Laboratório de Transmissão e Tecnologia do Calor

Models and Hybrid Solutions for Conjugated Heat Transfer Problems in Aeronautical Airfoils and Sensors

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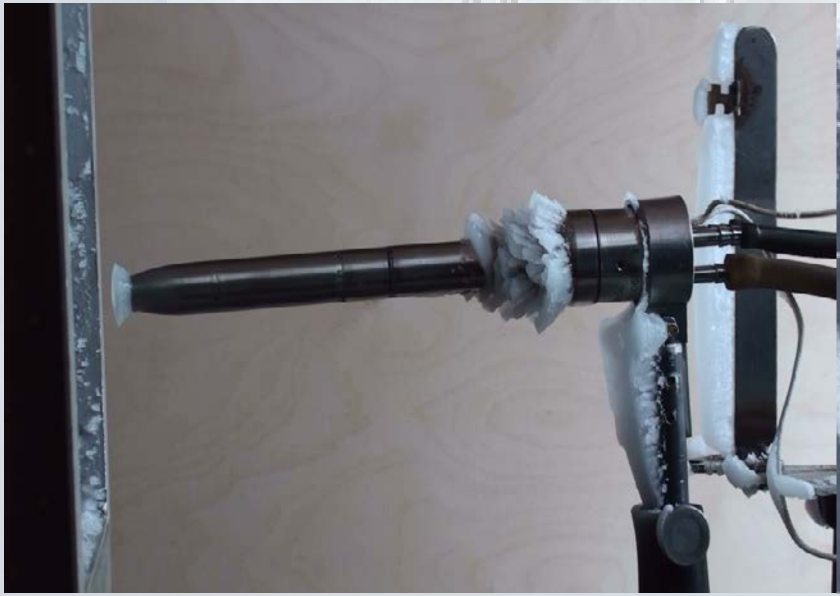
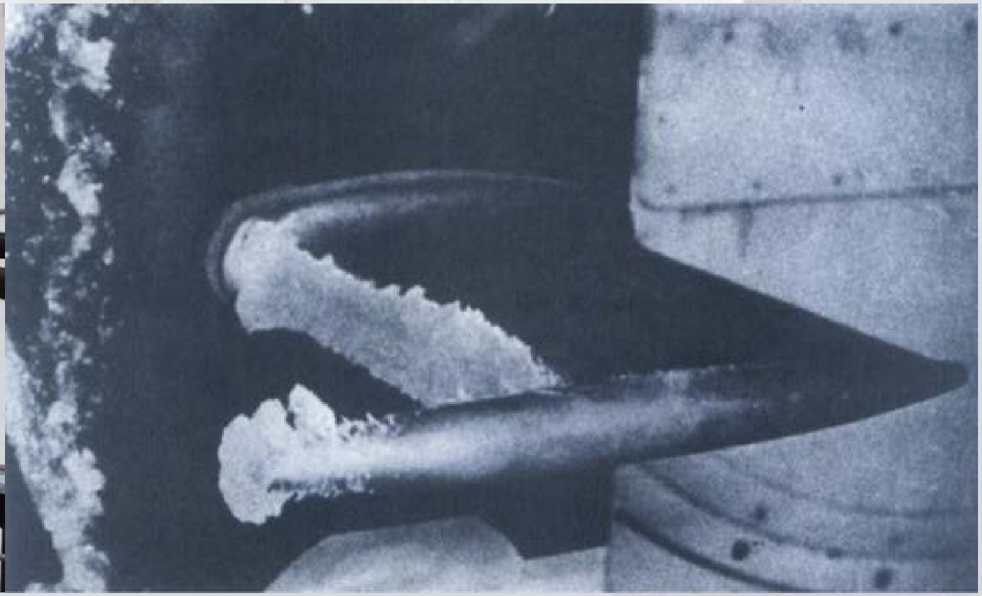
Summary

1. Motivation
2. Objectives
3. Physical and Mathematical Modeling
4. Solution Methodology
5. Results and Discussion
6. Conclusions

1. Motivation

- TsAGI e NASA

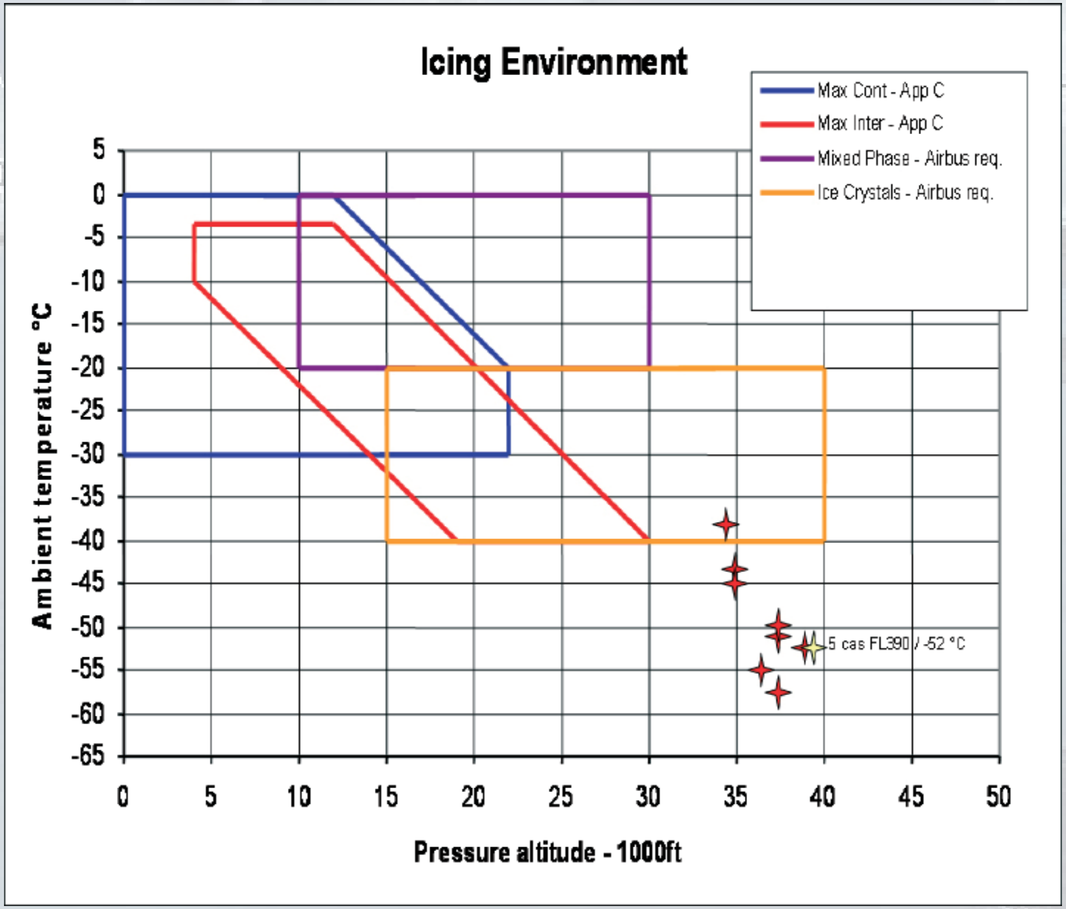



1. Motivation

- Accidents involving icing of Pitot probes

1. Motivation

- Certification Envelope and the AFF447 flight



1. Motivation

- Aerospace industry moving towards extensive use of composite materials

50% composite by weight

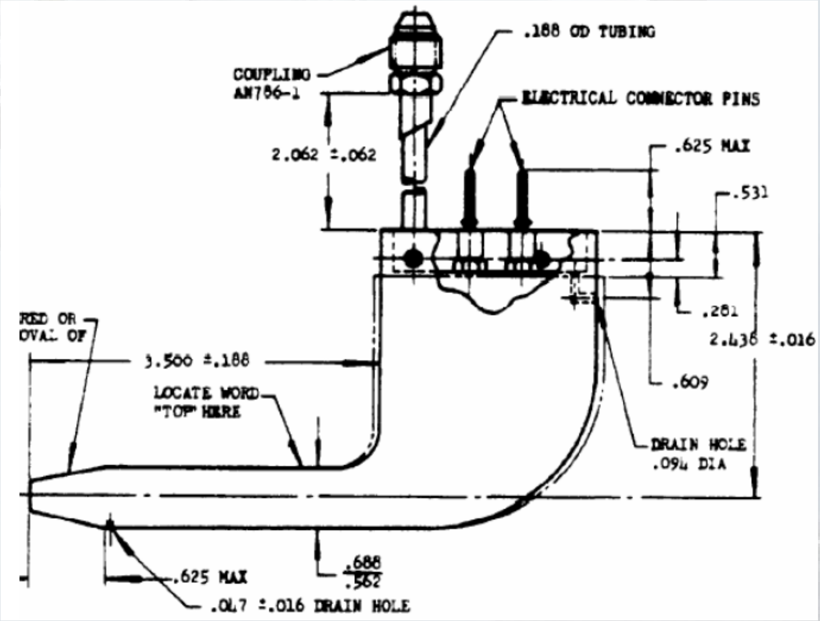
53% composite by weight

2. Objectives

- Show the importance of taking into account the mutual influence between the heat transfer in the solid and in the fluid in icing analysis
- Establish physical and mathematical models for thermal analysis of aeronautical surfaces in the icing wind tunnel
- Physically analyze the thermal behavior of those surfaces and propose design solutions to improve the efficiency of thermal protection systems

3. Physical and Mathematical Modeling

- Pitot tube PH-510 manufactured by AeroInstruments, Co., USA



3. Physical and Mathematical Modeling

- Pitot: Heat Conduction in the Solid

$$w(x)\frac{\partial T_s}{\partial t} = \frac{\partial}{\partial x}\left(k(x)\frac{\partial T_s}{\partial x}\right) + \frac{k(x)}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T_s}{\partial r}\right) + g(x,r,t), 0 \le x \le L, r_i(x) \le r \le r_o(x)$$

$$T_s(x,r,0) = T_0(x,r)$$

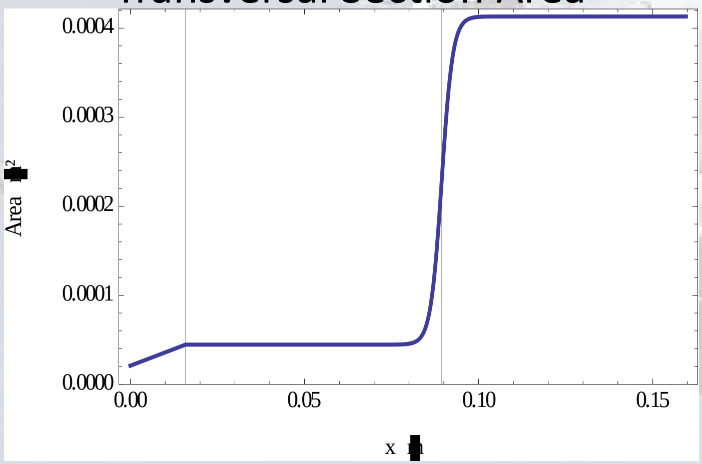
$$h_e T_s(0,r,t) - k(0)\left.\frac{\partial T_s}{\partial x}\right|_{x=0} = h_e T_{aw}; \quad h_L T_s(L,r,t) + k(L)\left.\frac{\partial T_s}{\partial x}\right|_{x=L} = h_L T_{aw}$$

$$\left.\frac{\partial T_s}{\partial r}\right|_{r=r_i(x)} = 0; \quad h(x)T_s(x,r_o(x),t) + k(x)\left.\frac{\partial T_s}{\partial r}\right|_{r=r_o(x)} = h(x)T_{aw}$$

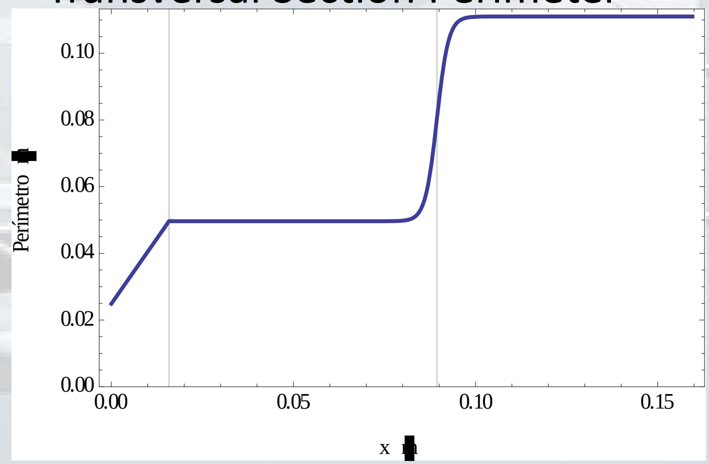
3. Physical and Mathematical Modeling

Entry Data

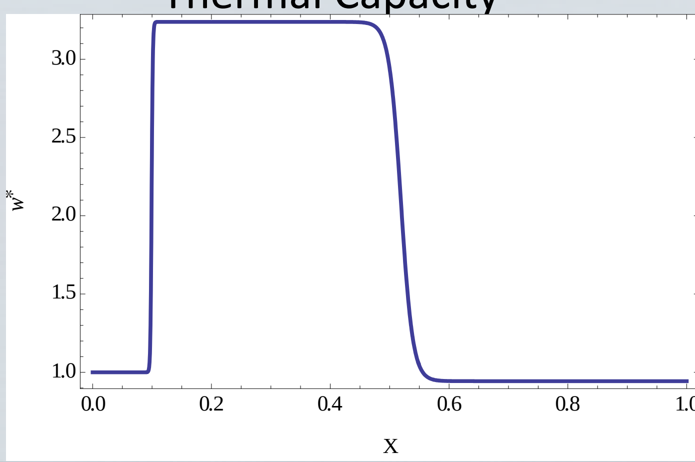
Transversal Section Area



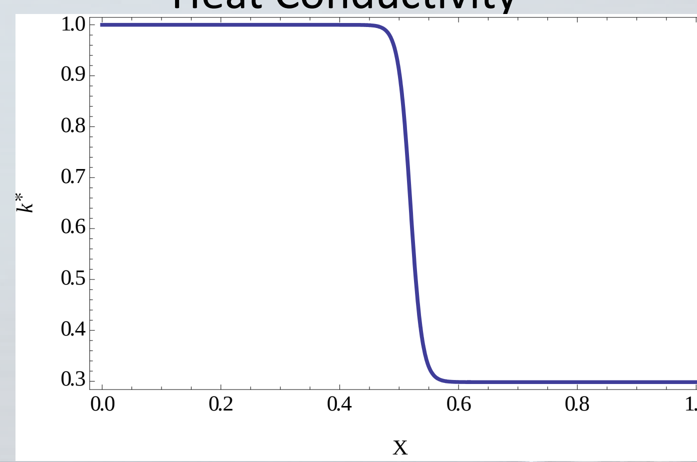
Transversal Section Perimeter



Thermal Capacity

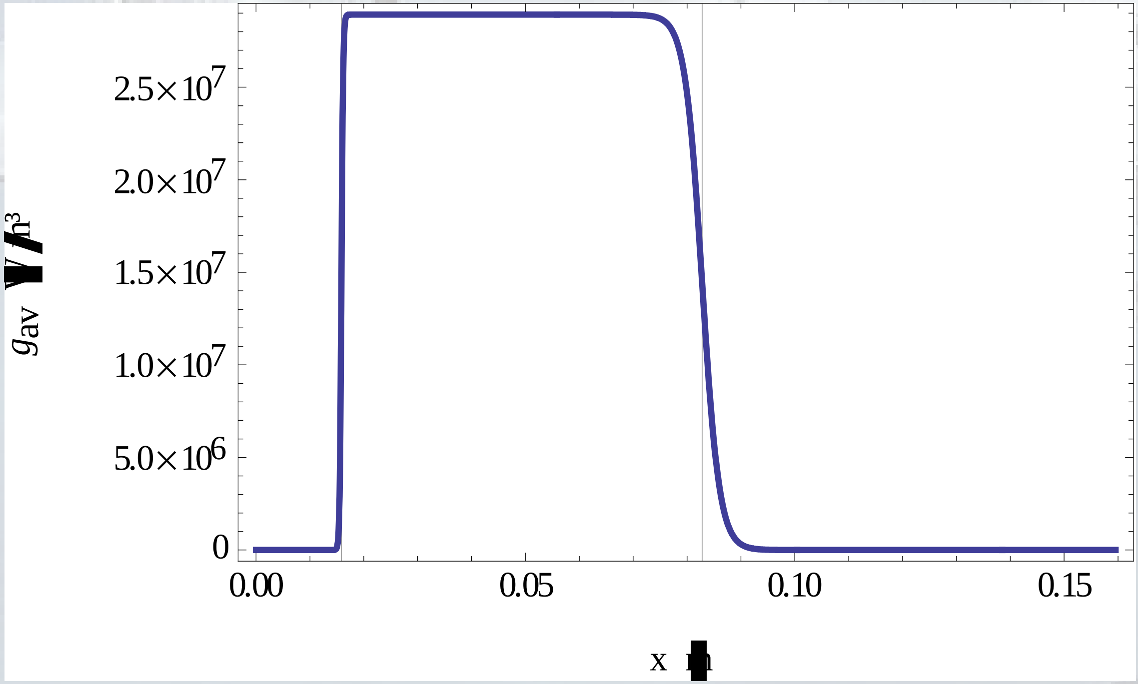


Heat Conductivity



3. Physical and Mathematical Modeling

- Het generation by Joule Effect



3. Physical and Mathematical Modeling

- Pitot: Boundary Layer Equations

$$\rho u \frac{\partial u}{\partial s} + \overline{\rho v}\,\frac{\partial u}{\partial y} = \rho_e u_e \frac{du_e}{ds} + \frac{1}{r}\frac{\partial}{\partial y}\left[(\mu+\mu_t)\, r \frac{\partial u}{\partial y}\right]$$

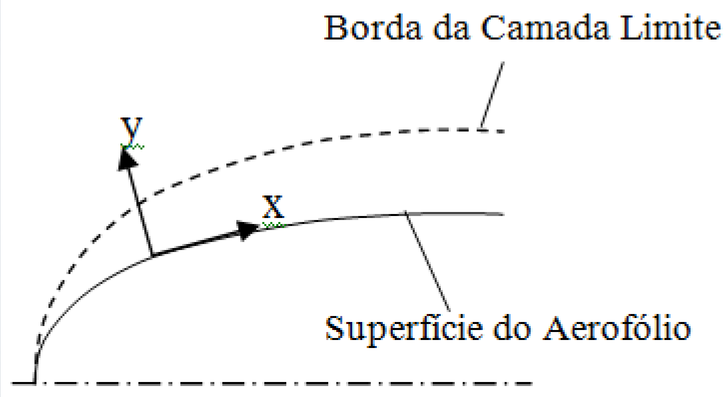
$$u(0)=0, \quad u(\infty)=u_e, \quad \left.\frac{\partial u}{\partial y}\right|_{y=\infty}=0$$

$$\rho u \frac{\partial H}{\partial s} + \overline{\rho v}\,\frac{\partial H}{\partial y} = \frac{1}{r}\frac{\partial}{\partial y}\left[\left(\frac{\mu}{Pr}+\frac{\mu_t}{Pr_t}\right) r\frac{\partial H}{\partial y}\right] + \frac{1}{r}\frac{\partial}{\partial y}\left[\mu r\left(1-\frac{1}{Pr}\right)+\mu_t r\left(1-\frac{1}{Pr_t}\right)\right]\frac{\partial}{\partial y}\left(\frac{u^2}{2}\right)$$

$$H(0)=c_p T_w, \quad H(\infty)=H_e, \quad \left.\frac{\partial H}{\partial y}\right|_{y=\infty}=0$$

3. Physical and Mathematical Modeling

- Airfoil: Mechanical boundary layer



$$\frac{\partial \bar{u}}{\partial x} + \frac{\partial \bar{v}}{\partial y} = 0$$

$$\bar{u}\frac{\partial \bar{u}}{\partial x} + \bar{v}\frac{\partial \bar{u}}{\partial y} = u_e \frac{du_e}{dx} + \frac{\partial}{\partial y}\left[(\nu + \nu_t)\frac{\partial \bar{u}}{\partial y}\right]$$

$$\frac{\partial \bar{p}}{\partial y} \approx 0$$

$$\nu_t = l^2 \frac{\partial \bar{u}}{\partial y}$$

$$l = \kappa(y + \Delta y)\left[1 - \exp\left(-\frac{y+\Delta y}{A}\right)\right]$$

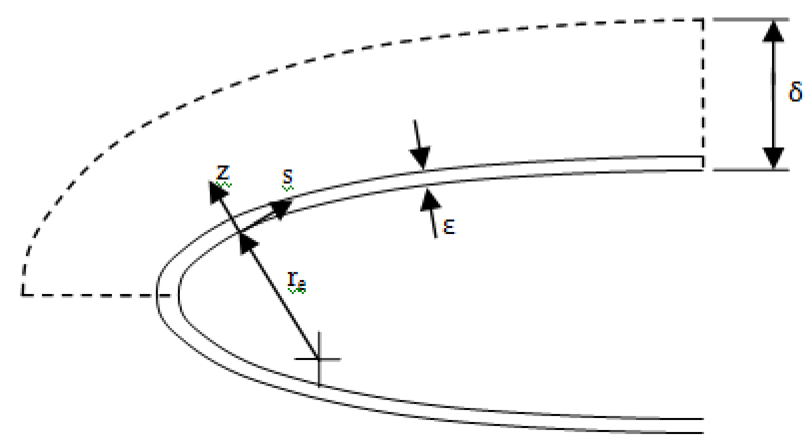
$$\Delta y = 0.9\frac{\nu}{u_\tau}\left[\sqrt{k_s^+} - k_s^+ \exp\left(-\frac{k_s^+}{6}\right)\right]$$

$$A = 26\frac{\nu}{u_\tau N}$$

$$N = \sqrt{1 - 11.8\frac{\nu u_e}{{u_\tau}^3}\frac{du_e}{dx}}$$

3. Physical and Mathematical Modeling

- Airfoil: Conjugated Heat Transfer Problem



$$w(z)\frac{\partial T}{\partial t} + w_f u(s,z)\frac{\partial T}{\partial s} + w_f v(s,z)\frac{\partial T}{\partial z} = k(z)\frac{\partial^2 T}{\partial s^2} + \frac{\partial}{\partial z}\left[k(z)\frac{\partial T}{\partial z}\right] + w_f\frac{\partial}{\partial z}\left[\frac{l^2}{Pr_t}\frac{\partial u}{\partial z}\frac{\partial T}{\partial z}\right] + G(s,z,t)$$

$$T(s,z,0) = T_\infty$$

$$\left.\frac{\partial T}{\partial s}\right|_{s=0} = 0; \left.\frac{\partial T}{\partial s}\right|_{s=L} = 0$$

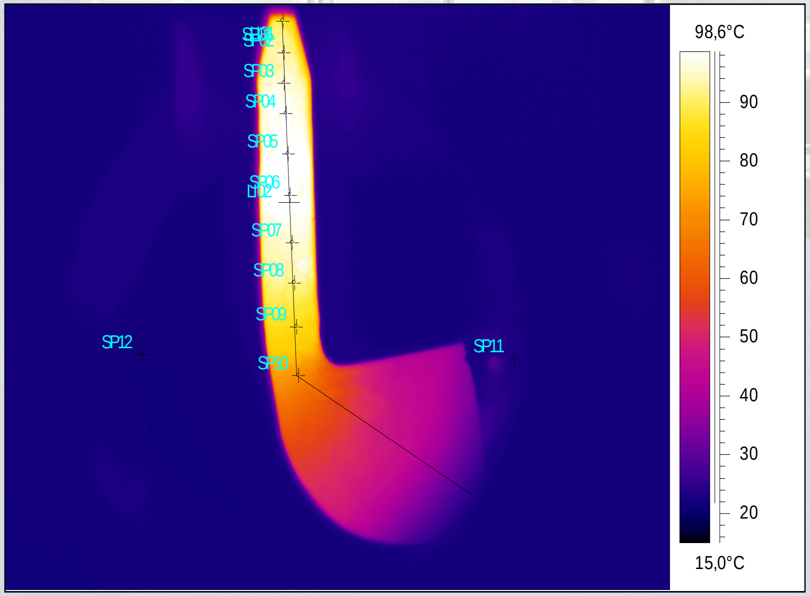
$$-k_s\left.\frac{\partial T}{\partial z}\right|_{z=0} = q_w; T(s,\delta,t) = T_\infty$$

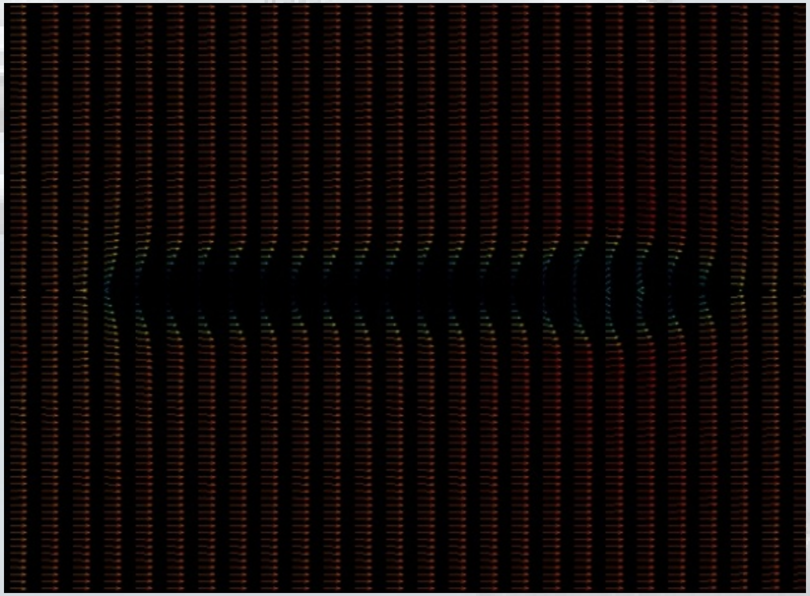
4. Solution Methodology

- Pitot Tube
  - Solid – GITT
  - Fluid – Karman-Pohlhausen Integral Method
  - Needs an iterative process to match the temperatures and heat fluxes at the interface
- Airfoil
  - Single Domain Formulation – GITT
  - Straightforward and without needing iterative processes

5. Results and Discussion

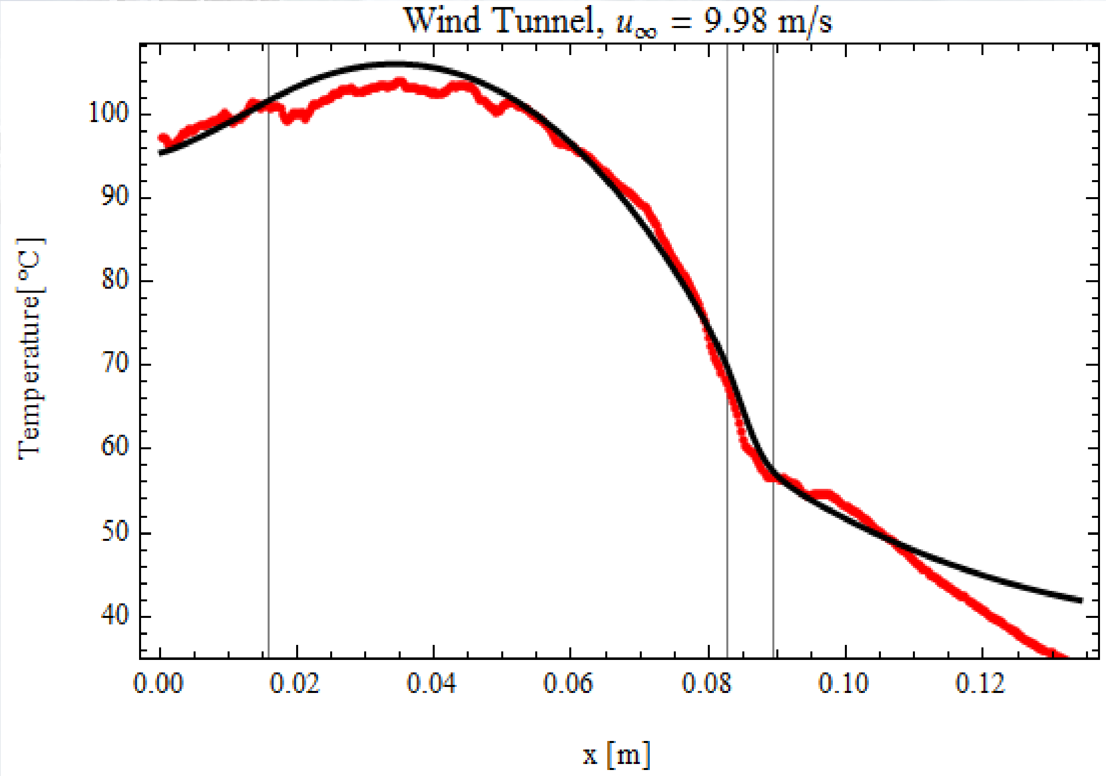
- Wind Tunnel





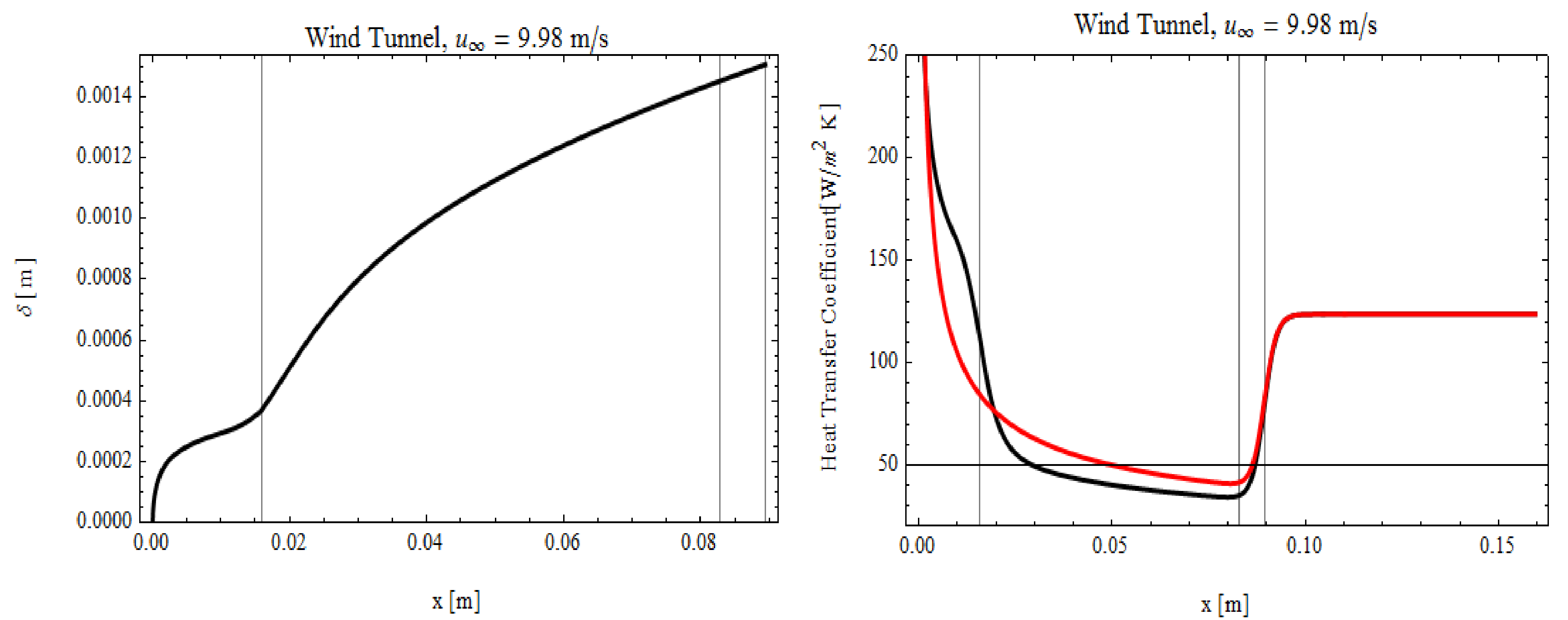
5. Results and Discussion

- Wind Tunnel – INMETRO (10 m/s)



5. Results and Discussion

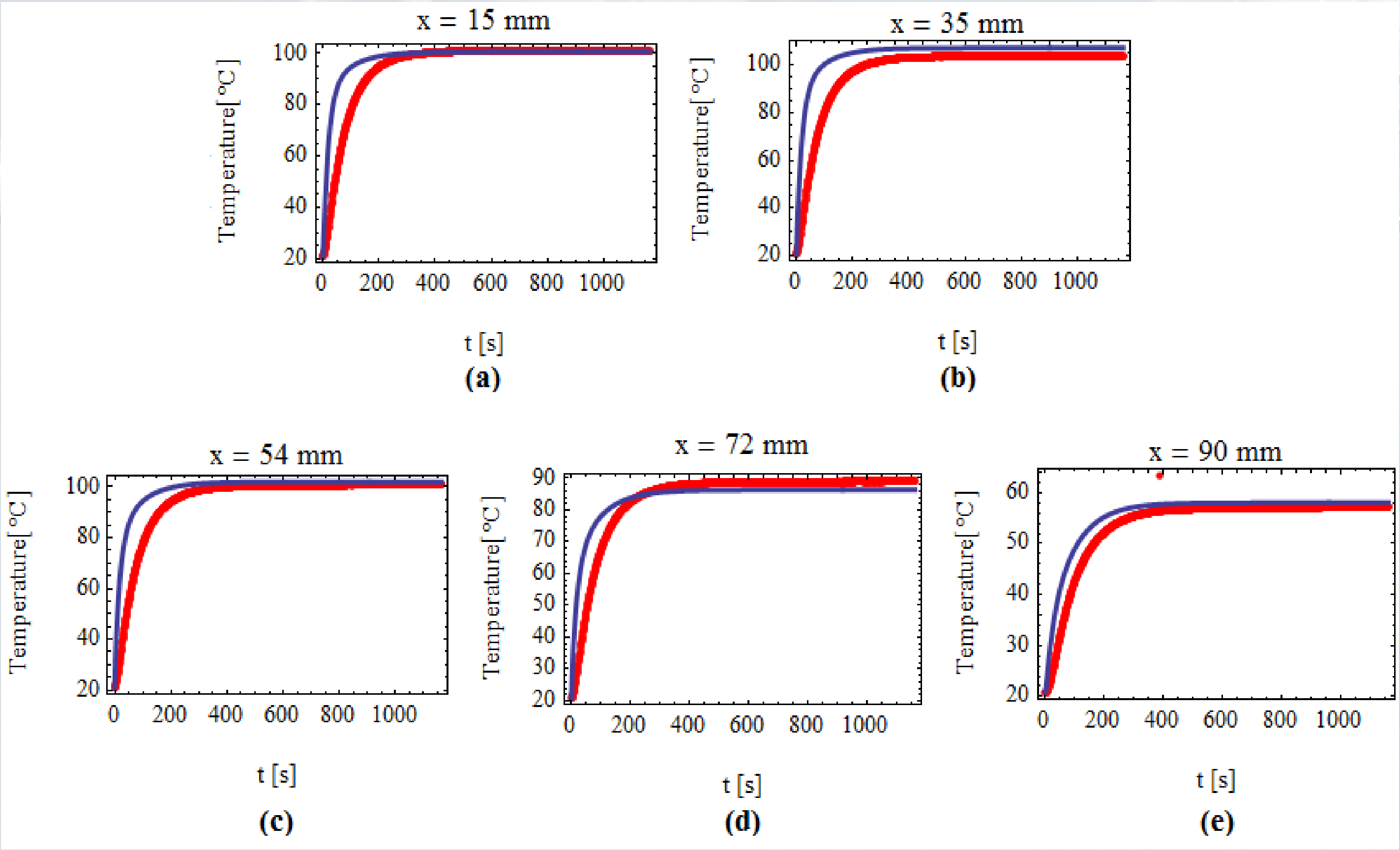
- Wind Tunnel – INMETRO (10 m/s)



(a) (b)

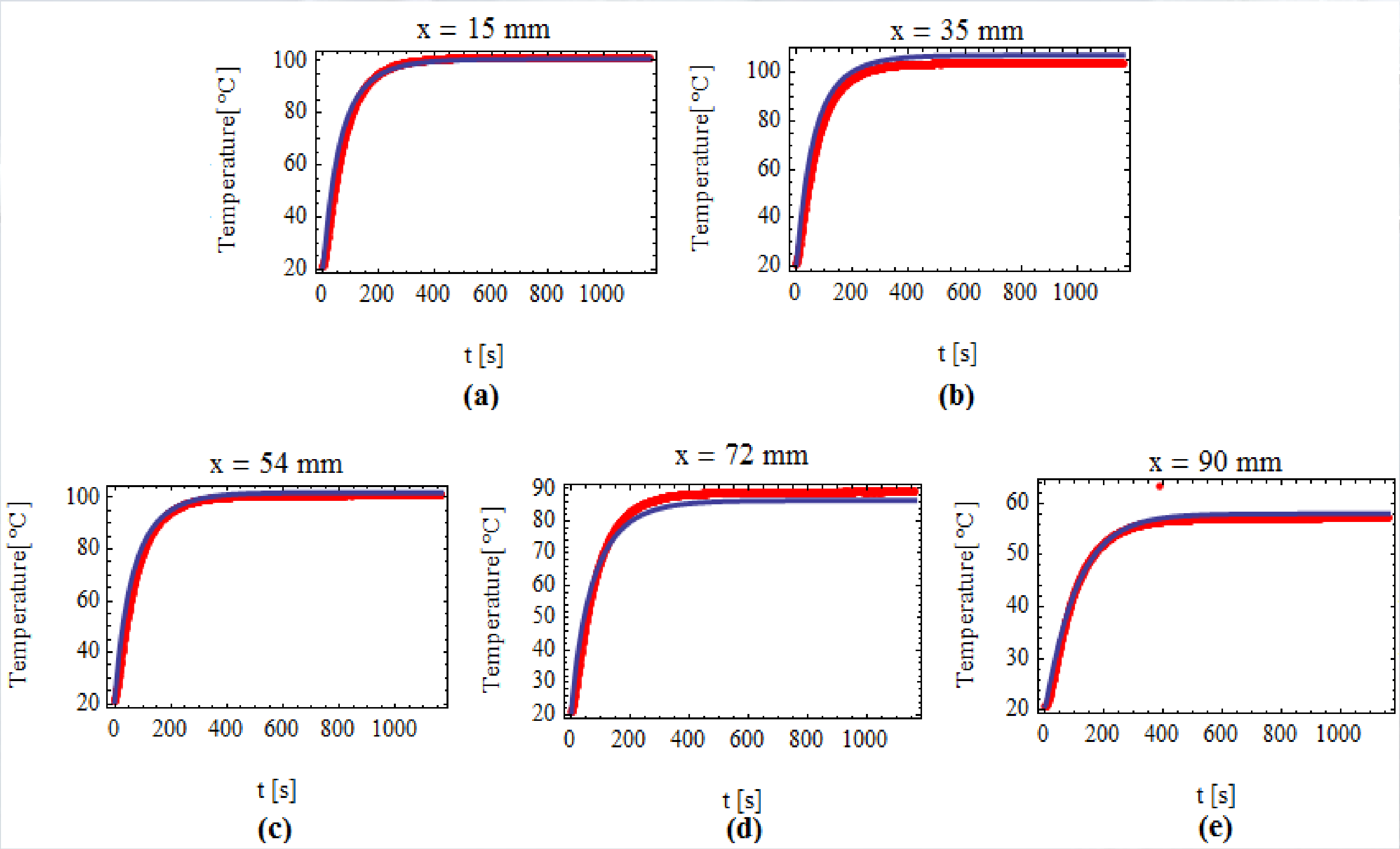
5. Results and Discussion

- Wind Tunnel – INMETRO (10 m/s)



5. Results and Discussion

- Wind Tunnel – INMETRO (10 m/s)

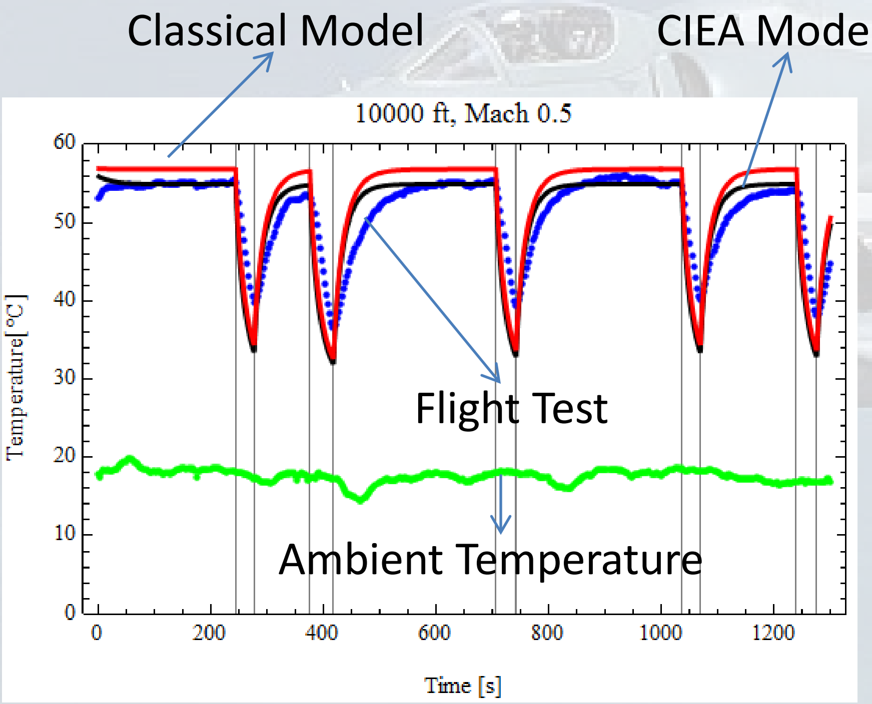


5. Results and Discussion

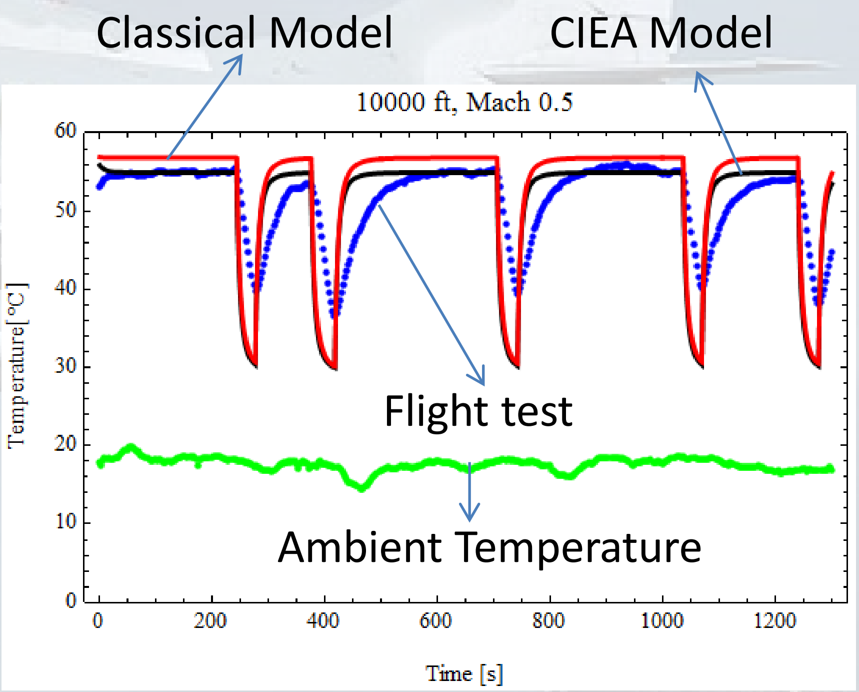
- A-4 Skyhawk flight tests (Brazilian Navy)

5. Results and Discussion

- A-4 Skyhawk: Mach 0.5, Altitude 10000 ft



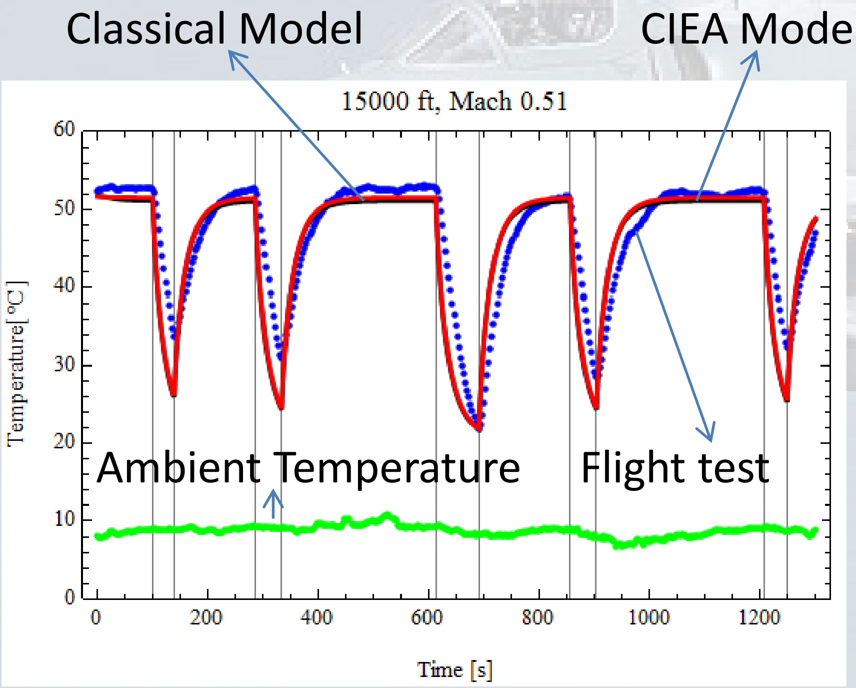
With Porcelain



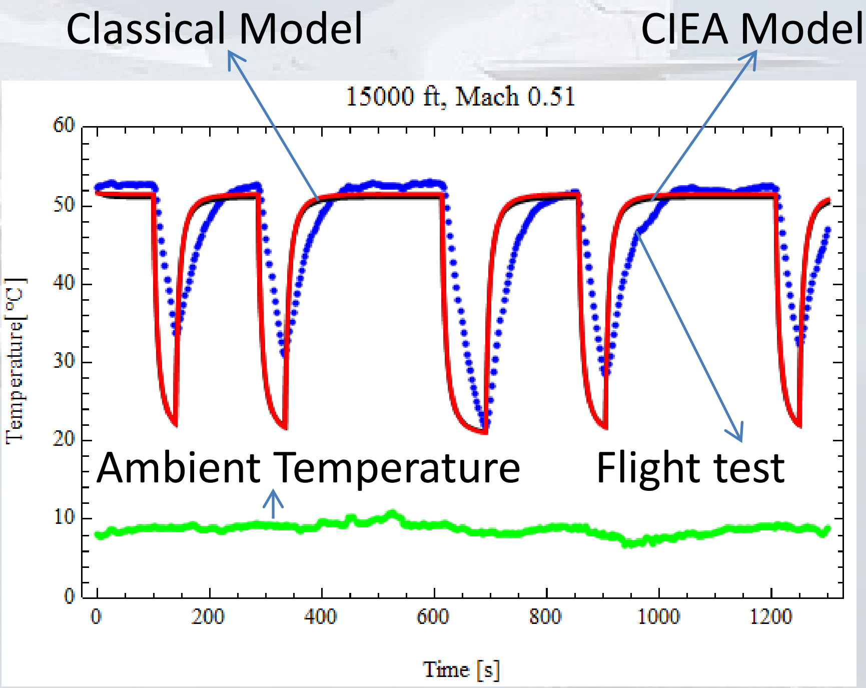
Without Porcelain

5. Results and Discussion

- A-4 Skyhawk: Mach 0.51, Altitude 15000 ft



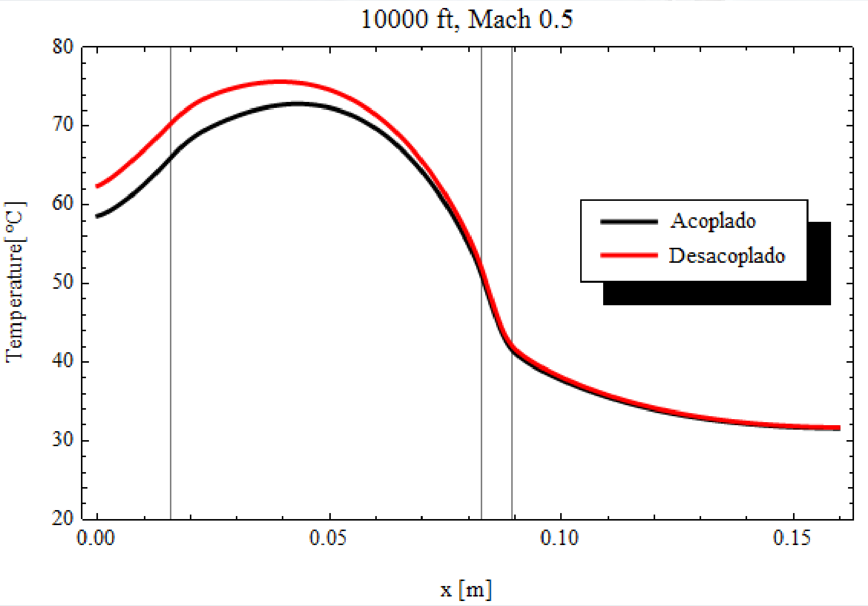
With Porcelain

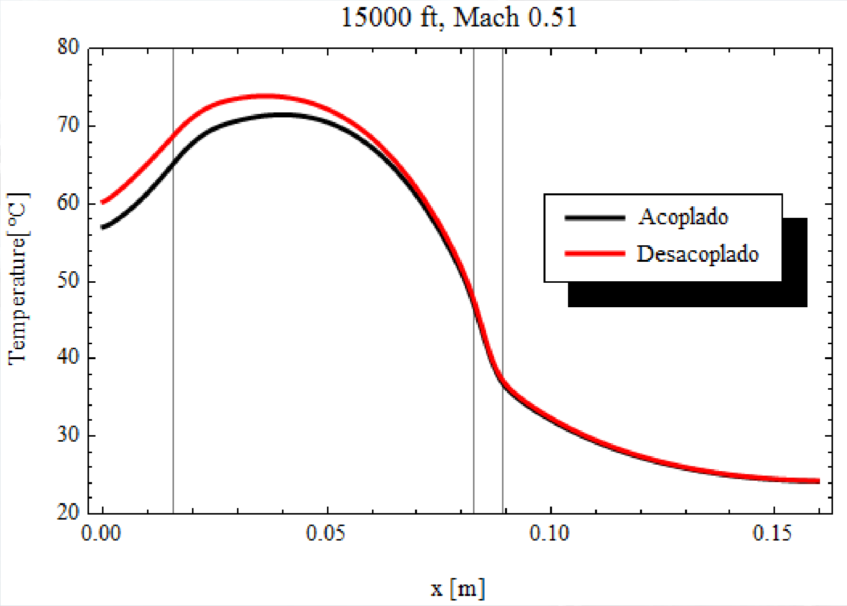


Without Porcelain

5. Results and Discussion

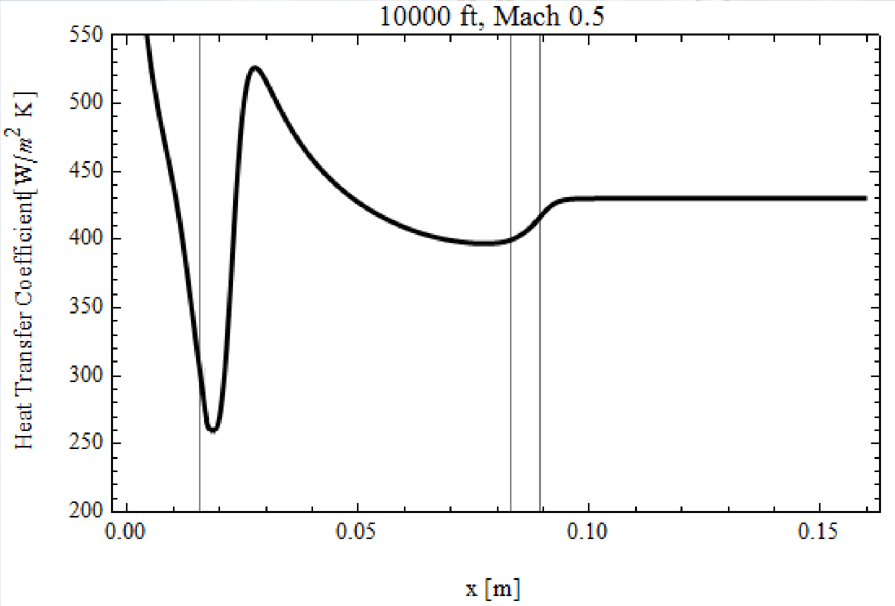
- A-4 Skyhawk: Steady-state response

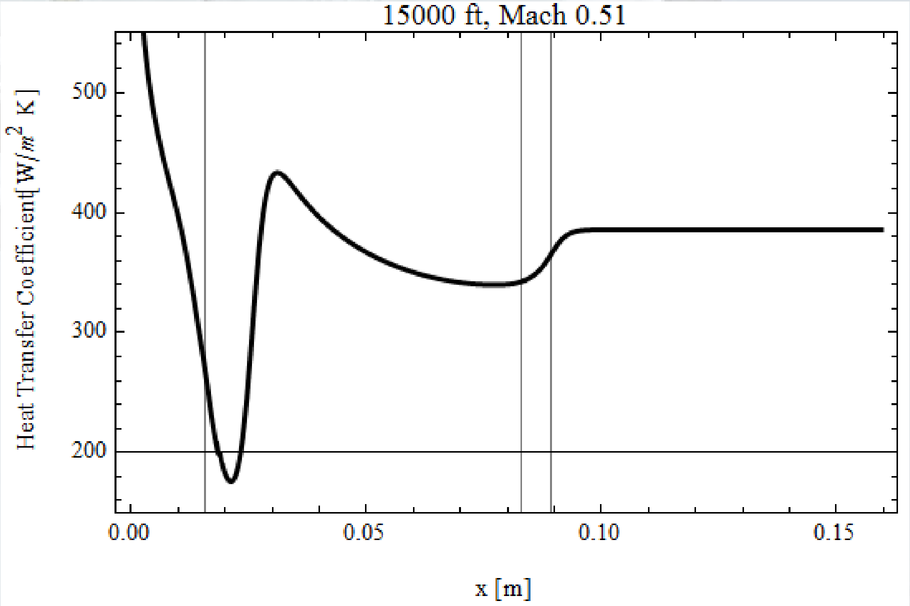




5. Results and Discussion

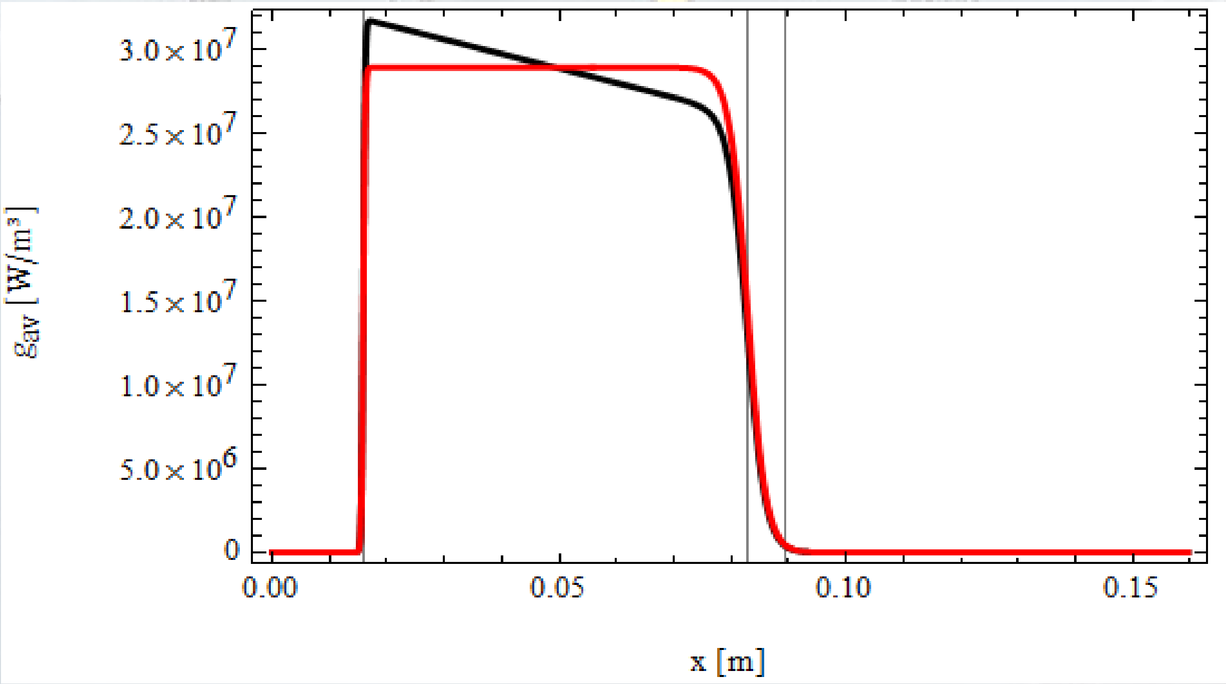
- A-4 Skyhawk: Heat Transfer Coefficient Distribution





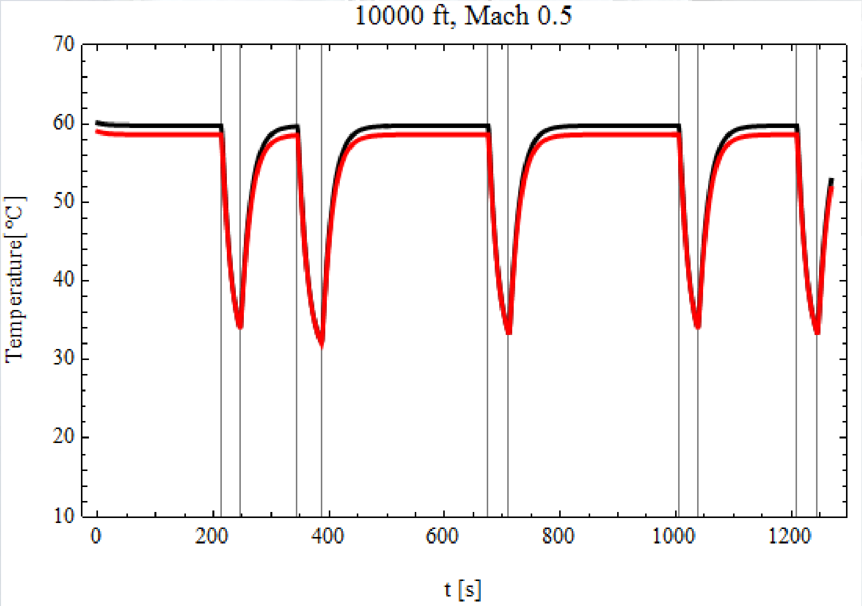
5. Results and Discussion

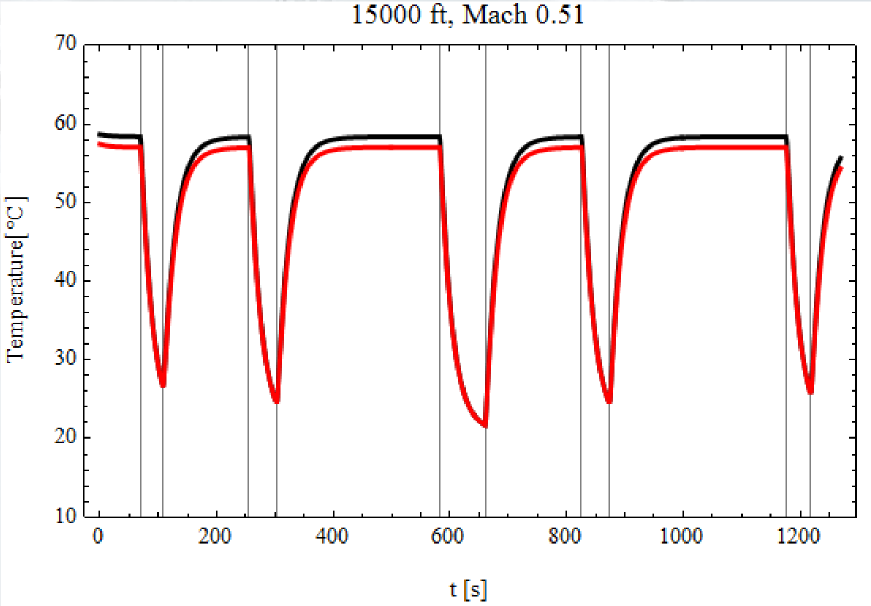
- Parametric Design Studies
  - Power Density



5. Results and Discussion

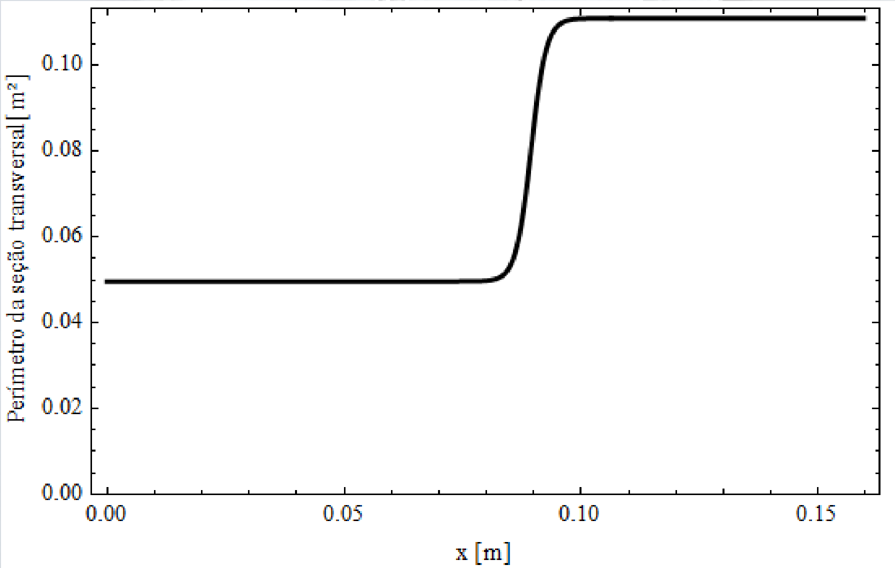
- Parametric Design Studies
  - Power Density (Temperature increases 2.3%)

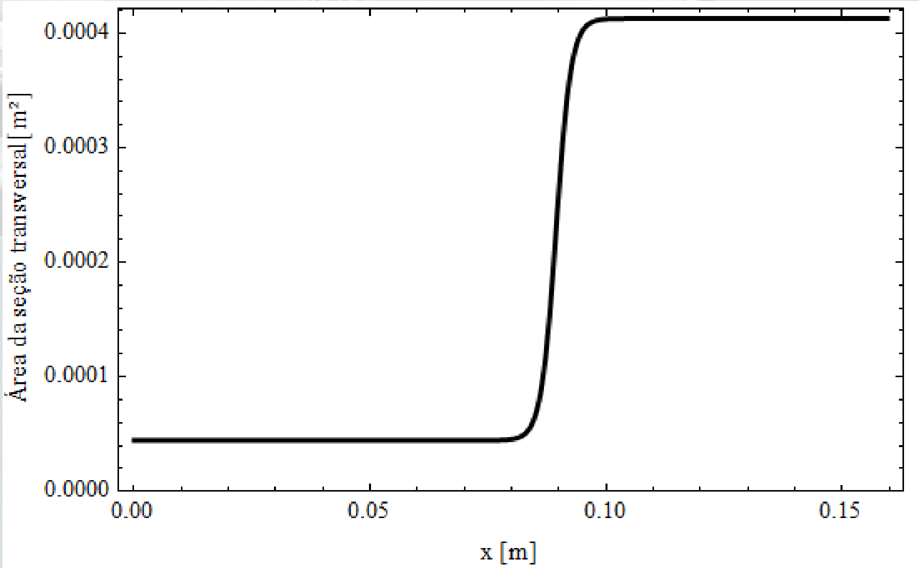




5. Results and Discussion

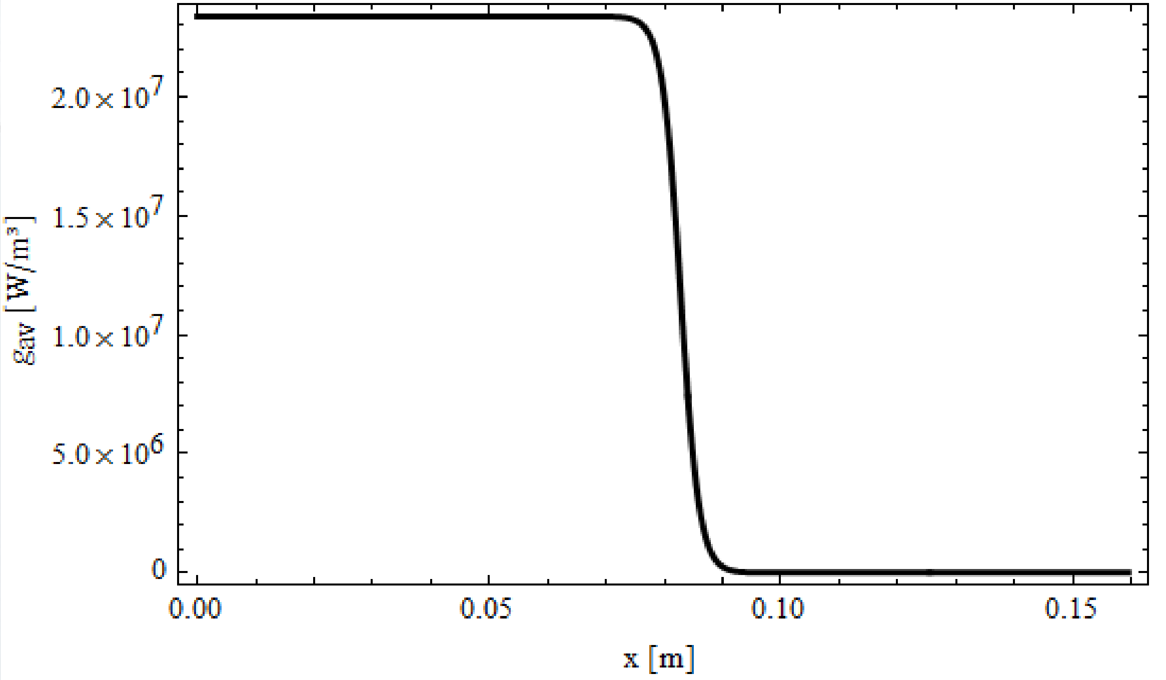
- Parametric Design Studies
  - Fully Cylindrical Probe





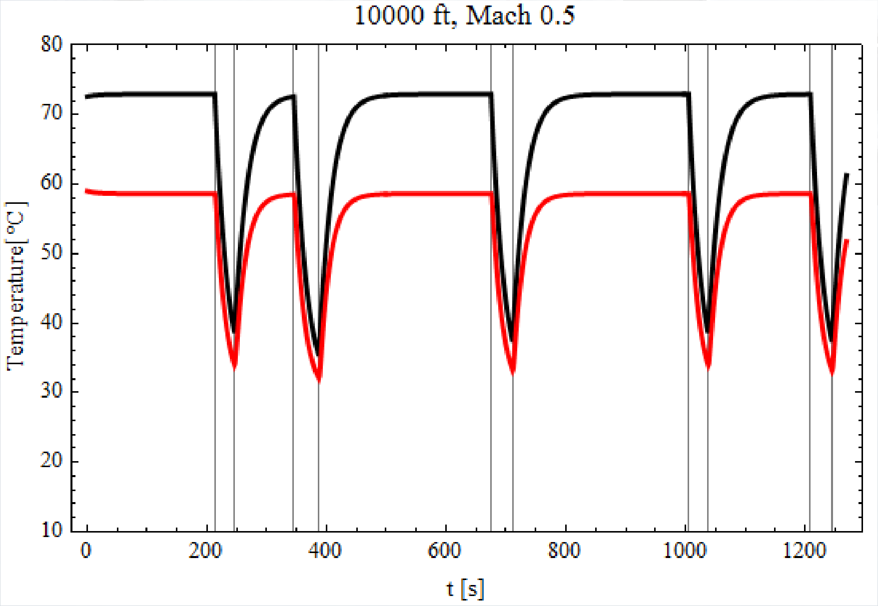
5. Results and Discussion

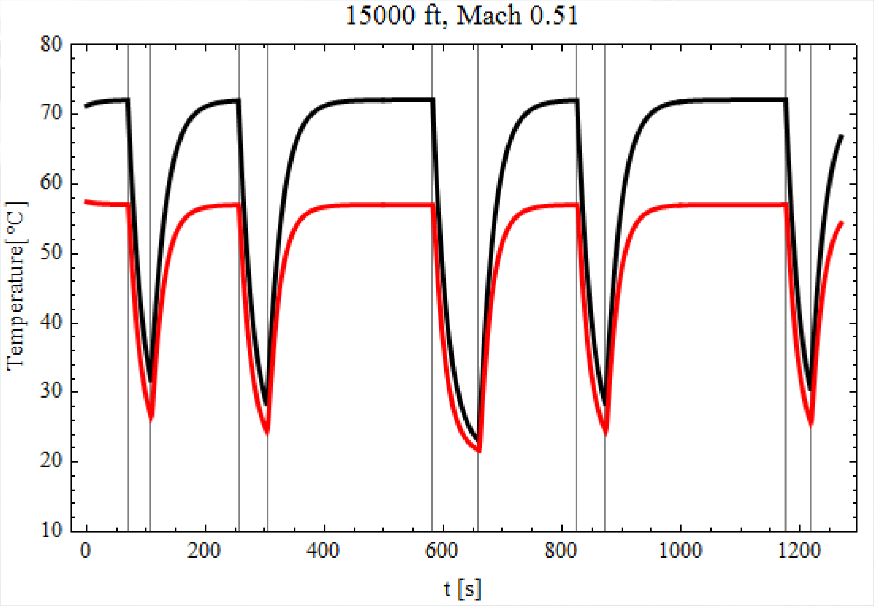
- Parametric Design Studies
  - Fully Cylindrical Probe



5. Results and Discussion

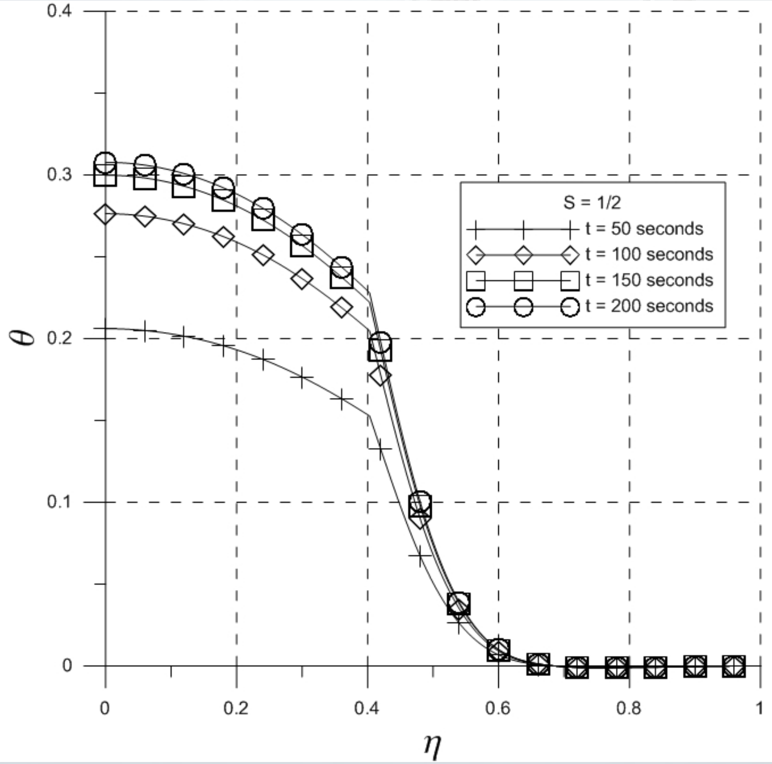
- Parametric Design Studies
  - Fully Cylindrical Probe (Temperature Increases 26%!!!)

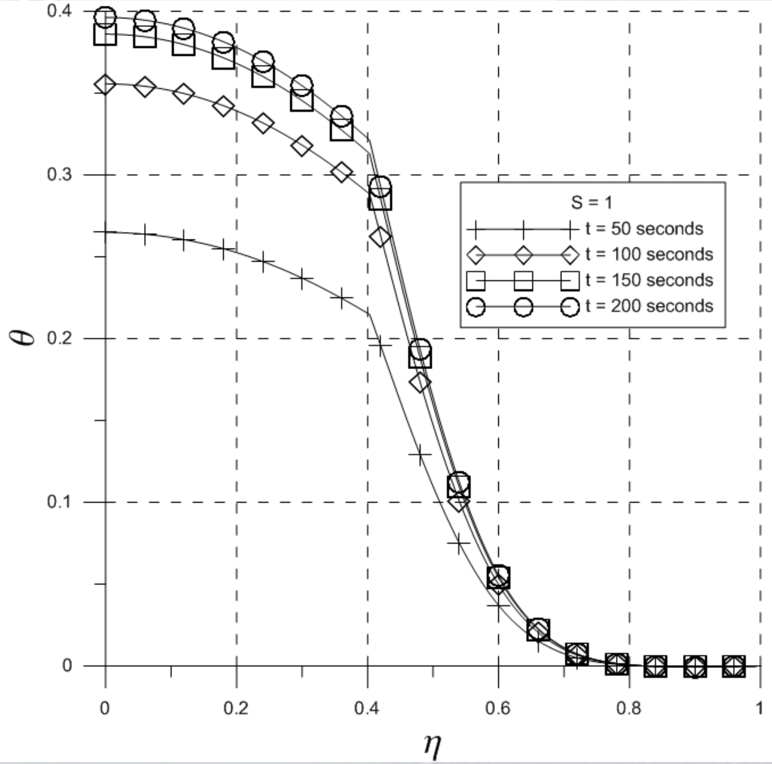




5. Results and Discussion

- Single Domain – Airfoil
  - Laminar Boundary Layer





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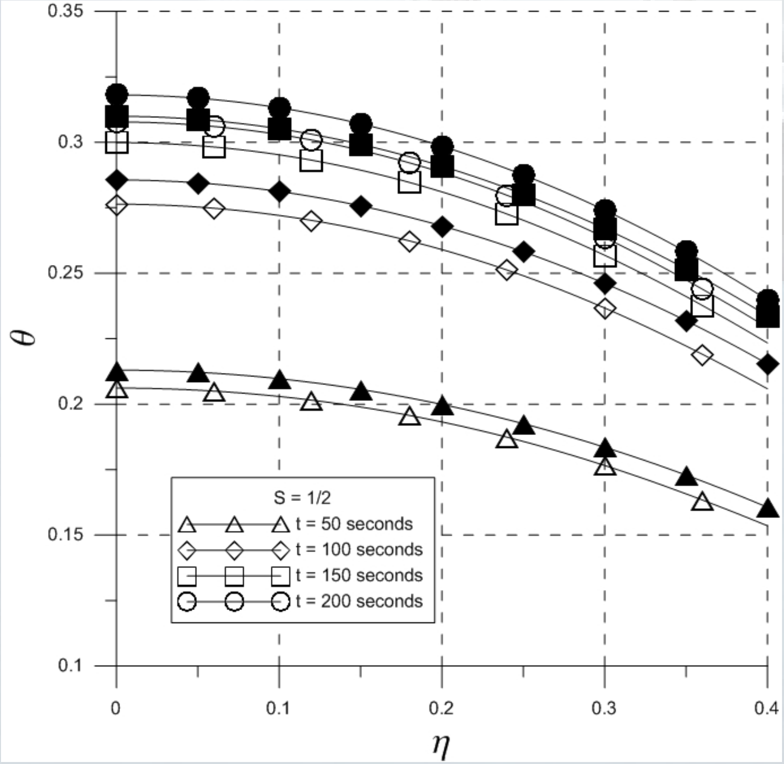

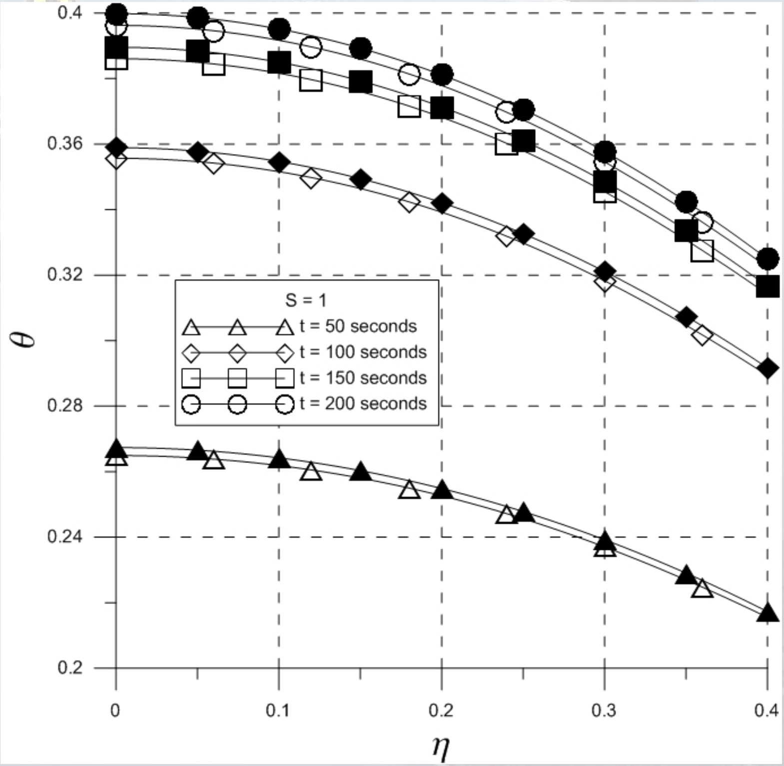

6. Conclusions

- A physical and mathematical model to reproduce the thermal behavior of aircraft surfaces was built and validated
- An important conclusion about the importance of taking into account the solid wall participation on the development of the fluid flow was made based on the conjugated heat transfer model proposed
- The analysis performed allowed the discovery of important directions to be considered in the design of Pitot tubes for icing environment reliability

Thanks for the attention!!