Ice Accretion and Wing Anti-Icing System Simulation

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Organization COPPE/UFRJ

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- Motivation

Conception, development and certification of anti-icing and de-icing wing systems.

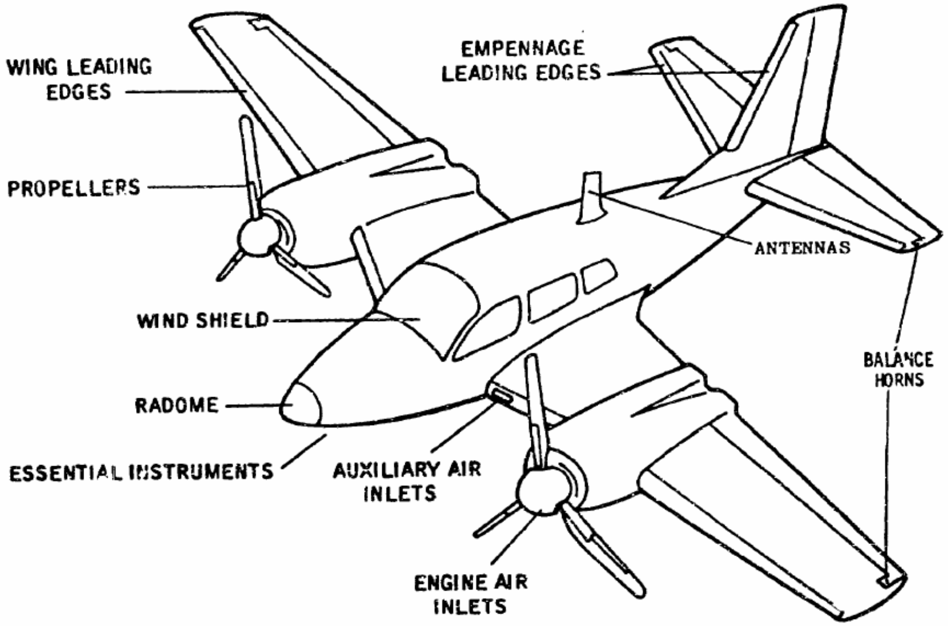
Modeling and simulation of anti-icing and de-icing systems.

Modeling and simulation of ice accretion in airplane wings and components.

Heat and mass transfer and liquid water runback.

Brazilian aeronautic industry

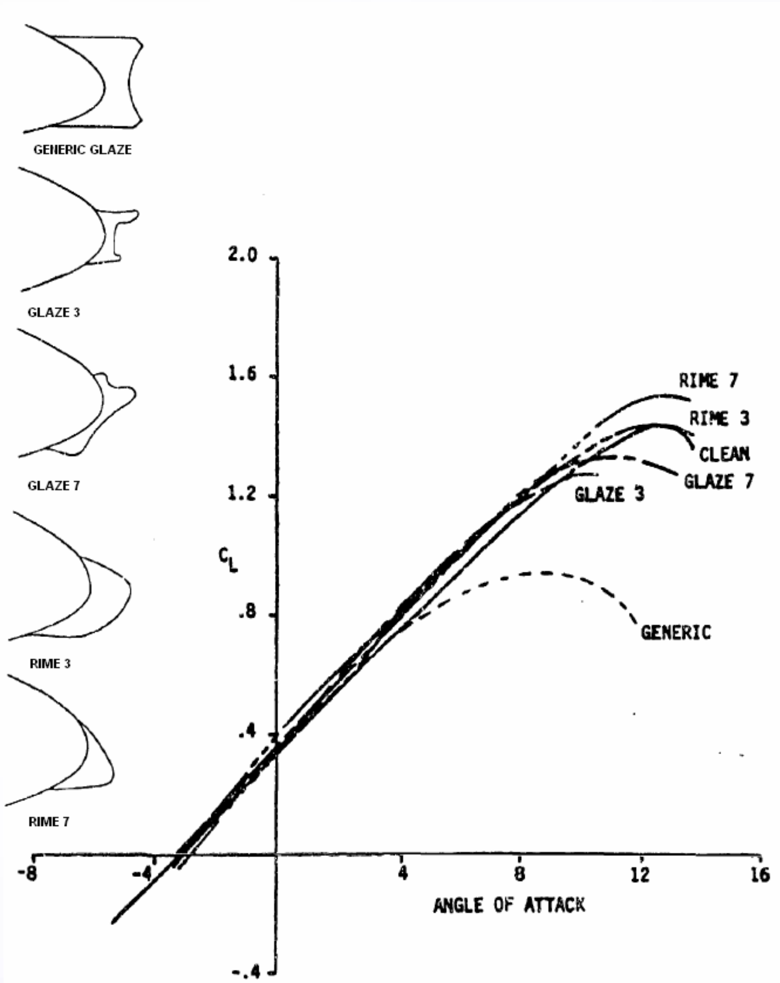
Aircraft Ice Accretion



- Condition for icing accretion
  - Subcooled water droplets
  - Non-protected Surfaces
  - Failure of Anti-icing system
- Consequences
  - Aerodynamic degradation
  - Weight increase
  - Ice shedding
  - Sensors malfunction

Source: Aircraft Icing Handbook Vol2
DOT/FAA/CT-88/8-2

Ice Accretion Efects

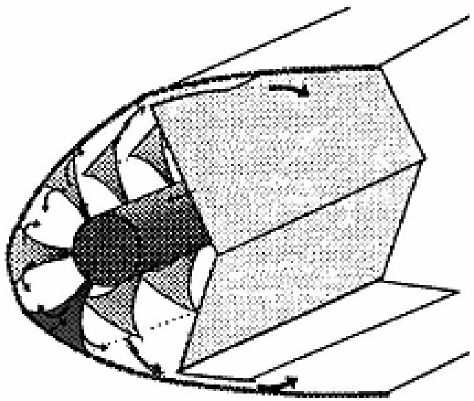


Source: Aircraft Icing Handbook Vol1, DOT/FAA/CT-88/8-1

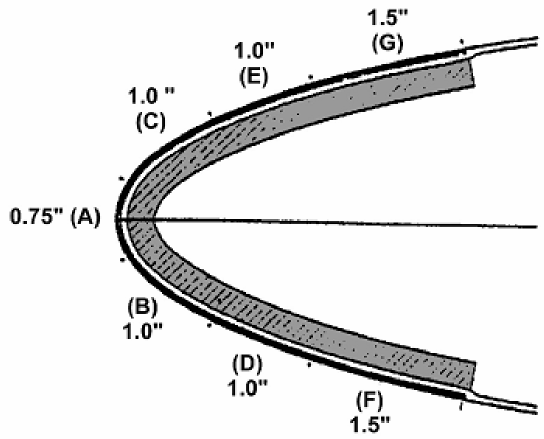
Anti-icing and De-icing Systems

Thermal Ant-icing and De-icing Systems

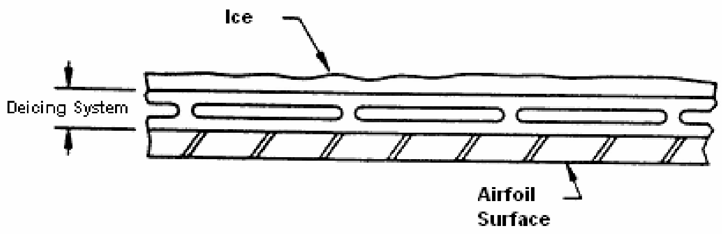
Piccolo Tube

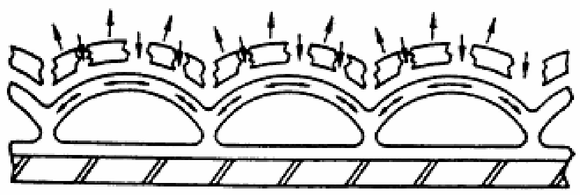


Electrical Resistance

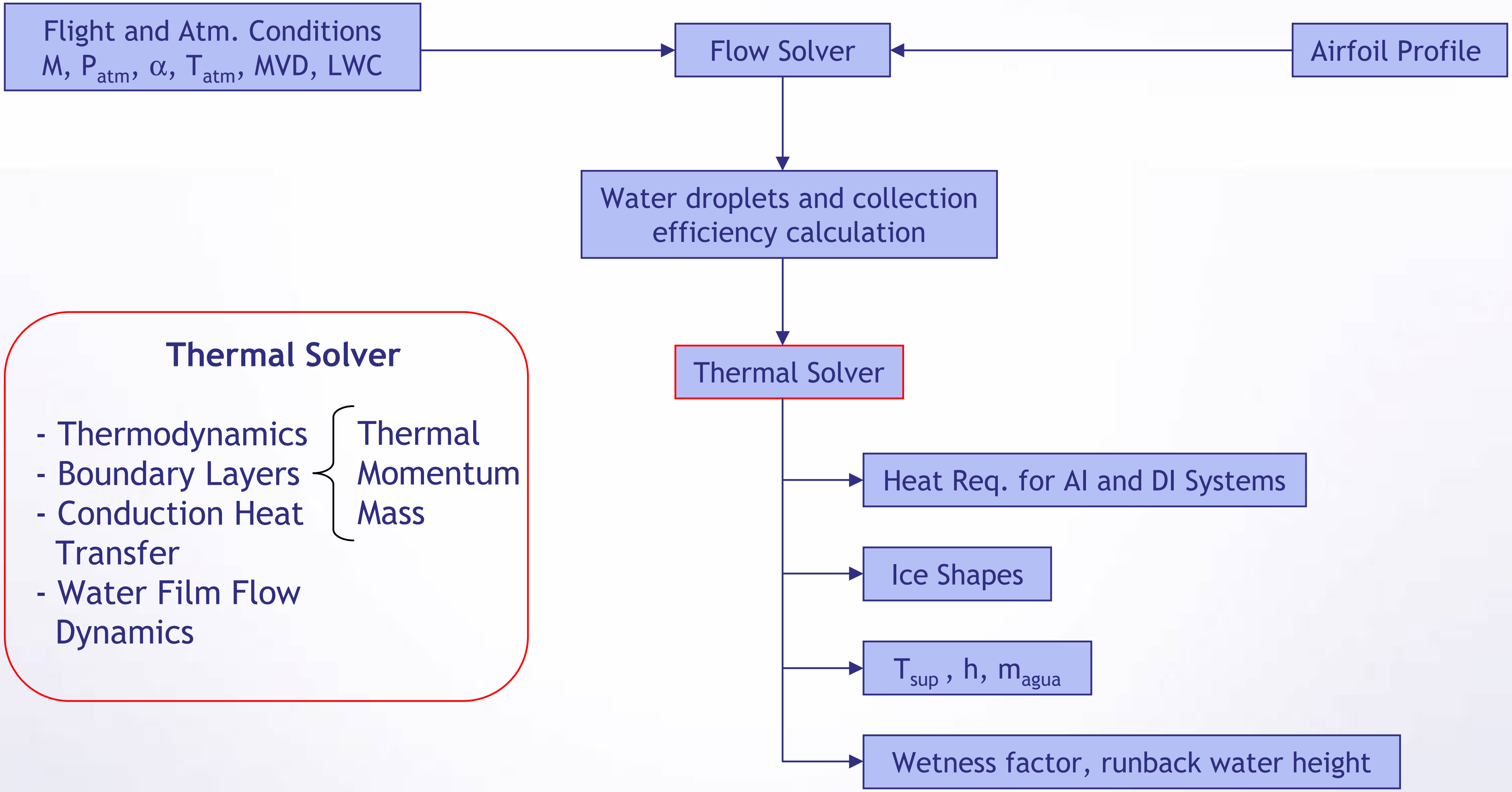


Mechanical De-icing System

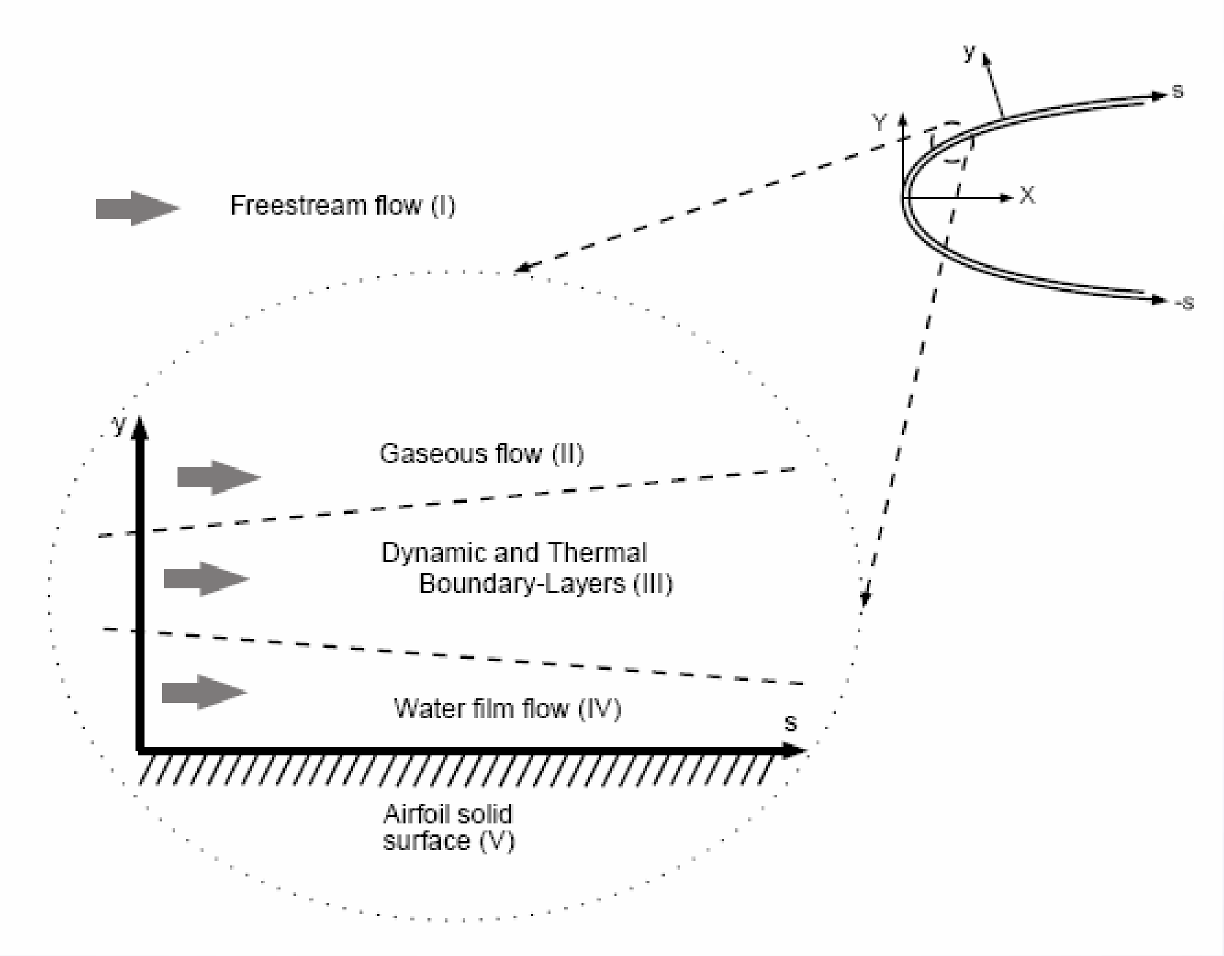




Anti-icing and icing accretion Simulation



Modeling Domains



Icing and Anti-Icing Codes

		Characteristics			
Code	**Authors**	**Boundary Layer**	**Wetness Factor**	**Lam-Turb Transition**	**Onset / Lenght**
ANTICE	Al-Khalil et al. (2001)	not calculated (exp. data)	rivulets	not calculated	not calculated
ONERA	Henry (1992)	diferential	not calculated	no info	no info
CANICE FD	Morency, Tezok e Paraschivoiu (1999)	diferential (Cebeci, 1971)	not calculated	intermittency (Chen,Thyson,1971)	w/o freestream turbulecence effect (Michel,1951)
M.Sc.Silva (1998-2002)	Silva (2002)	integral (Ambrok,1957)	not calculated	Probabilistic (Reynolds, Kays, Kline,1958b)	adjusted
Ph.D.Silva (2003-2009)	Silva (2009)	integral (Ambrok,1957), superposition (Reynolds, Kays, Kline,1958) and diferential (Cebeci, Cousteix, 2005)	rivulets	intermittency (Reynolds, Kays, Kline, 1958) and (Abu-Ghannam, Shaw, 1980)	adjusted and predicted (Abu-Ghannam, Shaw,1980)
LEWICE	Macarthur, Keller, Luers (1982)	integral (Makkonen)	not calculated	abrupt	Re_{ks}
ONERA	Guffond, Brunet (1988)	integral (Makkonen)	not calculated	abrupt	Re_{ks}
M.Sc. Stefanini (2006-2009)	Stefanini (2009)	integral (Makkonen)	not calculated	abrupt, intermittency (Abu-Ghannam, Shaw, 1980)	Re_{ks}, adjusted

Thermal Solver Development

- Thermal Boundary Layer
  - Non-isothermal surface
  - Effect of pressure gradient
  - Effect of mass transfer
  - Effect of surface roughness
  - Effect of the laminar-turbulent transition
  - Effect of the compressibility
- Water Runback Flow
  - Water film flow and breakdown
  - Rivulets flow

Laminar-Turbulent Transition

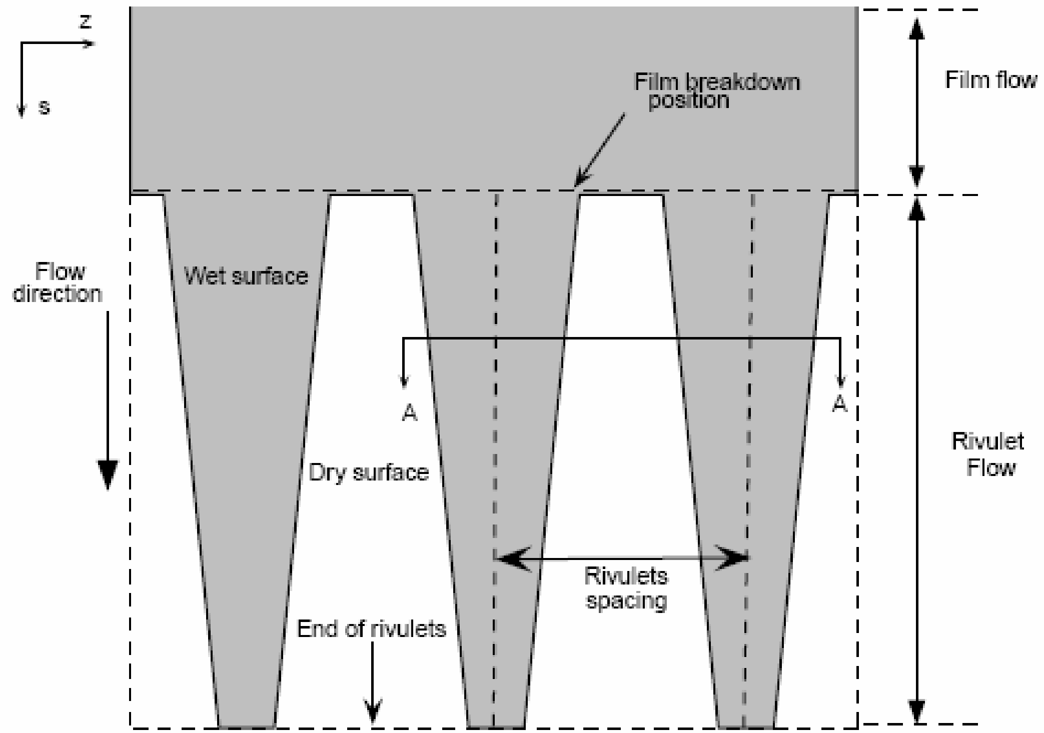
- Algebric correlations of Abu-Ghannam and Shaw (1980) for intermmitency function

$$\gamma(\mathrm{Re}) = 1 - \exp\left(-5\eta^3\right) \qquad \eta = \frac{\mathrm{Re}_s - \mathrm{Re}_{s,tr}}{\mathrm{Re}_{s,t} - \mathrm{Re}_{s,tr}}$$

- In the lamimar-turbulent transition region the Stanton number (St) is calculated using the intermmitency function

$$\mathrm{St}(\mathrm{Re}) = [1 - \gamma(\mathrm{Re})] \cdot St_{lam} + \gamma(\mathrm{Re}) \cdot St_{turb}$$

Film breakdown and Rivulets formation

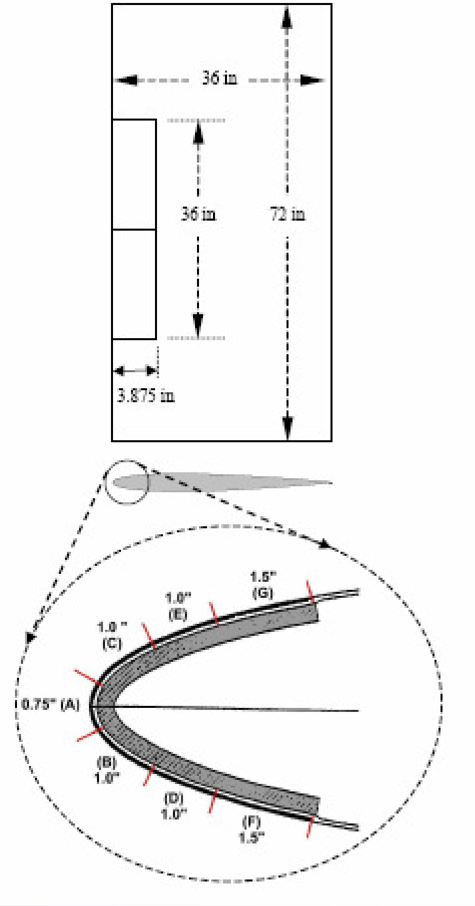


$$F = \frac{A_{wet}}{A_{total}}$$

$$A_{total} = A_{wet} + A_{dry}$$

- The film height varies with evaporation, temperature, pressure gradient and shear stress
- The rivulets will form when the film reaches critical height
- The dry and wet areas ratio affect heat transfer
- The water film breakdown occurs only downstream from impingement limits (Al-Khalil, 1991)

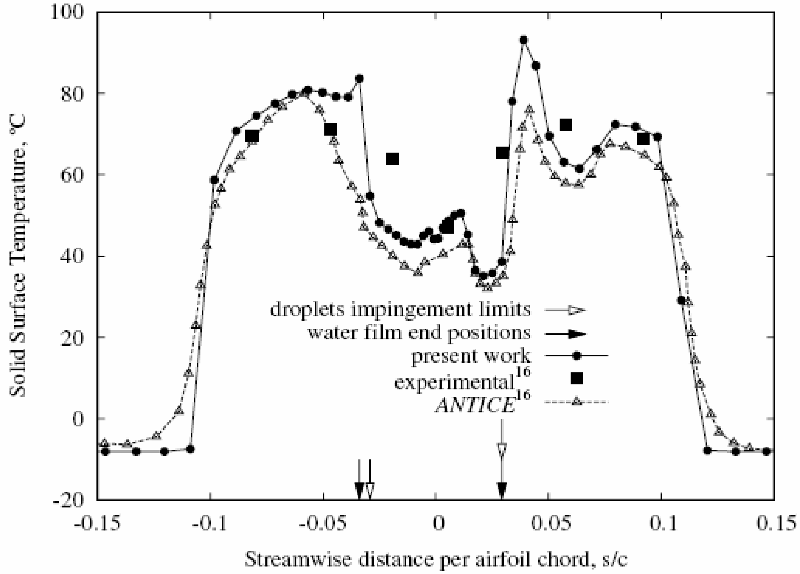
Anti-icing simulation - Selected test cases



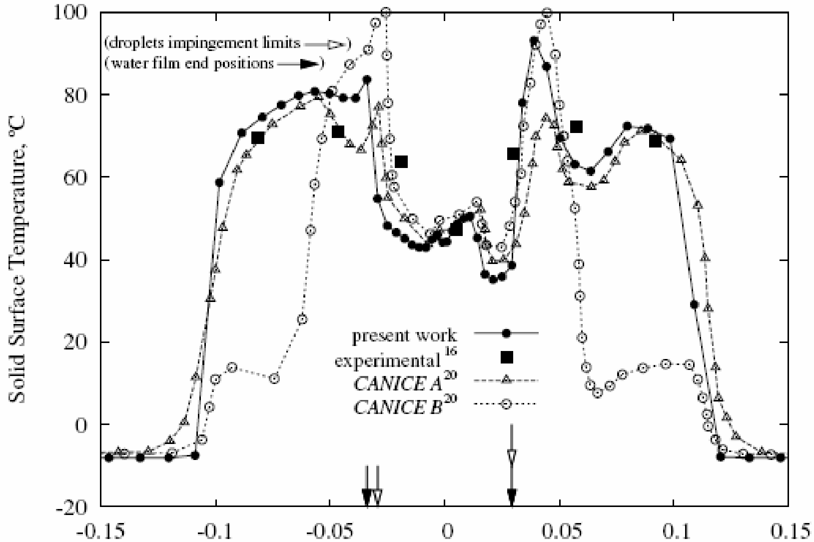
- Tests performed by Al-Khalil et al. (2001)
- NASA IRT Cleveland, OH, USA
- NACA0012 electrically heated
- Test series used to validate Lewice/Antice code

Parameter	22A	67A / 67B
V_{inf} [m/s]	44.7	89.4
T_{tot} [K]	264.4	251.5
α	0.0^o	0.0^o
LWC [g/m^3]	0.78	0.55
MVD [μm]	20.0	20.0
Turb. Level *Tu*	3.1%	3.1 and 3.0 %
$(s/c)_{prot}$	~ 10 %	~ 10%
$Re_{c,\ prot}$	$6.72 * 10^5$	$1.38 * 10^6$
Q elec. aver. [kW/m^2]	19.3	25.9 / 11.1
Mach	0.1369	0.2813

Basic B.L. Integral Model



Temperature distributions for case 22A: comparison with ANTICE.

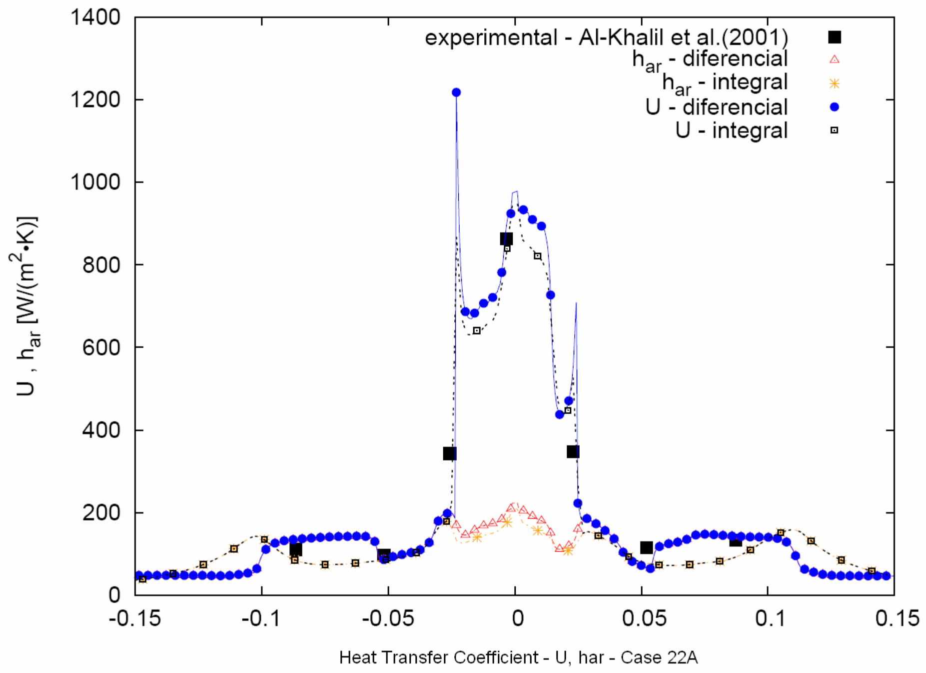


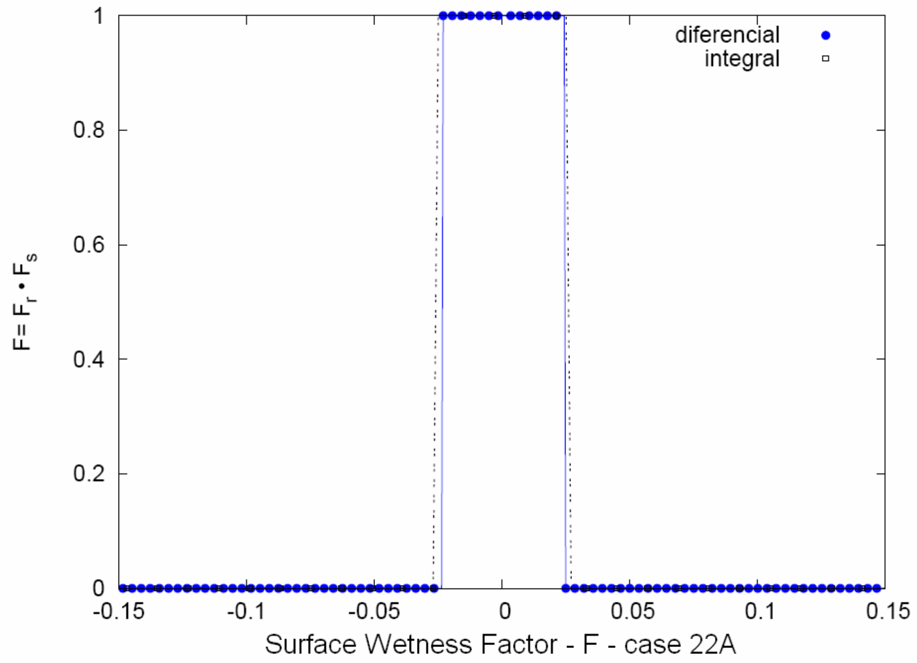
Temperature distributions for case 22A: comparison with CANICE A/B.

Comparison with ANTICE and CANICE A/B - case 22A

Note – Basic Model: smooth, w/o rivulet and w/o lam-turb transition prediction

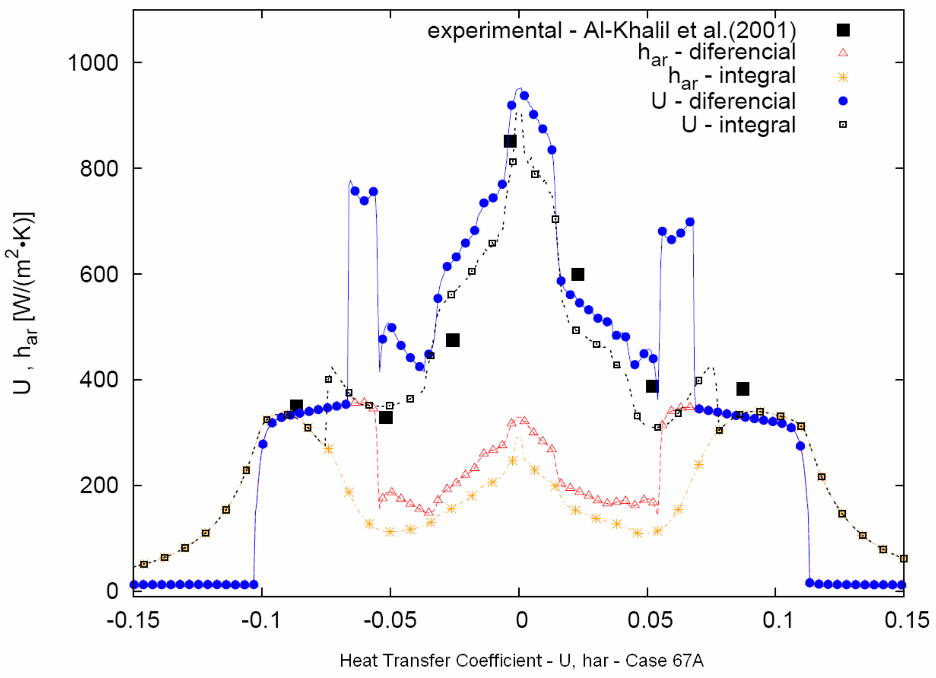
Diferencial B.L. model with Rivulet model

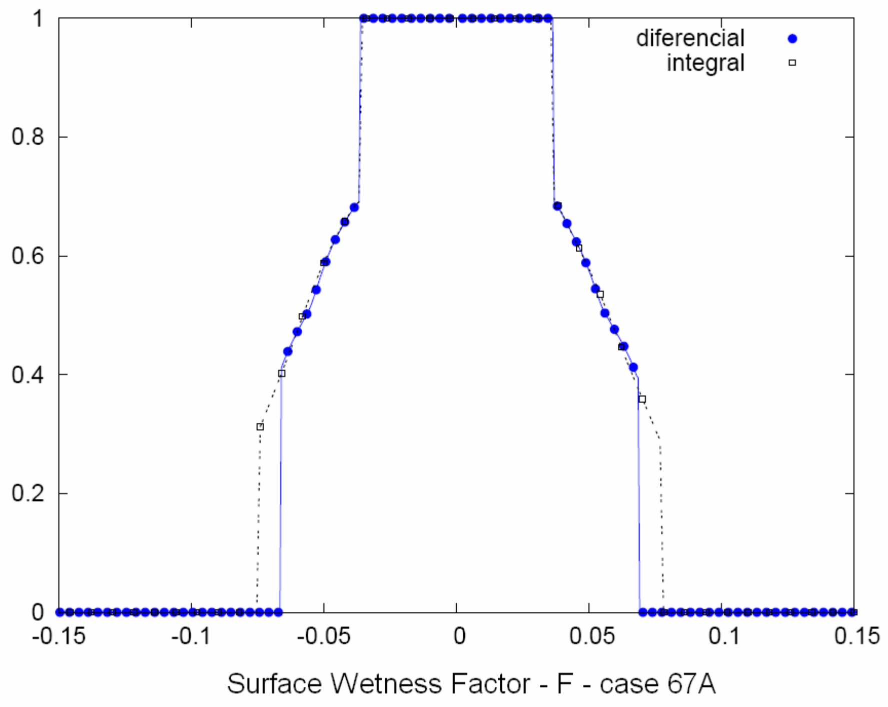




Comparison with Antice - case 22A

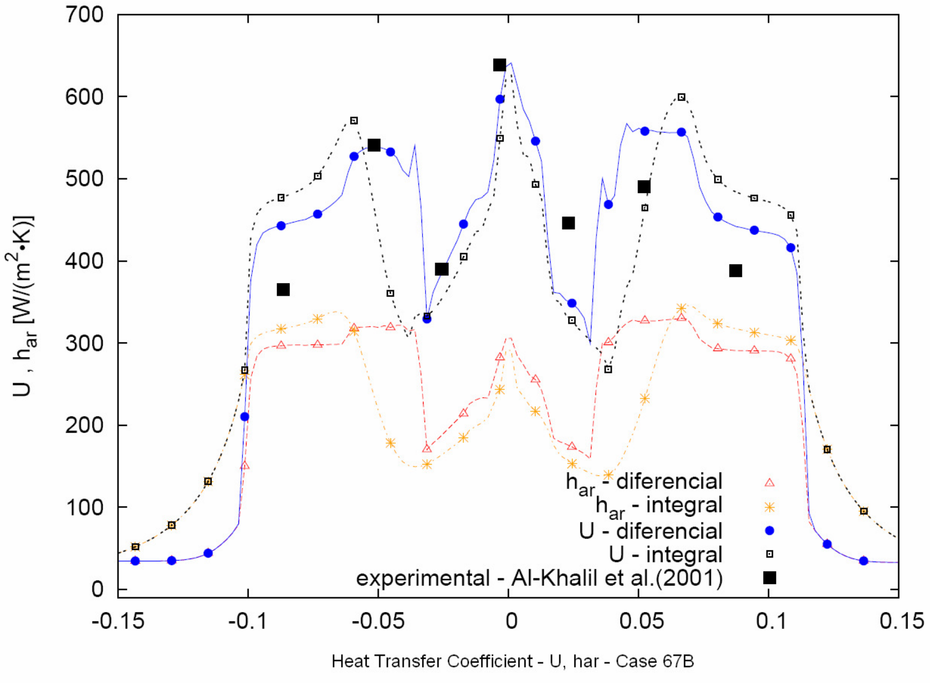
Diferencial B.L. model with Rivulet model

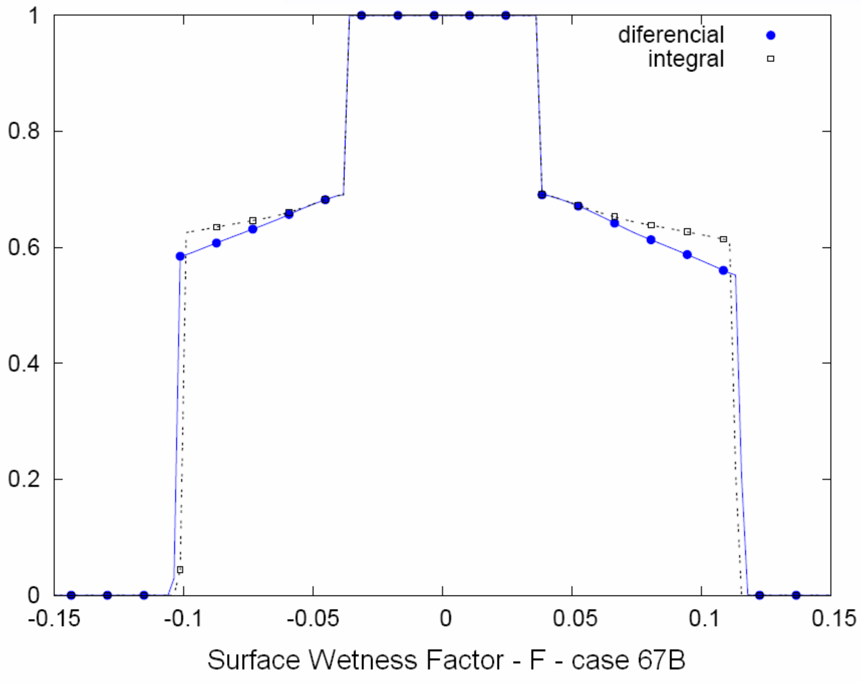




Comparison with Antice - case 67A

Diferencial B.L. model with Rivulet model





Comparison with Antice - case 67B

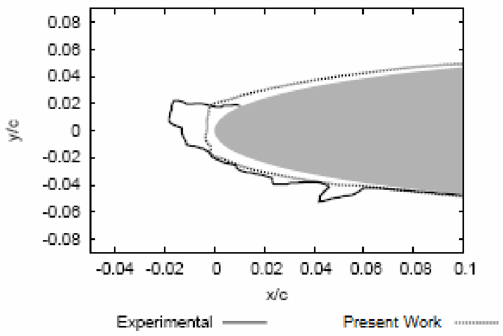
Icing accretion simulation - Selected test cases

- Kind (2001) published the results of a comprehensive comparison between icing codes and experimental data measured at several test conditions and icing tunnels around the world.

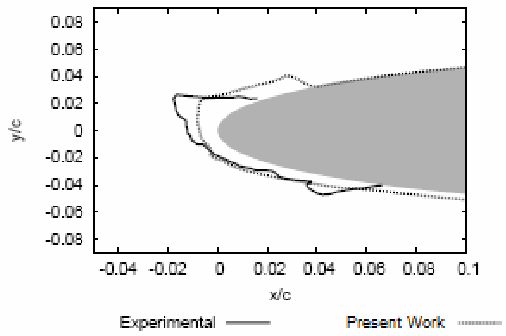
- Shin and Bond (1994) changed the free stream tunnel static temperature and liquid water content to evaluate the IRT-NASA results repeatability.

Parameter	Kind C13	Kind C14	Shin F01
V_{inf} [m/s]	67.0	57	67.1
T_{inf} [K]	264.4	267.6	Variable
α	0.0^o	0.0^o	4.0^o
LWC [g/m^3]	0.65	1.04	1.00
MVD [μm]	40.0	27.73	20.0
Duration [s]	672.0	247.2	360.0
Airfoil	NACA0012	NACA0012	NACA0012

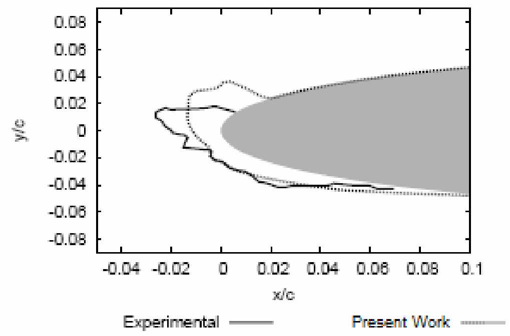
Basic B.L. model with Abrupt Transition



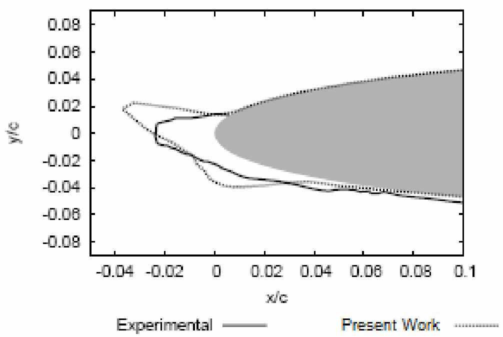
T_{∞}=270,9 K



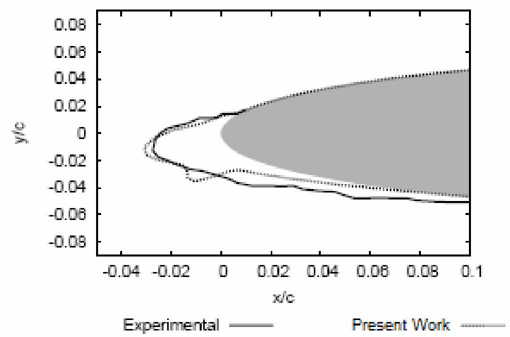
T_{∞}=269,3 K



T_{∞}=267,6 K



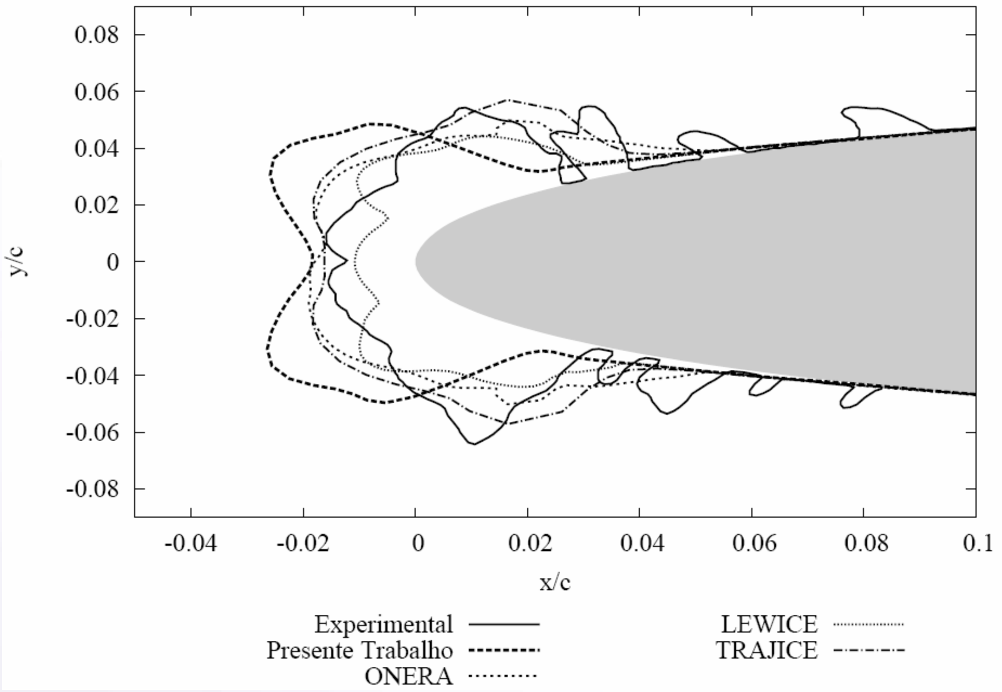
T_{∞}=262,1 K



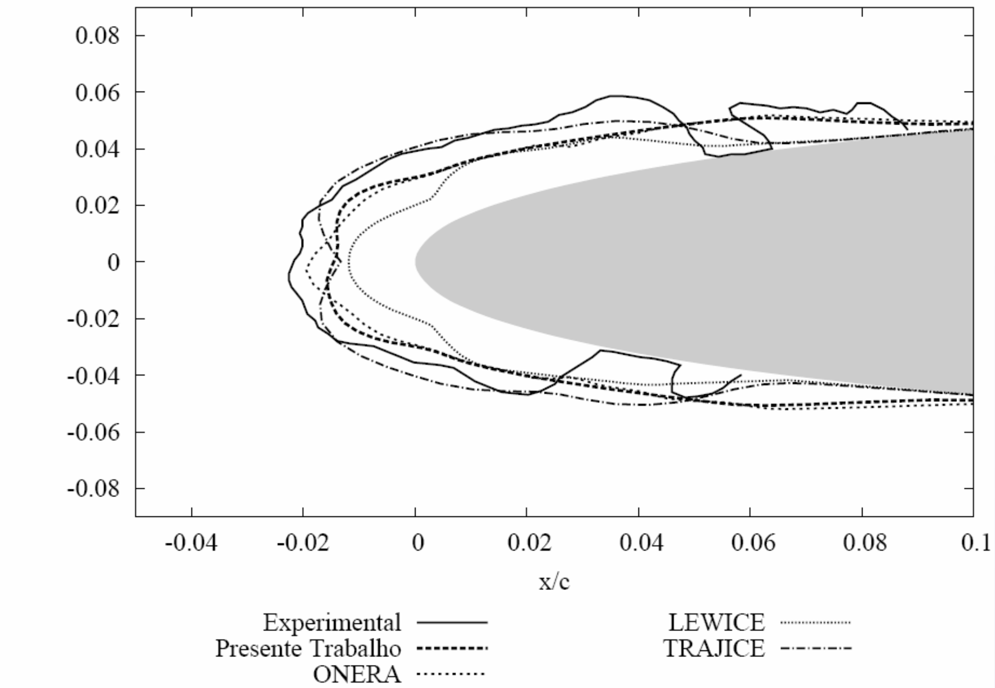
T_{∞}=247,3 K

Comparison with experimental data - case F01 (α= 4º)

Basic B.L. model with Abrupt Transition



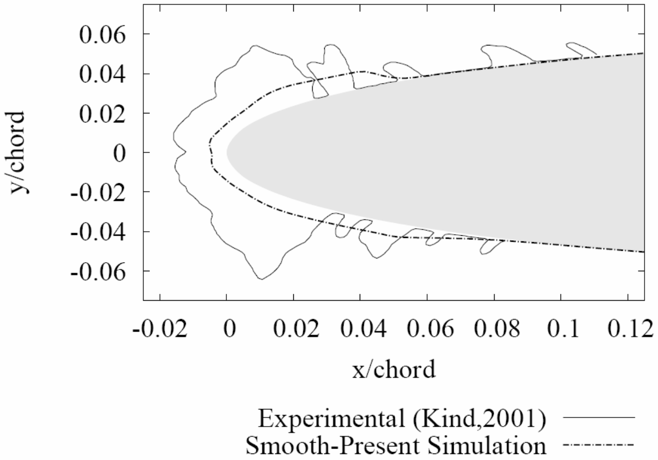
case C13



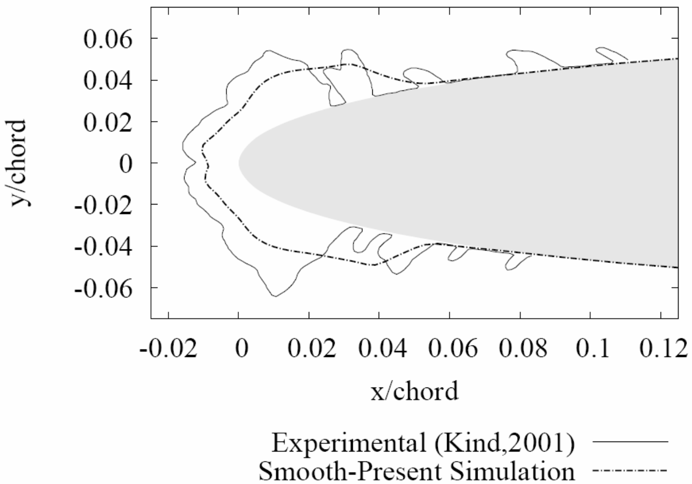
case C14

Comparison with experimental data and other codes results - case C13 and C14

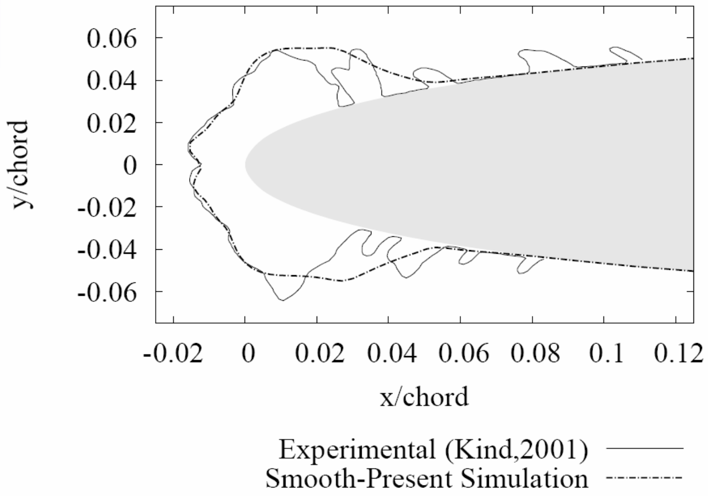
Basic B.L. model with Smooth Transition



t=224(s)



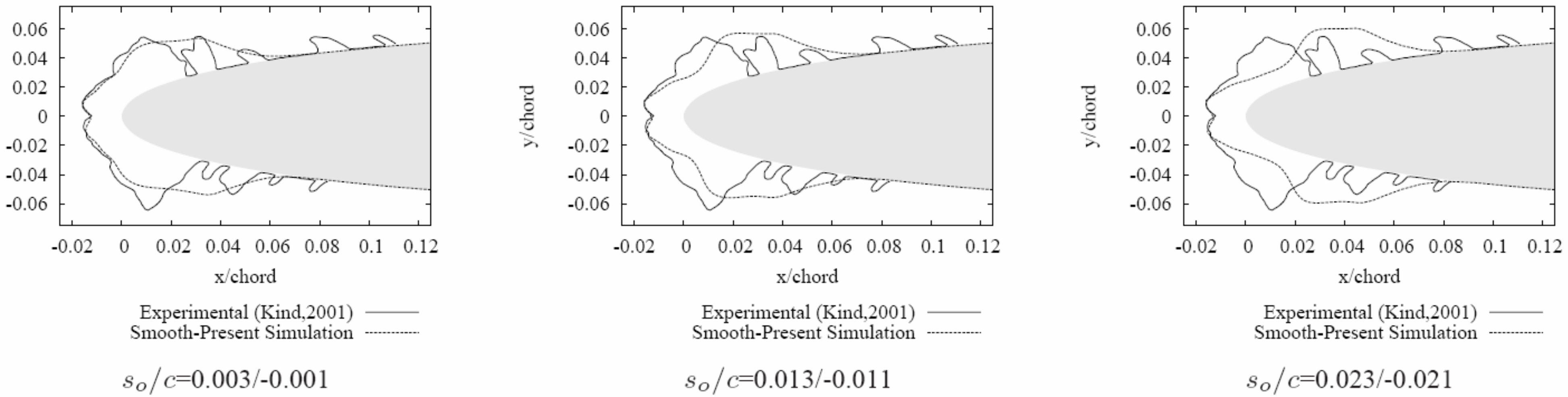
t=448(s)



t=672(s)

Icing Growth - case C13 (α= 0º)

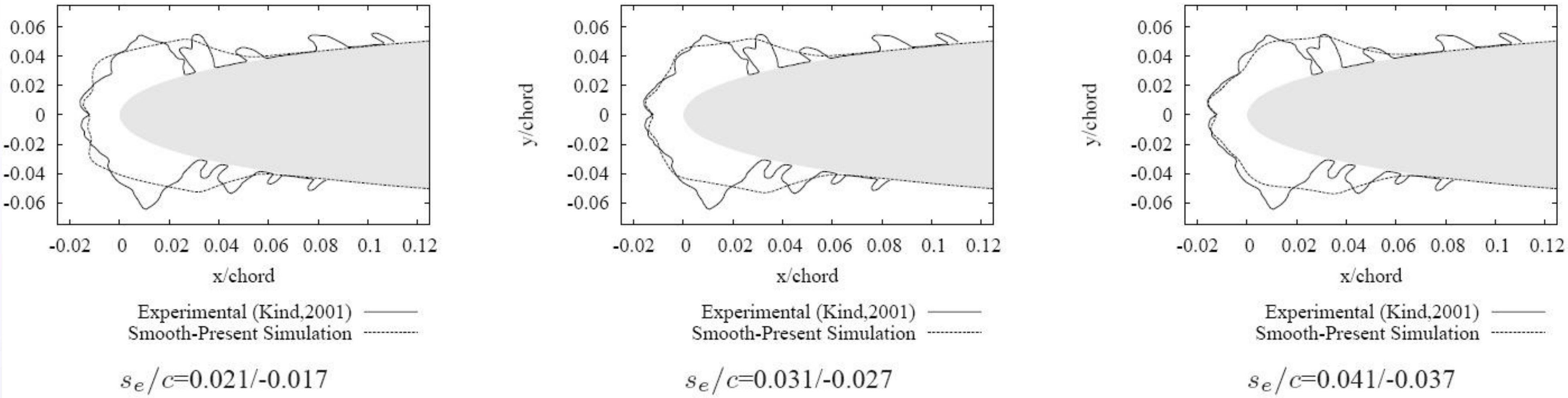
Basic B.L. model with smooth transition



Transition onset : variable
Transition length : fixed at l/c = 0.038 / 0.036 (Outb/Inb)
Sand grain roughness : fixed at ks = 0.125 mm

Variation of transition onset with fixed transition lenght - case C13 (α= 0º)

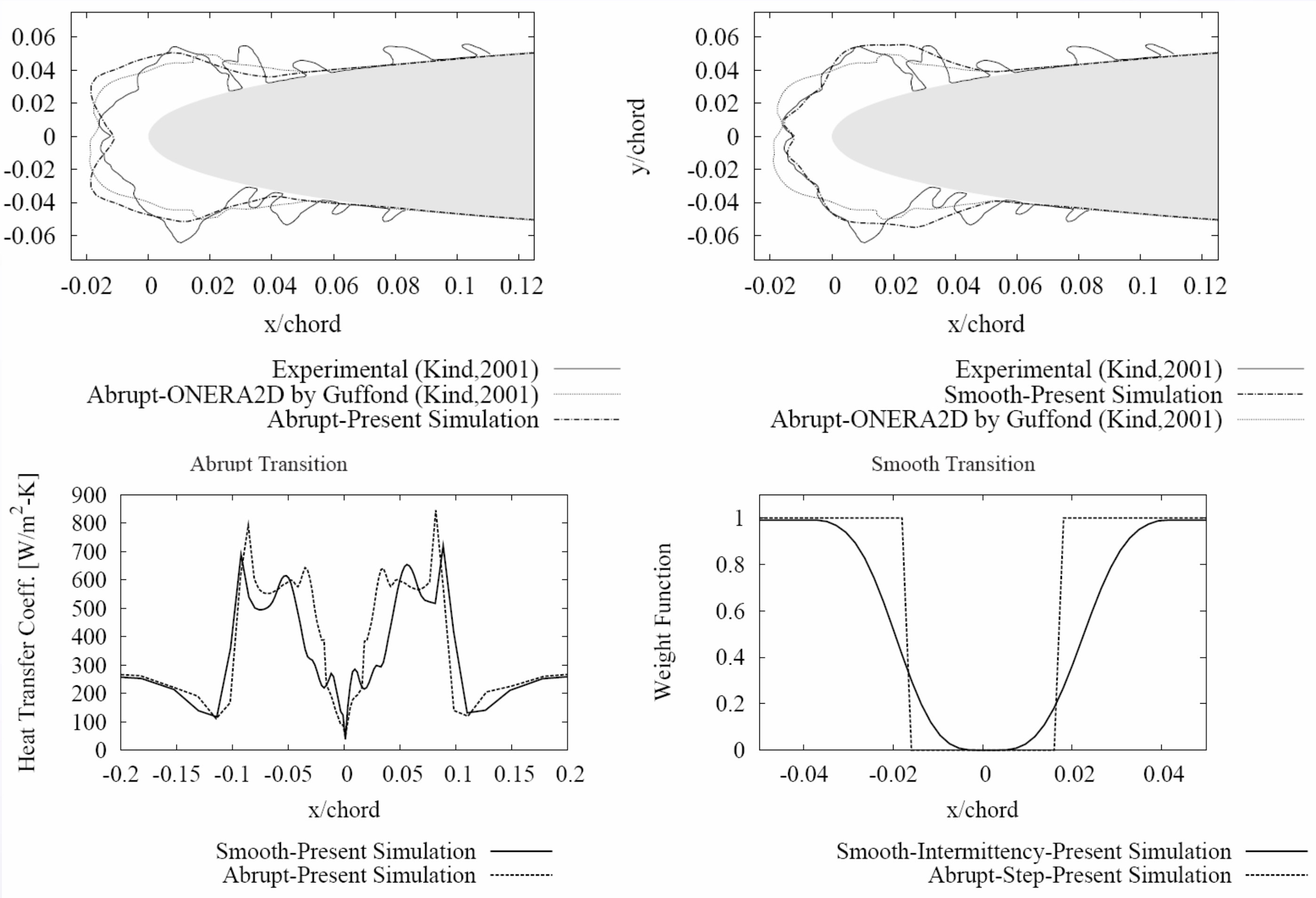
Basic B.L. model with smooth transition



Transition length : variable
Transition onset : fixed at s_o/c = 0.003/-0.001 (Outb/Inb)
Sand grain roughness : fixed at ks = 0.125 mm

Variation of transition lenght with fixed transition onset - case C13 (α= 0º)

Basic B.L. model with smooth and abrupt transition



(a) Convective Heat Transfer Coefficient

(b) Intermittency (smooth) and Step (abrupt) Functions

Onset and length of the transition adjusted for a fixed sand grain roughness - case C13

Future Developments

- Modeling of transitory icing accretion on airfoils for application in electro-thermal de-icing systems
- Effects of water film roughness in the boundary layer
- Water Droplets coalescence and water film formation
- Effects of the evaporation and heating flux in the thermal boundary layer
- Development of 3D anti-icing models
- Development of scale laws to support tunnel tests of airfoils with anti-icing systems

Published Works

- Silva, G. A. L., Silvares, O. M., and Zerbini, E. J. G. J.,; Hefazi, H; Chen, H. H.; Kaups, K.. Differential Boundary-Layer Analysis and Runback Water Flow Model Applied to Flow Around Airfoils with Anti-ice Systems.In Proceeding of 1st AIAA Atmospheric and Space Environments, San Antonio, 2009. Reston: AIAA, 2009.
- Silva, G. A. L., Silvares, O. M., and Zerbini, E. J. G. J., “Aircraft wing electrothermal anti-icing: Heat and mass transfer effects”. In Proceedings of Eurotherm, 5th European Thermal- Sciences Conference, Eindhoven,2008, Eurotherm
- Silva, G. A. L., Silvares, O. M., and Zerbini, E. J. G. J., “Differential and integral analyses of the convective heat transfer around ice protected airfoils”. In Proceedings of CHT- 08, ICHMT International Symposium on Advances in Computational Heat Transfer, Marrakesh,2008, Ankara: ICHMT, 2008
- Silva, G. A. L., Silvares, O. M., and Zerbini, E. J. G. J. Boundary-layers integral analysis - heated airfoils in ice conditions. In AIAA Paper 2008-0475, AIAA Aerospace Sciences Meeting and Exhibit, 46th, Reno, 2008, Reston:AIAA,2008
- Stefanini, L. M., Silvares, O. M., Silva, G. A. L., and Zerbini, E. J. G. J. Boundary-layers integral analysis - airfoil icing. In AIAA Paper 2008-474 (Reston, January 2007), AIAA Aerospace Sciences Meeting and Exhibit, 46th, 2008, Reno, Reston: AIAA, 2008.

Published Works

- Silva, G. A. L., Silvares, O. M., and Zerbini, E. J. G. J. Numerical simulation of airfoil thermal anti-ice operation. Part 2: Implementation and results. Journal of Aircraft 44, 2 (March-April 2007), 634–41.
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- CSULB – California State University, Long Beach
- USP – Universidade de São Paulo
- ATS4i – Aero-Thermal Solutions for Industry

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