Rough Cylinder in Cross Flow - A new heat transfer option

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Our Office ATS4i Engenharia Estudos e Projetos Ltda. Rua Cotoxo, 611 cj. 63 - São Paulo, SP, Brazil - CEP 05021-000

- The Company General Overview
- Ice Protection Engineering
- Cylinder in Cross Flow - a new heat transfer option
- Wall Functions Developed
- Numerical Results

ATS4i Company

- The Aero-Thermal Solutions for Industry, ATS4i, is a company that provides engineering solutions for thermal and fluid flow equipments, systems or processes;
- ATS4i has a hard-to-find specialized team that can use at same time classic engineering methods and recent numerical simulation;
- ATS4i services aggregates engineering value to customer products by making them higher valued, less risky, more efficient and/or more comprehensive;
- ATS4i has experience:
  - ✓ Aircraft Ice Protection
  - ✓ Aircraft ECS - Bleed and Air Conditioning
  - ✓ Aerospace systems
  - ✓ Combustion Equipments and Processes
  - ✓ Power generation
  - ✓ Thermal process/equipments

ATS4i Team

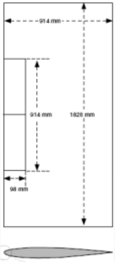
- Francisco Sousa
  - ✓ *1970-80 Consultant in Industrial Combustion*
  - ✓ *1980-2010 Institute for Technological Research - Combustion Laboratory*
  - ✓ *Since 2010 at ATS4i*
- Guilherme da Silva, Ph.D.
  - ✓ *1996 trainee at Institute for Technological Research (IPT) - Combustion Laboratory*
  - ✓ *1997-2007 Embraer - Air Managements Systems*
  - ✓ *PhD 2008 - Heat and Mass Transfer in Two-Phase Flow in Anti-ice Systems*
  - ✓ *Since 2009 at ATS4i*
- Marcos Arima, Ph.D.
  - ✓ *1998-2007 Institute for Technological Research (IPT) - Combustion Laboratory*
  - ✓ *PhD 2008* - Theoretical-experimental study on two-dimensional confined jets
  - ✓ *Since 2009 at ATS4i*

Ice Protection vs. Icing Simulation

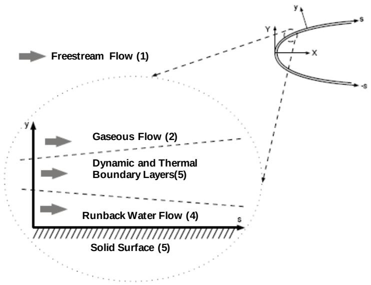
- Ice Protection Simulation is applied to predict the performance of anti-ice (steady state) or de-icing (cycling/transient) systems

- Icing Simulation is applied to predict ice shapes formed on external aerodynamic surfaces – failure cases and/or unprotected surfaces

ATS4i In-house 2D Anti-ice Modeling Capabilities

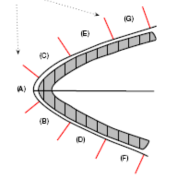


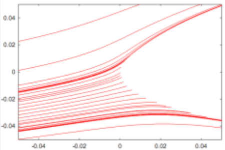
External Flow Solution By Potencial or RANS Codes



Boundary Layer by Integral or Differential Methods in non-isothermal transpired surfaces with laminar-turbulent transition

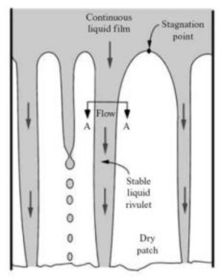
Power Density of Electro-thermal Anti-ice System





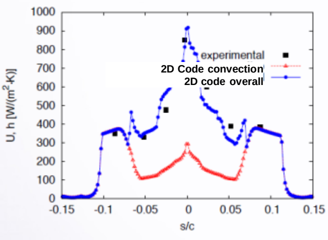
2D Impingement

Runback Film and Rivulets Model

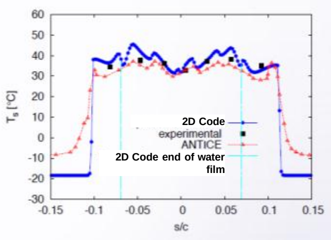


ATS4i In-house 2D Anti-ice Analysis Typical Results

Heat Transfer Coefficient



Airfoil Surface Temperatures



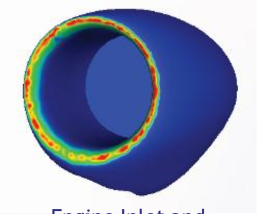
caso	$\dot{q}_{tot}$ kW	$\overline{\dot{q}''}_{tot}$ kW/m²	$\overline{\dot{q}''}_{agua}$ kW/m²	$\dot{q}_{req}$ kW	$\overline{\dot{q}''}_{req}$ kW/m²	$\dot{q}_{req}/\dot{q}_{tot}$ %	$\Delta\dot{q}_{req}$ %	$\Delta\dot{q}_{evap}$ %
22A diferencial	3, 2	16, 4	33, 5	1, 6	36, 8	49, 3	102, 8	142, 7
22A integral	3, 3	16, 7	33, 5	1, 6	35, 3	49, 2	103, 3	157, 5
67A diferencial	4, 7	23, 8	26, 7	3, 8	30, 9	81, 2	23, 1	75, 6
67A integral	4, 7	24, 0	26, 1	3, 6	25, 8	75, 5	32, 4	80, 5
67B diferencial	2, 1	10, 4	10, 3	2, 4	11, 9	116, 4	−14, 1	−19, 1
67B integral	2, 1	10, 4	10, 5	2, 5	12, 8	121, 7	−17, 9	−19, 1

Total and Density of Power Margins

	Upper Surface				LowerSurface			
Caso	s_r mm	s_{imp} mm	s_{prot} mm	s_r/s_{prot} %	s_r mm	s_{imp} mm	s_{prot} mm	s_r/s_{prot} %
22A diferencial	22, 2	24, 4	103, 3	21, 5	−21, 1	−26, 0	−93, 6	22, 6
22A integral	22, 9	24, 7	103, 3	22, 1	−22, 9	−26, 5	−93, 6	24, 4
67A diferencial	62, 6	33, 7	103, 3	60, 6	−60, 4	−33, 7	−93, 6	64, 6
67A integral	70, 2	33, 7	103, 3	68, 0	−67, 7	−33, 7	−93, 6	72, 4
67B diferencial	105, 6	35, 1	103, 3	102, 2	−94, 9	−35, 1	−93, 6	101, 4
67B integral	103, 4	35, 1	103, 3	100, 2	−92, 7	−35, 1	−93, 6	99, 1

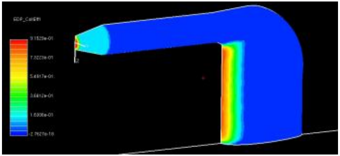
Ice/Water Remaining Margins

ATS4i 3D Ice Protection Analysis with CFD++

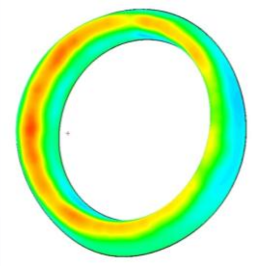


Engine Inlet and Wing impingement

Pitot Collection Efficiency

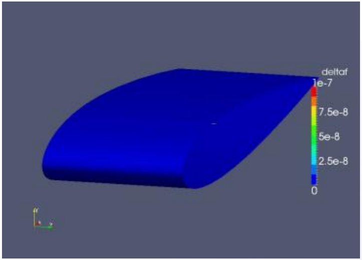


Engine Inlet and Wing Dry Air Temperatures with Hot Air on Ground



ATS4i 3D in-house Ice Protection Simulation Capabilities

- ATS4i has in-house capabilities:
  - ✓ Scientific background in CFD and turbulence;
  - ✓ Experience in ice protection systems development;
  - ✓ Knowledge of theory but also practical as regulations, standards and technical references;
  - ✓ Simulation applied to certification process;
  - ✓ Papers published in icing area



Liquid Water Flow around NACA 0012
to see the animation of water runback flow contact us aerospace@ats4i.com.br

Ice Protection Simulation - Why to Use?

- To check anti-ice system thermal performance, for example:
  - ✓ *IMPINGEMENT LIMITS [m]*
  - ✓ *TOTAL WATER CATCH [kg/(m*s)]*
  - ✓ *REMAINING ICE/WATER [kg/(m*s)]*
  - ✓ *ANTI-ICE POWER DENSITY [W/m2]*
  - ✓ *FREEZING POSITION [m]*
  - ✓ *HEATING/COOLING CYCLING TIMES [s] - de-icing case*
- To check design margins of anti-ice system thermal performance, for example:
  - ✓ *Impingement limits compared with protected area limits*
  - ✓ *Remaining water compared with total catch*
  - ✓ *Anti-ice average power density compared with full evaporative requirement*
  - ✓ *Freezing position compared with protected area limits*
  - ✓ *Highest temperature compared with material/structural temperature limits*

Icing Literature Research

- Integral Methods:
  - ✓ *Makkonen (1985), Guffond & Brunet (1998), Wrigth (1995) , Gent et al. (2000)*
  - ✓ *Stefanini, Silvares, Silva and Zerbini (2010)*

- 2D Differential Methods (RANS boundary-layer):
  - ✓ *Cebeci, Chen, Kaups, Schimke, Shin (1992)*

- 3D Differential Methods (RANS):
  - ✓ *Few references found that presents validation of heat transfer coefficient over airfoil and/or cylinder rough icing surfaces with CFD*
  - ✓ *Silva, Arima, Branco and Pimenta (2011)*
  - ✓ *CFD++ Stefanini Heat Transfer Option*

Selected one case from Achenbach (1977) runs

- ✓ *Used to validate icing codes heat transfer analysis*
- ✓ *Representative Reynolds for icing - Re = 2.2E5*
- ✓ *Transcritical regime ($Re_D > Re_{D,crit}$ minimum drag)*
- ✓ *Laminar-Turbulent Transition near stagnation region*
- ✓ *Closed packed pyramidal roughness - k_s=900E-5*
- ✓ *"Isothermal" wall kept by electrical heating strips*
- ✓ *Delta wall temperature ΔT not informed (9 or 60 K)*
- ✓ *Cylinder diameter - 0.15 m*
- ✓ *Tunnel*
  - ➢ atmospheric
  - ➢ cross section – 0.5 by 0.9 m
  - ➢ blockage ratio – 1:6 (important!)
  - ➢ outlet and inlet length and shapes not informed

Traditional Momentum and Heat Analogy

- Smooth turbulent skin friction coefficient evaluated (Cf_0)
- Skin friction (Cf) coefficient corrected for roughness effects
- Stanton number evaluated from corrected Cf and St_k
- St_k as defined per Owen and Thomson (1963)
- Developed by several researchers: Kays and Crawford (Stanford University 60's to 80's), validated for icing by Makkonen (1985)
- Used in classic 2D icing codes – Lewice (NASA-USA), Onera2D (France), Trajice (UK), Turbice (Finland) and others

Momentum and Heat Analogy Factor Concept

- Full Turbulent over smooth surfaces → Pr_t only
- Full Turbulent over rough surfaces → Pr_t and St_k
- Double layer concept → roughness sub-layer in series with turbulent

$$St = \frac{C_f/2}{Pr_t + \frac{\sqrt{C_f/2}}{St_k}}$$

$$t^+ = \delta t_0^+ + \frac{Pr_t}{\kappa} \ln\left(\frac{32.6 \cdot y^+}{Ks^+}\right)$$

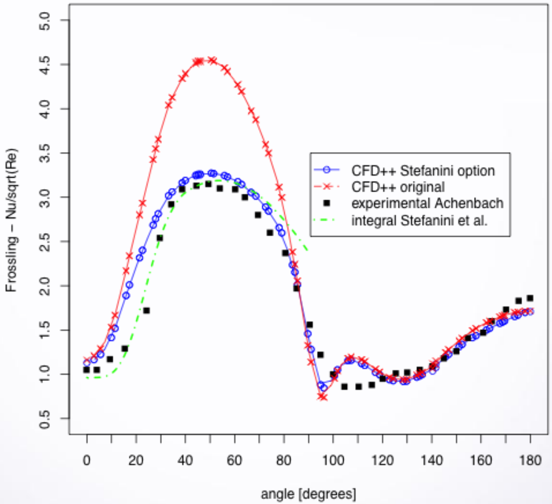
$$St_k = C \cdot (Ks^+)^a \cdot Pr^b$$

$$\delta t_0^+ = \frac{1}{St_k} = \frac{\rho c_p u_\tau}{h_k}$$

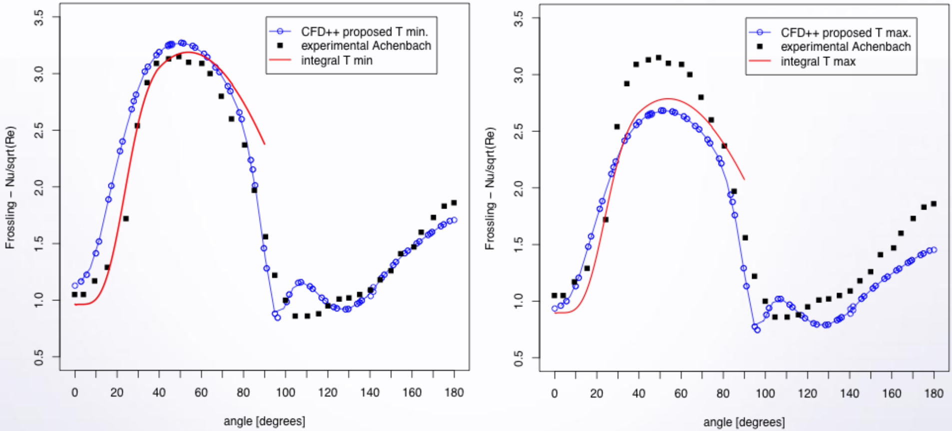
New Heat Transfer Option in CFD++

- Momentum
  - ✓ *Factory settings - already validated*
- Thermal
  - ✓ *Collaboration with Metacomp's Scientists (Uriel, Nili, Prasanth)*
  - ✓ *Implemented by Metacomp since version 10.5 beta*
  - ✓ *New Stefanini Heat Transfer option available*
    - Based on Stanford momentum and heat analogy
    - Effect of thermal resistance due to roughness sub-layer
    - Stefanini et al. Coefficients (C, a, b) of St_k
    - Stefanini et al. demonstrated that two parameters (Ks and C) are necessary to represent the closed-packed pyramidal roughness of Achenbach (1977)
    - Makkonen (1988) validated its icing integral analysis with Achenbach (1977)

Heat Transfer Results



Wall Temperature Effect



Notes

- CFD++ wall functions has a new heat transfer option
- It replicates the Owen-Thomson (1963) analogy, however, uses the Stefanini et al. (2010) constants for closed-packed pyramids of Achenbach (1977)
- Achenbach (1977) data used herein were used by Makkonen (1985) and others after him to simulate ice
- The segregated validation of the heat transfer is a requirement for any CFD numerical tool to be applied in aircraft icing or ice protection system simulation

Special Thanks to

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