de Pesquisas Tecnológicas

Mectron Organização Odebrecht

1. Introduction
2. SAE AIR1168/4 Analytical Model
3. Simple Analysis - Coupled Heat and Mass Transfer
4. Inclusion of effects of Impingement and Ice Crystals
5. Conclusions and Possible New Directions

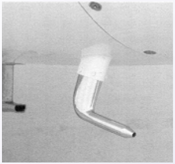
1. Introduction

Air Data Probes Ice Protection:



- ✓ *High water droplets collection efficiency*
- ✓ *Usually fuselage mounted*
- ✓ *Typically electrically heated*
- ✓ *Ice crystals can enter in the probe*

- ✓ *Certification based on FAA TSO-C16a and FAA FAR 25 sections and Ap. C*
- ✓ *Next versions of TSO-C16 may refer to future SAE AS 5562*



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

When designing, testing and certifying ice protection system for Pitot tubes, some questions will appear:

- What are the most critical conditions to base my design?
  - ✓ *Standards, regulations and scientific-engineering knowledge*
- How can I prove that my design is adequate?
  - ✓ *By test, analysis or simulation*
- How can I test it in tunnel to represent actual atmospheric flight condition?
  - ✓ *Similarity rules and procedures for icing tunnel testing*

Objectives

- ✓ *To compare traditional and new standards to verify criticality and applicability of each one*
- ✓ *To perform heat transfer flight-tunnel similarity studies in order to verify simple scaling limits*
- ✓ *To collaborate with UFRJ-COPPE research efforts to define test conditions for their icing tunnel*

Scope

- ✓ *Heat and mass transfer aspects of ice protection of probes*
- ✓ *NO focus on absolute results! Only comparative.*
- ✓ *Do a simple analysis FIRST to understand trends and phenomena*

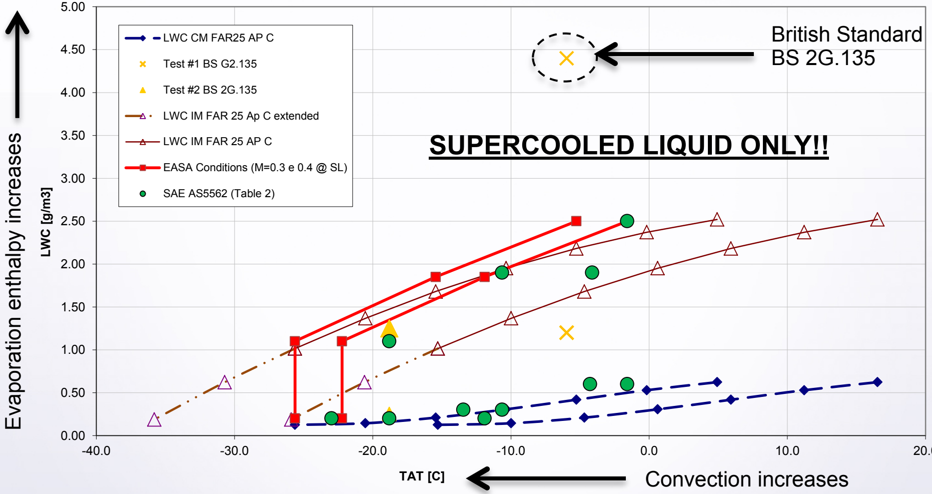
Main References

- ✓ *FAA FAR 25 Appendix C*
- ✓ *British Standard BS 2G.135*
- ✓ *FAA TSO C16a (refers AS8006, BS2G.135 and FAR 25 AP. C)*
- ✓ *EASA Conditions (see Duvivier, 2007)*
- ✓ *EASA ETSO-C16a (see FAA TSO C16a)*
- ✓ *SAE AS5562 (WIP/Draft)*

Future TSO version can refer to that!

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

SIMPLE Comparison - No model based



Certification Means of Compliance

- ✓ *Flight Test*
  - PRO: It represents actual aircraft operation
  - CON: It is expensive
  - CON: It is hard to control all variables
  - CON: It depends on atmospheric condition (it needs an icing hunter)
- ✓ *Icing Tunnel Test*
  - PRO: It is less expensive than flight test
  - PRO: It controls all variables
  - CON: It is limited to represent actual operation (envelope limits)
- ✓ *Analysis and Simulation*
  - PRO: It is less expensive than flight test
  - PRO: It controls all variables
  - PRO: It is represent actual aircraft operation (envelope "corners")
  - CON: It needs validation with flight and tunnel data (spot checks!)

Future SAE AS5562 (Draft)

Ice and Rain Qualification Standards for Air Data Probes

- ✓ *Under development*
- ✓ *Studies based on draft version of SAE AS5562*
- ✓ *Used only two types of information from future AS5562 in this presentation:*
  - ➢ Conditions
    - – Supercooled Liquid,
    - – Ice Crystals
    - – Mixed Phase Icing
    - – Rain
  - ➢ Testing
    - – Operational limitations (similarity guidelines)

Ice Crystals Conditions

as per future SAE AS5562 (Draft)

Table 4: Ice Crystal Test Conditions

Test Condition	Class	Altitude (KFt)	Airspeed (KTAS/Mach)	SAT (deg C)	MMD (μ)	IWC (g/m³)	Duration (Min)
S1	1	23	240/.39	-20	150 - 250	6.5	2
	2	28	341/.55			7.3	
	3		382/.62				
	4						
S2	1	23	231/.39	-40	150 - 250	3.9	2
	2	31	327/.55			5.6	
	3	37	488/.82			6.4	
	4		512/.86				
S3	2	31	313/.55	-60	150 - 250	3.4	2
	3	42	466/.82			5.1	
	4	45	489/.86			5.2	
S4	4	45	477/.86	-70	150 - 250	4.7	2

Tunnel Condition Adjustment

as per standard future SAE AS5562 (Draft):

- ✓ *Altitude limitation*
  - $TAS_{test} = TAS_{ref}$ → keep true air speed
  - $TAT_{test} = TAT_{ref}$ → keep total air temperature
  - $SAT_{test} = SAT_{ref}$ → keep static air temperature
- ✓ *Airspeed or Static Air Temperature limitations:*
  - $TAT_{test} = TAT_{ref}$ → keep total air temperature
  - $LWC_{test} = LWC_{ref} * TAS_{ref} / TAS_{test}$ → change LWC to keep water catch
  - $IWC_{test} = IWC_{ref} * TAS_{ref} / TAS_{test}$ → change IWC to keep ice crystals catch

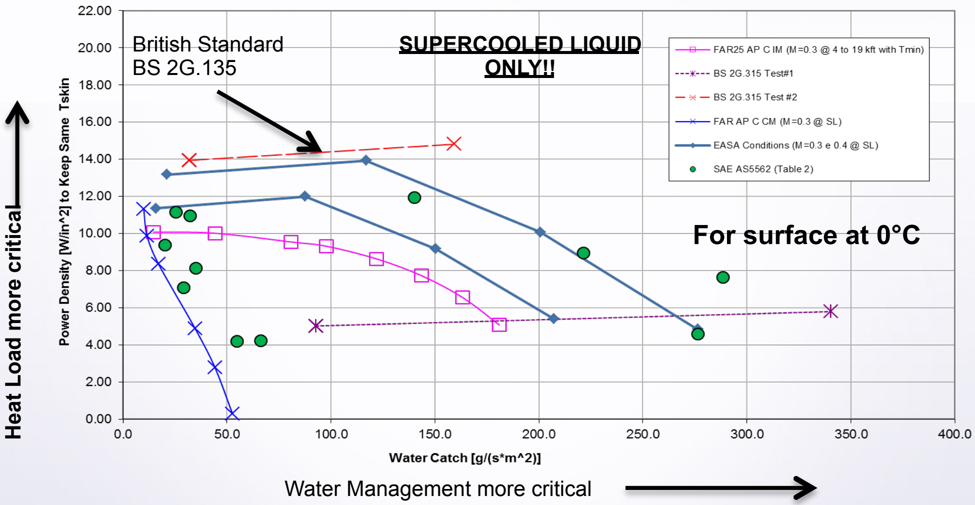
2. SAE AIR1168/4 Analytical Model

SUPERCOOLED LIQUID ONLY!!

Model Based on AIR1168/4

- ✓ ***Assumptions***
  - Zero-Dimensional (lumped analysis)
  - Collection Efficiency b = 0.85
  - Surface fully wet → F=1
  - Impingement area = total area of the analysis
  - Temperatures above 0°C
  - Thin Water Film
  - Effects considered:
    - Convection
    - Water Vaporization
    - Water Impingement
  - Only supercooled liquid water
  - No conduction or other heat lossess
  - **No ice melting effect**

Standard/Regulations Comparison - Based on AIR 1168/4 Model



Similarity as per SAE AS5562 - Based on AIR 1168/4 Model

Altitude Limitation Alt=Atl(M)

	SAT	Mach	LWC CM	Alt [kft]	Pamb [Pa]	V [m/s]	CAS	Tsup [K]	Trec [K]	qo/so [W/in2]	qo [W]
	-30.0	0.440	0.125	20.0	46564	137.5	200	273.15	251.6	7.47	353
Keep TAS, TAT,SAT, with same qo	-30.0	0.440	0.125	5.0	84448.9	137.5	262	269.35	251.6	7.46	353

TAS and Altitude Limitation Alt=Alt(M)

	SAT	Mach	LWC CM	Alt [kft]	Pamb [Pa]	V [m/s]	CAS	Tsup [K]	Trec [K]	qo/so [W/in2]	qo [W]
	-30.0	0.440	0.125	20.0	46564	137.5	200	273.15	251.6	7.47	353
Keep Mimp, TAT, with same qo	-25.2	0.285	0.191	3.0	90875	90.0	178	274.22	251.6	7.46	353

Marginal or not conservative as required

SAT and Altitude Limitation Alt=Alt(M)

	SAT	Mach	LWC IM	Alt [kft]	Pamb [Pa]	V [m/s]	CAS	Tsup [K]	Trec [K]	qo/so [W/in2]	qo [W]
	-40.0	0.440	0.187	19.0	48548	134.7	200	273.15	241.3	10.03	475
Keep TAT, Mimp, with same qo	-35.0	0.271	0.301	2.8	91389	83.9	169	275.02	241.3	10.04	475

3. Simple Model - Evaporative Cooling with Coupled Heat and Mass Transfer

SUPERCOOLED LIQUID ONLY!!

Simple Model - Evaporative Cooling Only

✓ ***Assumptions***

- Zero-Dimensional (lumped analysis)
- Collection Efficiency b = 0.85
- Surface fully wet → F=1
- Temperatures above 0°C
- Thin Water Film
- Effects considered:
  - Convection
  - Water Vaporization
- Only supercooled liquid water
- No conduction or other heat lossess
- No impingement effect
- No ice melting effect

Evaporative Cooling - Coupled Heat and Mass Transfer*

$$\frac{\dot{m}''_{evap}}{g_m} = B_m = \frac{g_h}{g_m} \cdot \frac{1}{h_{lv}} \cdot \left[c_{mix} \cdot (T_{rec} - T_{surf}) + \frac{\dot{q}''_{surf}}{g_h} \right]$$

$$\mathrm{B_m} = \frac{\mathrm{m_{H2O,S}} - \mathrm{m_{H2O,G}}}{\mathrm{m_{H2O,S}} - 1}$$

$$\frac{g_m{}^*}{g_m} = \frac{B_m}{\ln(1 + B_m)}$$

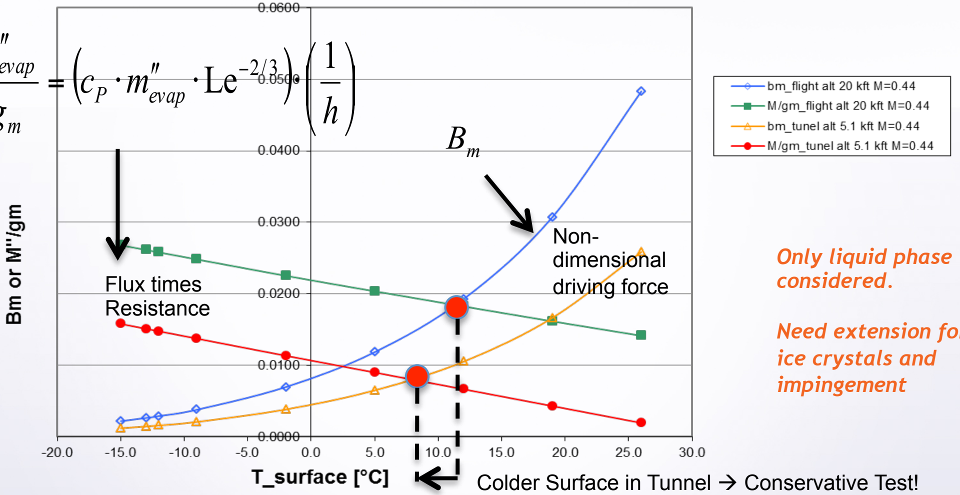
$$\frac{g_m}{g_h} = Le^{2/3} \Leftrightarrow \frac{g_m}{h/cp} = Le^{2/3}$$

$$m_{H2O,i} = \frac{p_{vap,i}}{1.61 \cdot p_{amb} - 0.61 \cdot p_{vap,i}}$$

(*) Spalding, 1962

Graphical Method of Solution - Based on Simple Model

$$\frac{m''_{evap}}{g_m} = \left(c_P \cdot m''_{evap} \cdot \mathrm{Le}^{-2/3}\right)\left(\frac{1}{h}\right)$$



Colder Surface in Tunnel → Conservative Test!

Only liquid phase considered.

Need extension for ice crystals and impingement

Study of Similarity Rules proposed by SAE AS5562 - Based on Simple Model

Power Density [W/in2]	Power Density [W/m2]	Paltitude [kft]	SAT	P [Pa]	Mach	V [m/s]	Trec [C]	Tsup [C]
Altitude Limitation Alt=Alt(M)								
12.0	18600	20.0	-30.0	46564	0.44	137.5	-21.5	7.1
12.0	18600	5.1	-30.0	84076	0.44	137.5	-21.5	3.4
TAS and Altitude Limitation Alt=Alt(M)								
12.0	18600	20.0	-30.0	46564	0.44	137.5	-21.5	7.1
12.0	18600	3.0	-25.1	90877	0.29	90.0	-21.5	9.9
SAT and Altitude Limitation Alt=Alt(M)								
12.0	18600	20.0	-40.0	46564	0.44	134.7	-31.9	4.0
12.0	18600	2.8	-35.1	91383	0.27	83.9	-31.9	6.5

Despite simple, model has same trends for super cooled liquid water than AIR 1168/4 model

4. Proposed Model to Include Impingement and Ice Melting Effects

SUPERCOOLED LIQUID WATER AND ICE CRYSTALS

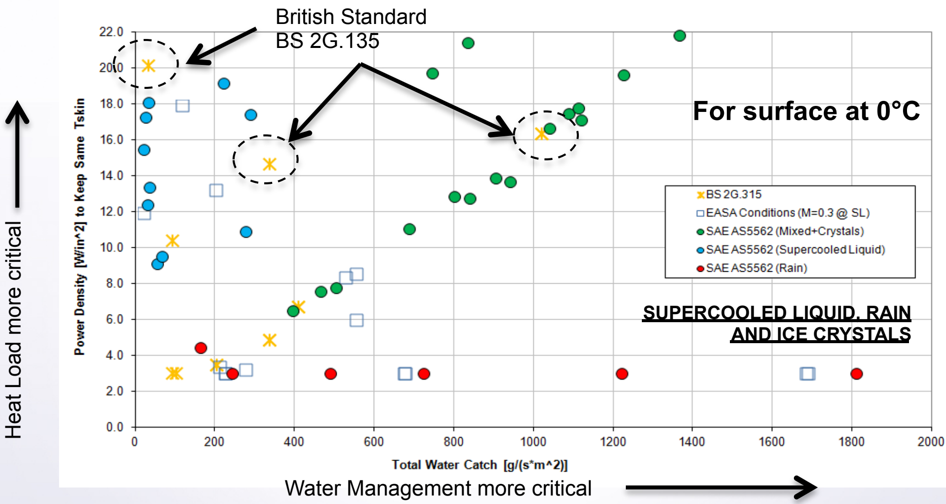
Proposed Model

= evaporative cooling + impingement + ice melting effects

✓ ***Assumptions***

- Zero-Dimensional (lumped analysis)
- Collection Efficiency b = 0.85
- Surface fully wet → F=1
- Temperatures above 0°C
- Thin Water Film
- Running wet OR Fully evaporative
- Additional Effects considered (others kept):
  - Water Impingement effect
  - Ice melting effect
- Ice Crystals and Mixed Phase
  - Low Convection in Enclosed Space inside Probe Tube
  - Internal Probe Ambient Temperature -5 °C (Arbitrary, need thermal analysis)

Standards/Regulations Comparison - Based on Proposed Model



Study of Similarity Rules proposed by SAE AS5562

LWC [g/m3]	Beta	Power Density [W/in2]	Power Density [W/m2]	Paltitude [kft]	SAT	P [Pa]	Mach	V [m/s]	Trec [C]	Mimp [g/(s*m2)]	Tsup [C]
Altitude Limitation Alt=Alt(M)											
0.125	0.85	12.0	18600.0	20.0	-30.0	46564	0.44	137.5	-21.5	14.6	5.3
0.125	0.85	12.0	18600.0	5.1	-30.0	84076	0.44	137.5	-21.5	14.6	1.8
TAS and Altitude Limitation Alt=Alt(M)											
0.125	0.85	12.0	18600.0	20.0	-30.0	46564	0.44	137.5	-21.5	14.6	5.3
0.191	0.85	12.0	18600.0	3.0	-25.1	90877	0.29	90.0	-21.5	14.6	7.7
SAT and Altitude Limitation Alt=Alt(M)											
0.125	0.85	12.0	18600.0	20.0	-40.0	46564	0.44	134.7	-31.9	14.3	1.6
0.201	0.85	12.0	18600.0	2.8	-35.1	91383	0.27	83.9	-31.9	14.3	3.4

Marginal or not conservative as required

IWC=0 No Ice crystals considered. Only LWC!

Conclusions and Possible New Directions

Conclusions

- ✓ *Simple Evaporative Cooling Model does provide qualitative results that allow trade-off and similarity for supercooled liquid water*
- ✓ *Modified Evaporative Cooling Model (ice crystals + water catch) results are adequate to perform rapid/simplified :*
  - ➢ Analysis of similarity flight-tunnel regarding heat transfer effects
  - ➢ Comparison between air data probe standards/documents conditions in terms of heat load and water catch
- ✓ ***The similarity proposed by AS5562 must be complemented by a Thermal Heat Load Analysis, what eventually may lead to heat less the probe in tunnel***

Suggested Next Steps

- ✓ *To perform a thermal analysis to assess the temperature inside the air data probe tube, which must include thermal radiation*
- ✓ *To study the transient ice melting problem inside probe tube with supercooled water, ice crystals and mixed phase*
- ✓ *To predict the 3D impingement over the probe*
- ✓ *To estimate the 3D water runback (film, beads, rivulets) movement and the surface wetness factor*
- ✓ *To correlate 3D results in order to use in simple analytical 0-D (lumped/black-box models)*

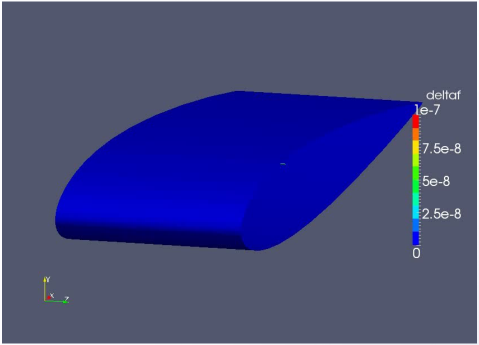
For supercooled liquid water and rain ice protection, it is important to consider:

1) runback water flow (rivulets/film);
2) laminar-turbulent transition and
3) stream-wise temperature variation.

Runback affects

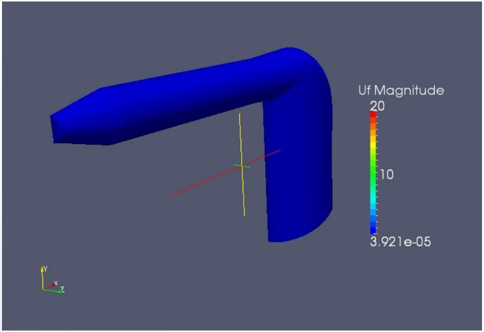
- ✓ The heat demand for ice protection systems → evaporative cooling
- ✓ The glaze ice accretion process

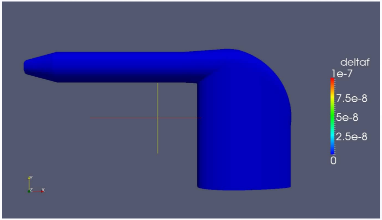
3D structures and swept wing → simple runback models (2D or quasi-3D) can not be applied.

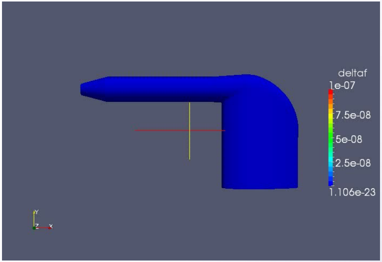


Feasibility demonstrated by the present Pilot/Prototype Simulation →
Now need an application/Research Project

Generic Probe Results







Liquid Water ONLY
Freezing Rain and In-Cloud
Need test data for validation!

Thank you !

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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)*
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- ✓ *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)*