Heat Transfer in Aeronautical Structures with Ice Accretion

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Outline of Presentation

- Describe some of the methods of calculating heat transfer and ice accretion in aeronautical structures for a given set of flight and weather conditions
- Review some of the results available from the literature for illustration and comparison purposes

Terminology

- **Icing** of an aircraft occurs when it flies through a cloud of small supercooled water droplets

- **Two types** of ice accretion mechanisms have been identified, resulting in two physically and geometrically different formations

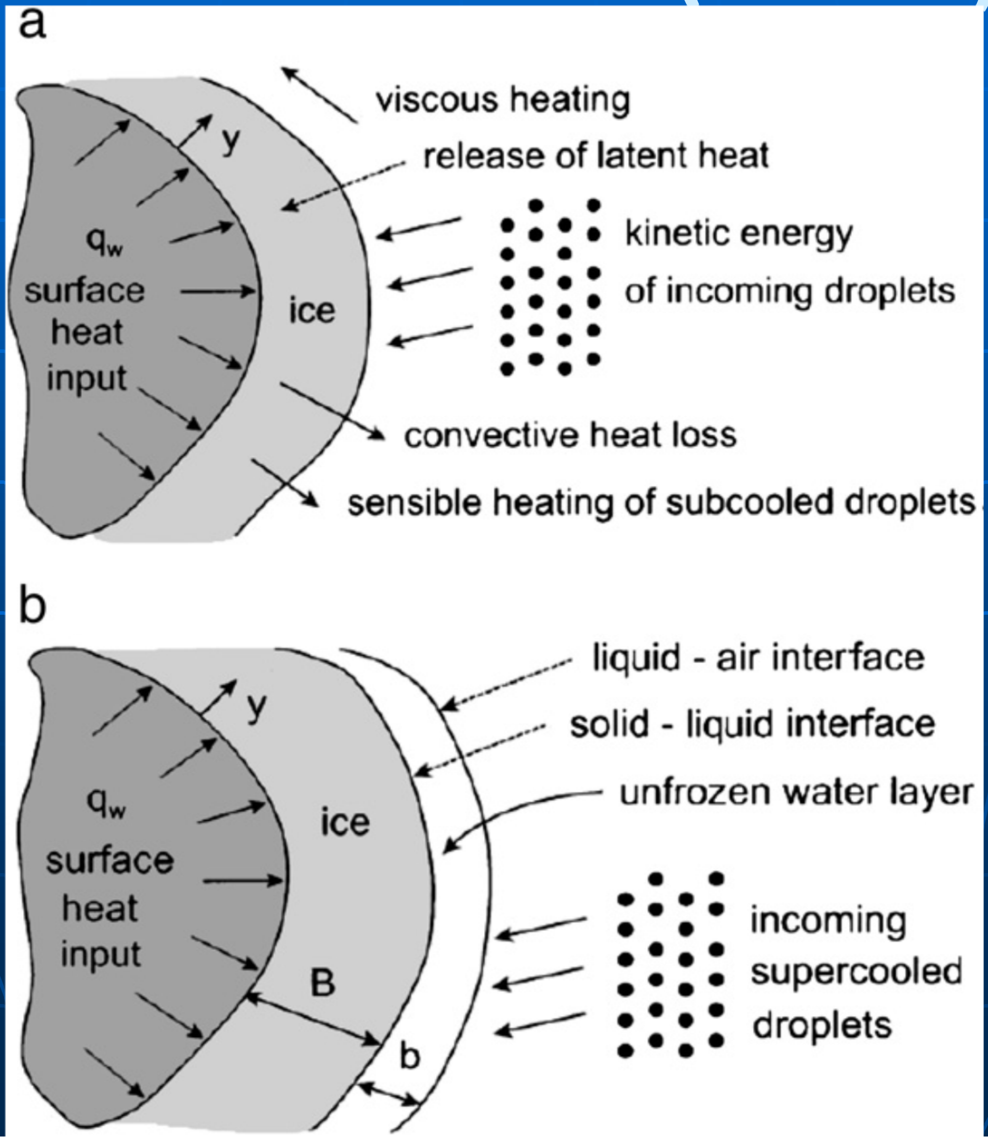
Ice Accretion: Type I (Rime Ice)

- For low liquid water content, air temperature, and flight speed, the accreting ice is characterized by a **white opaque color** and a **low density** (less than 1 gm/cm^3).
- This formation is called **rime ice** and is more likely to occur on relatively streamlined shapes extending into the incoming air.
- **Rime ice** forms upon impact of the water droplets with the surface and is characterized by a freezing fraction of unity.

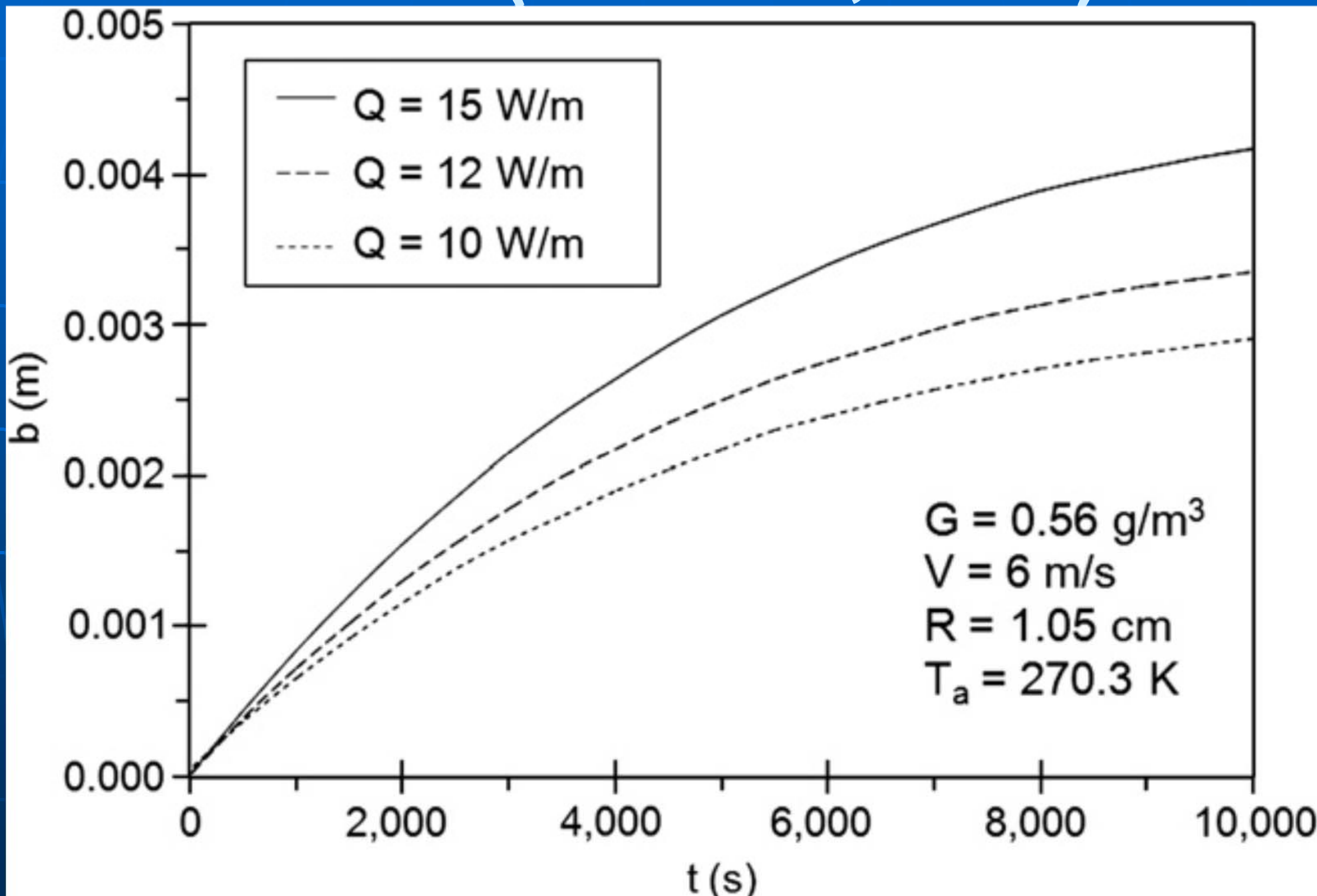
Ice Accretion: Type II (Glaze Ice)

- When both the liquid water content and the flight speed are high, while the air temperature is near freezing, the resulting ice formation will be characterized by a **clear color** and a **density near 1 gm/cm^3**.
- This mechanism of formation results in **glaze ice** which is usually associated with the presence of liquid water and a freezing fraction less than one.

Rime Ice (a) and Glazed Ice (b) G.F. Naterer (2011)



Transient Growth of the Unfrozen Liquid Layer for Different Surface Heating Rates (Naterer,2011)



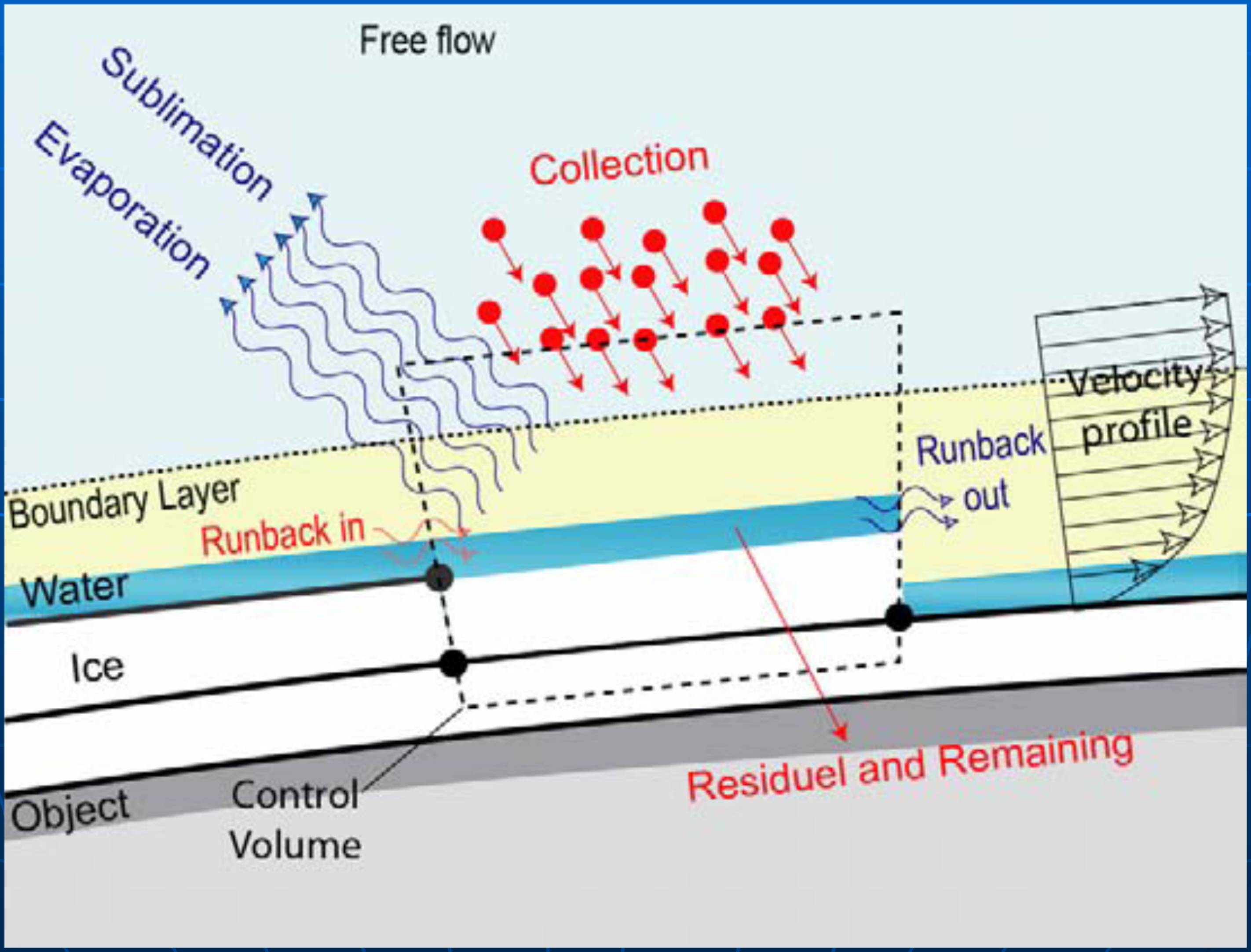
Energy Fluxes on Surfaces in Flight

- The inlet energy flux comprises terms which are due to <u>freezing</u>, <u>aerodynamic heating</u>, <u>droplet kinetic energy</u>, and external sources (such as the de-icing heater).
- The outlet energy flux includes terms which are due to <u>convection</u>, <u>radiation</u>, <u>evaporation</u>, <u>sublimation</u>, <u>droplet warming</u>, and <u>aft conduction</u>.

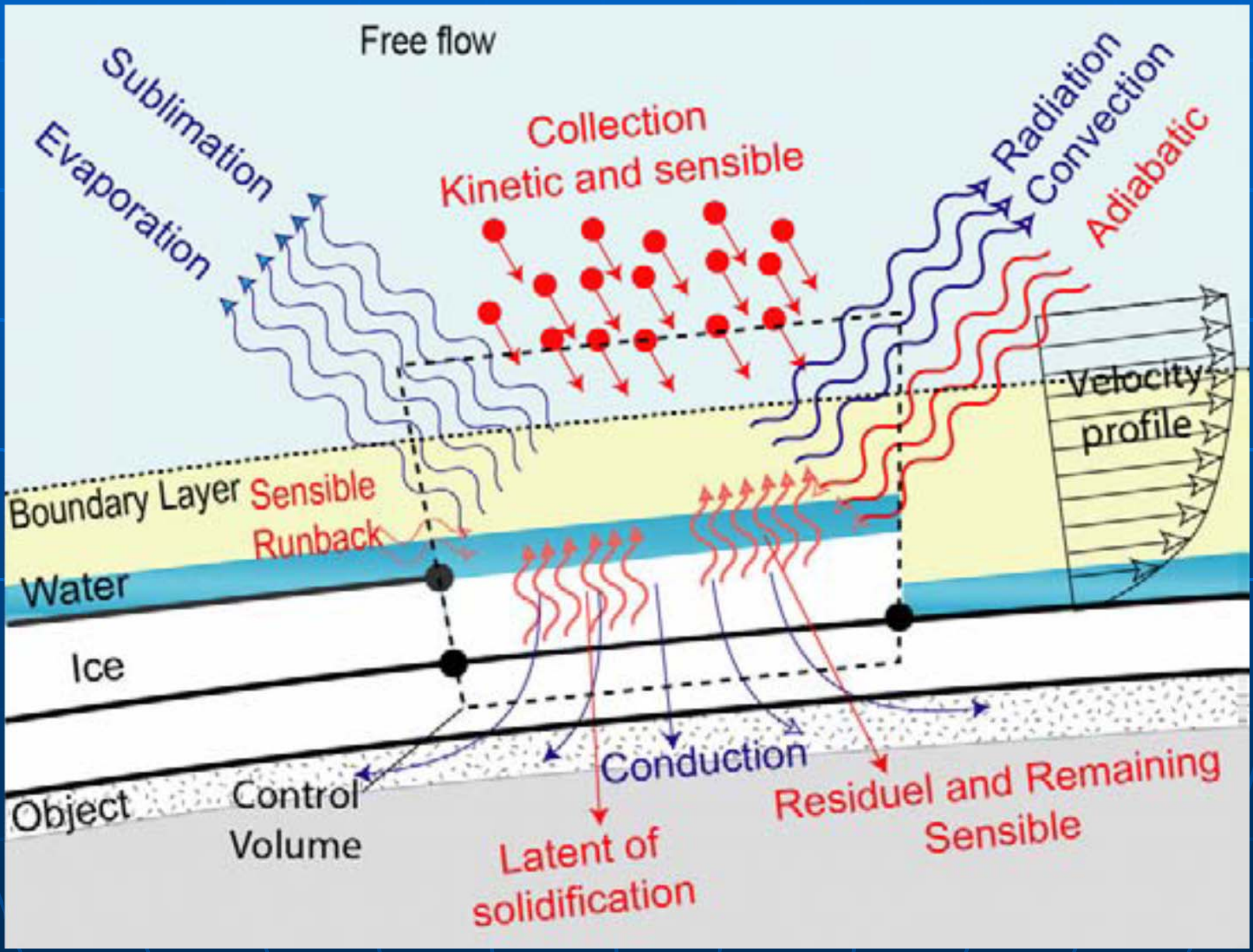
Energy Fluxes on Surfaces in Flight (Cont.)

- For aircraft wings, both the wing leading edge and the after-body regions should be considered in any modeling effort

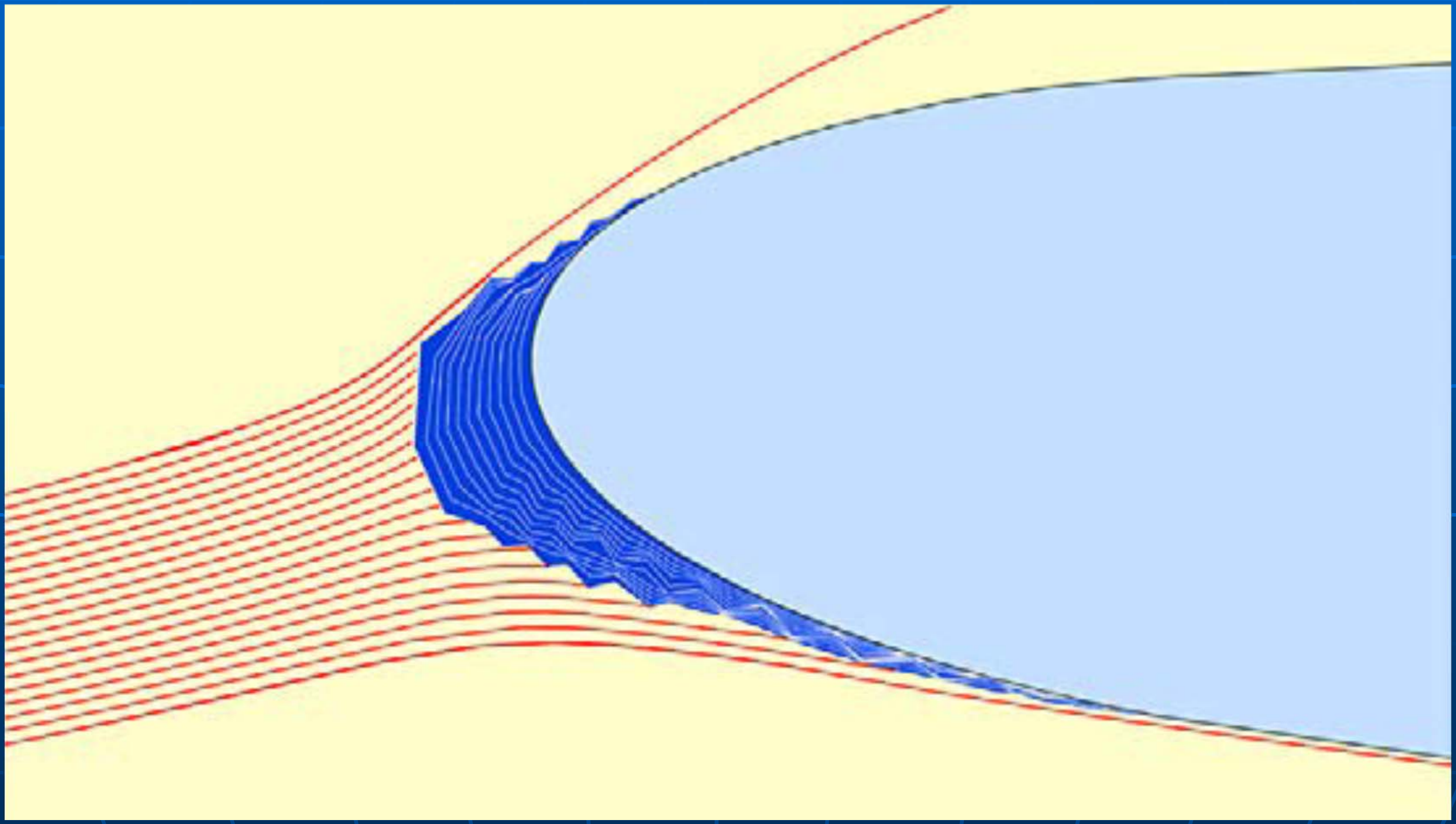
<u>Mass Balance</u>: G. Fortin, J. Laforte, A. Ilinca, *Int. J. Thermal Sciences* 45 (2006) 595–606 (Université du Québec à Rimouski)



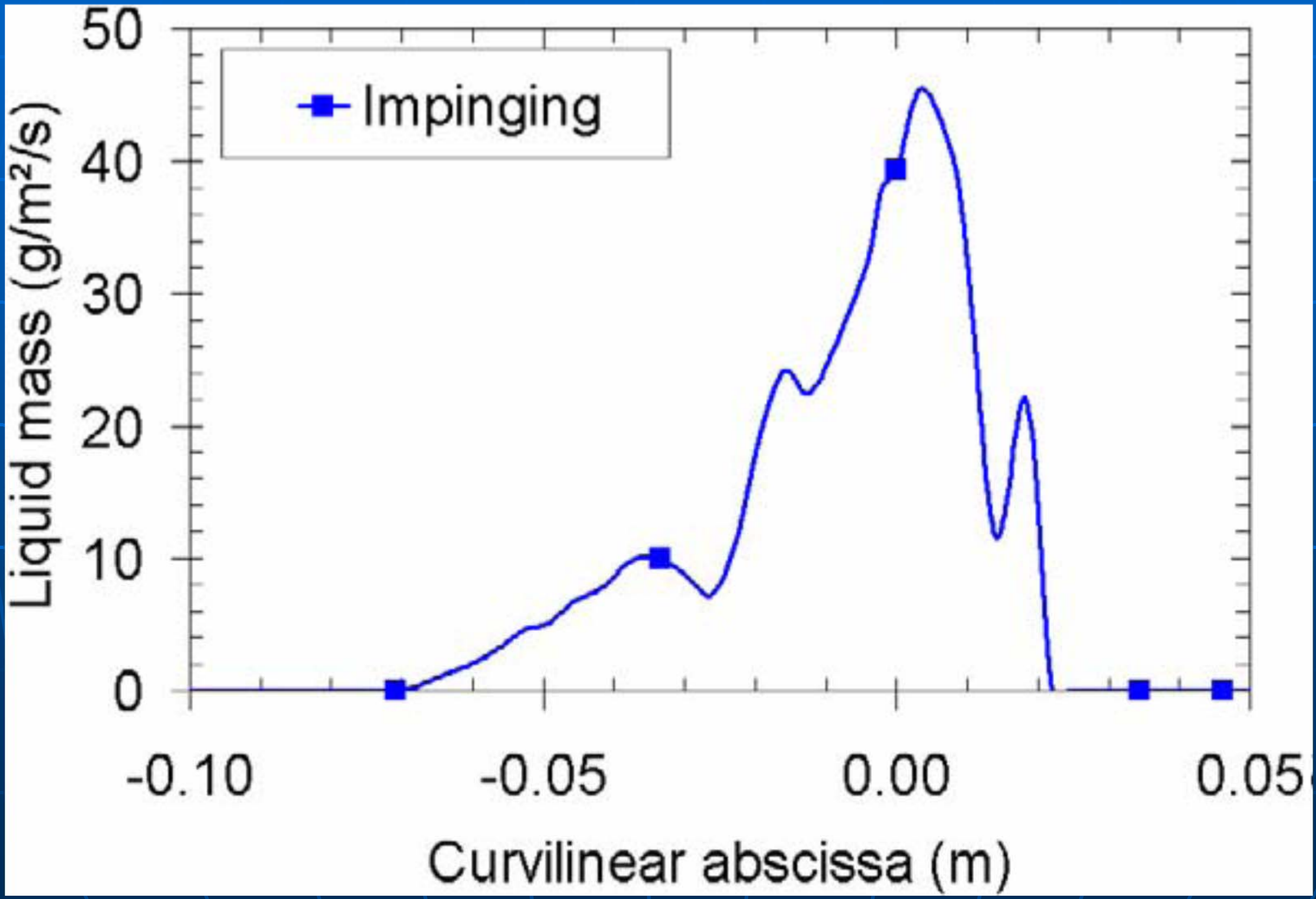
Energy Balance: Fortin et al. (2006)



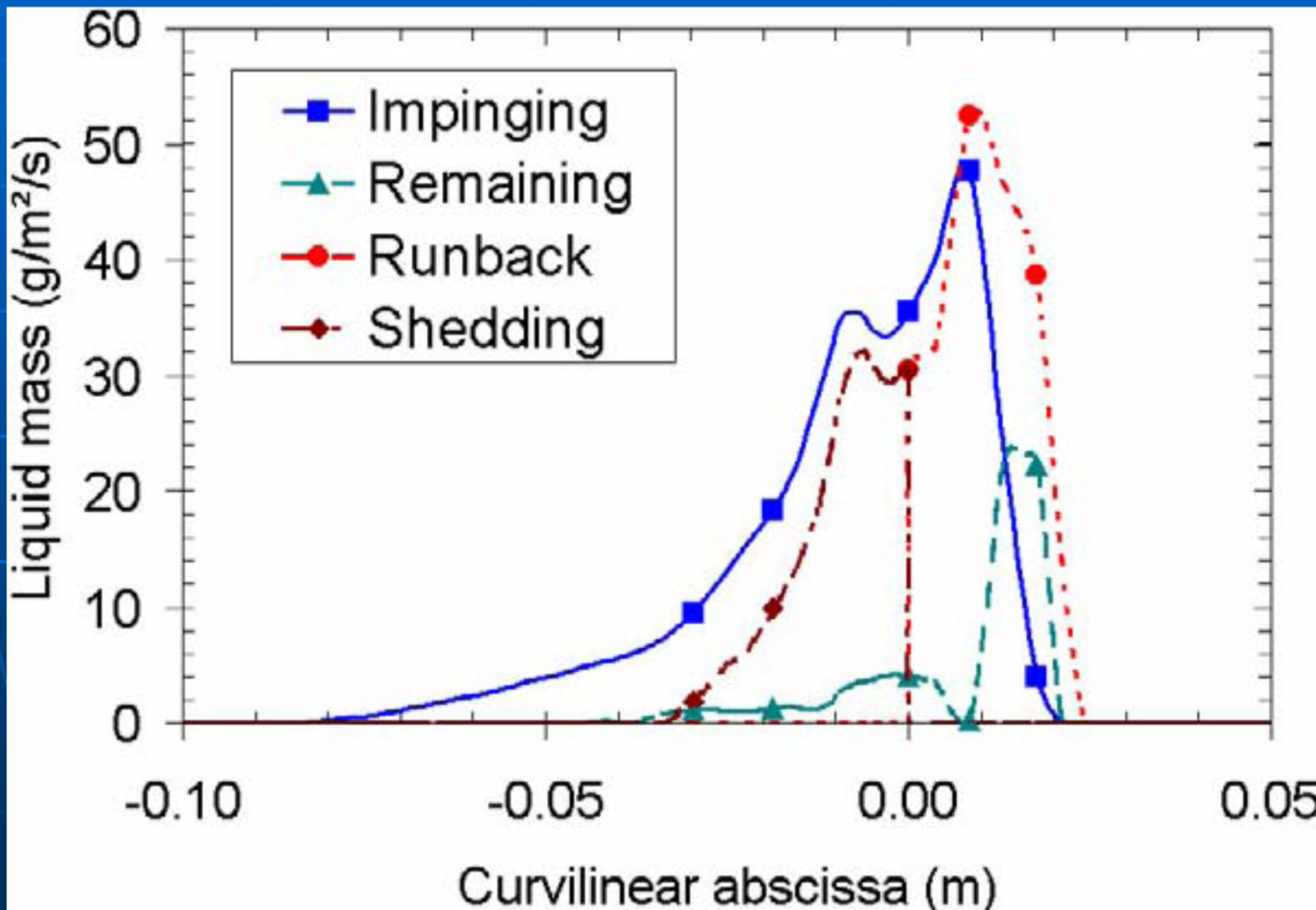
Droplet Trajectory: Fortin et al. (2006)



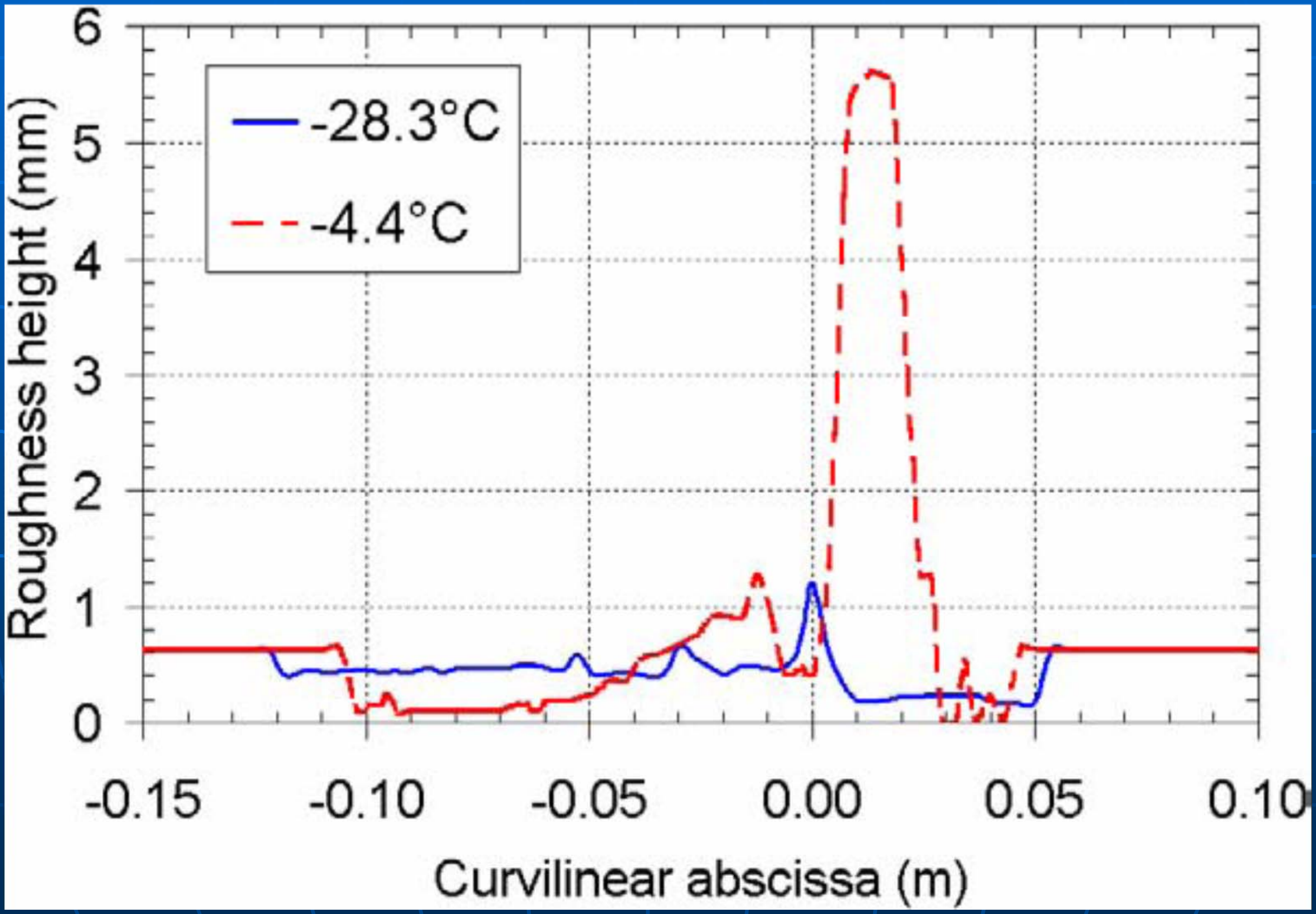
Liquid Water Mass at -28.3C: Fortin et al. (2006)



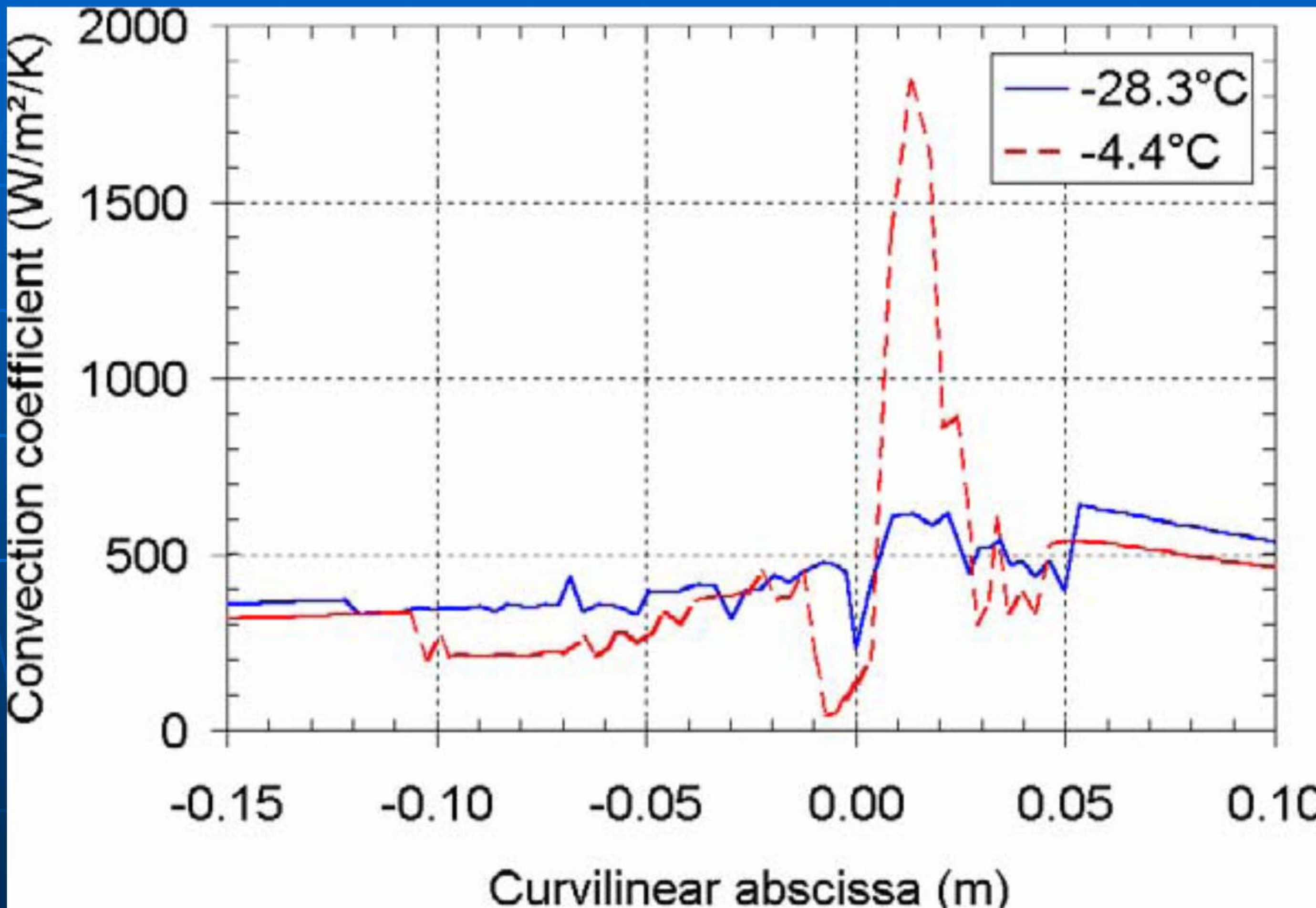
Liquid Water Mass at -4.4C: Fortin et al. (2006)



Roughness Distribution: Fortin et al. (2006)



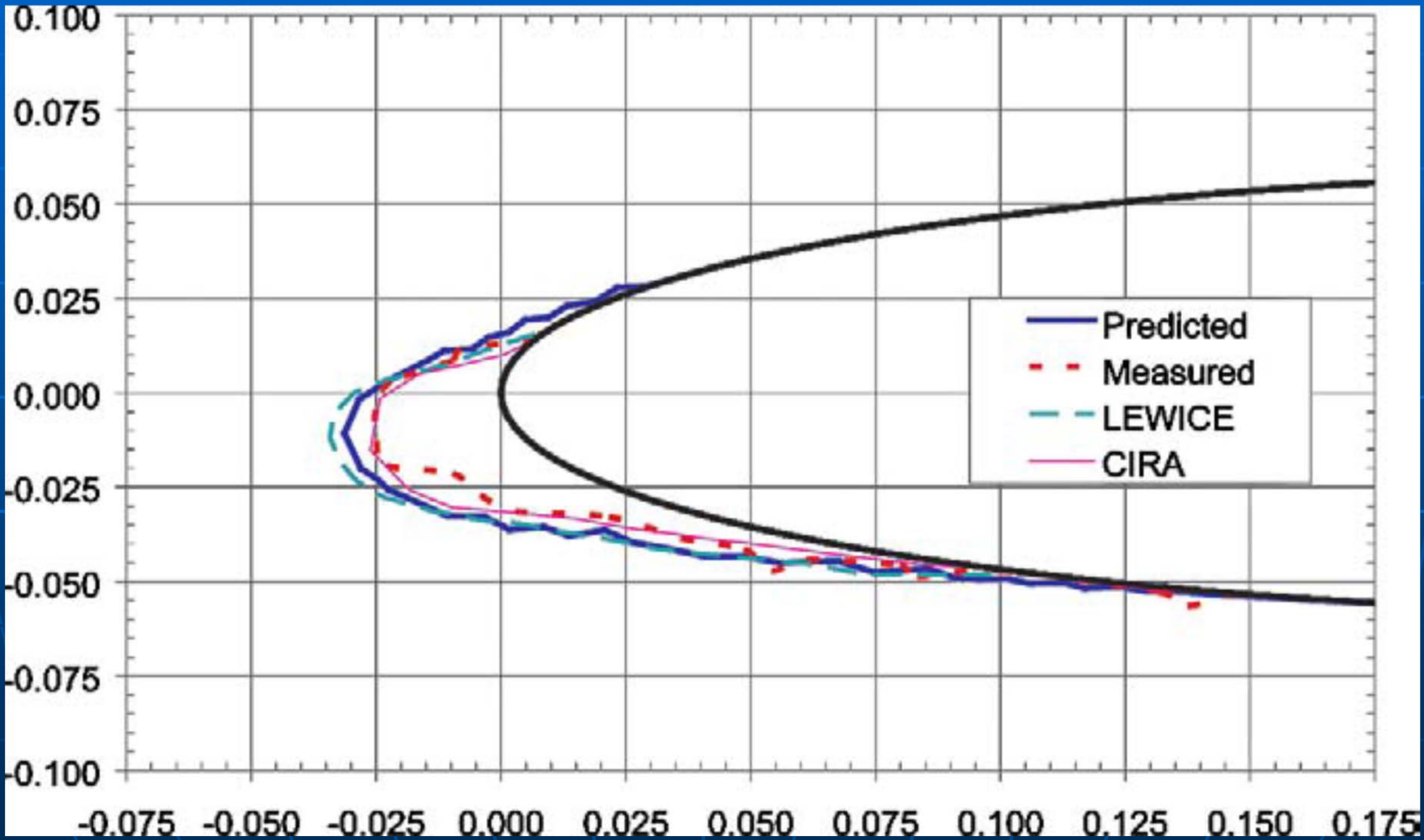
Convective Heat Transfer Coefficient: Fortin et al. (2006)



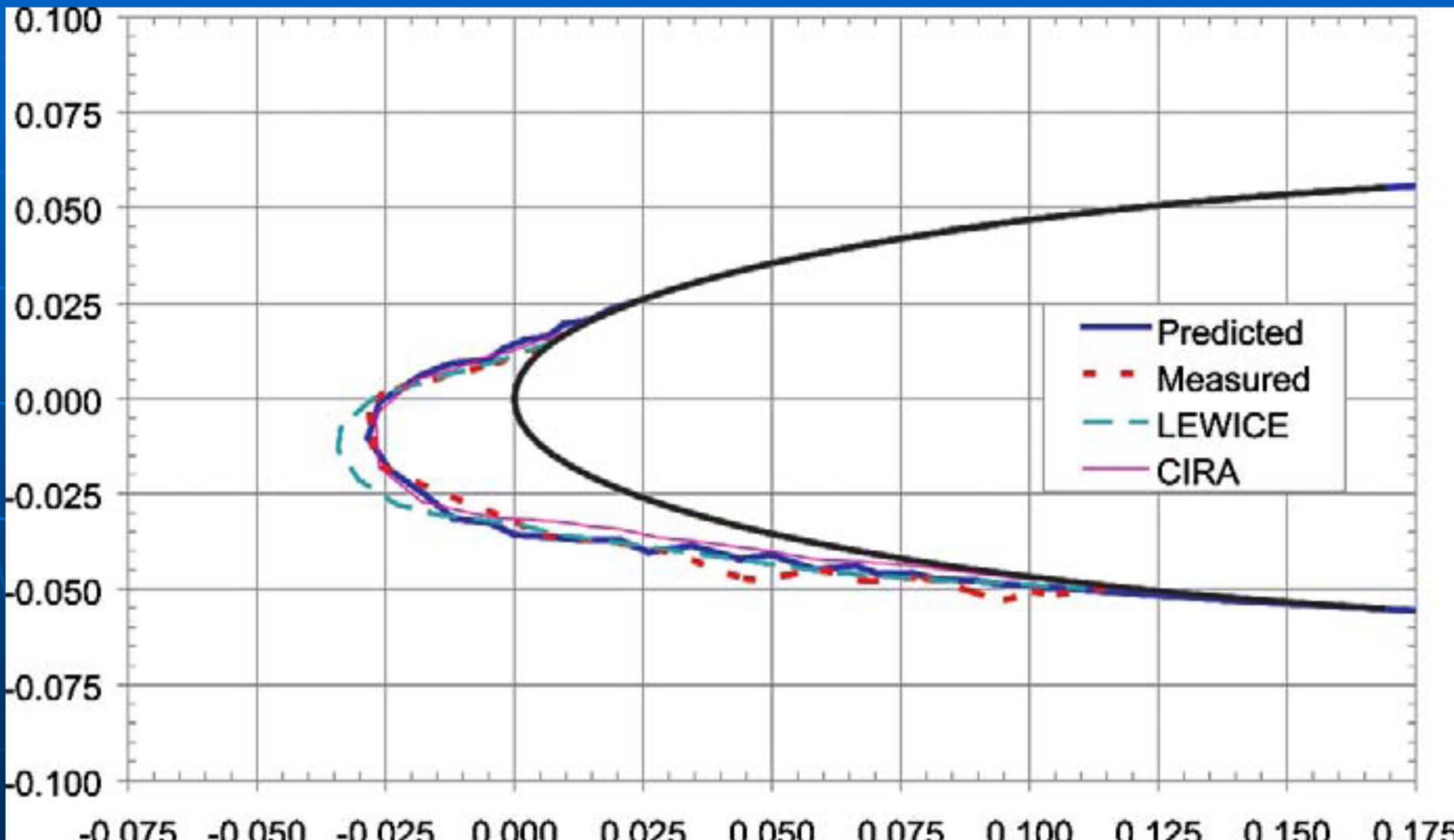
Literature for Comparison

- W.B. Wright, Users manual for the improved NASA Lewis ice accretion code LEWICE 1.6, NASA Contractor Report, May 1995, pp. 95.
- G. Mingione, V. Brandi, Ice accretion prediction on multielements airfoils, J. Aircraft 35 (2) (1998)
- J. Shin, T. Bond, Experimental and computational ice shapes and resulting drag increase for a NACA 0012 airfoil, NASA Technical Manual 105743, January 1992.
- G. Fortin, J. Laforte, A. Ilinca, Heat and mass transfer during ice accretion on aircraft wings with an improved roughness model, *Int. J. Thermal Sciences* 45 (2006) 595–606

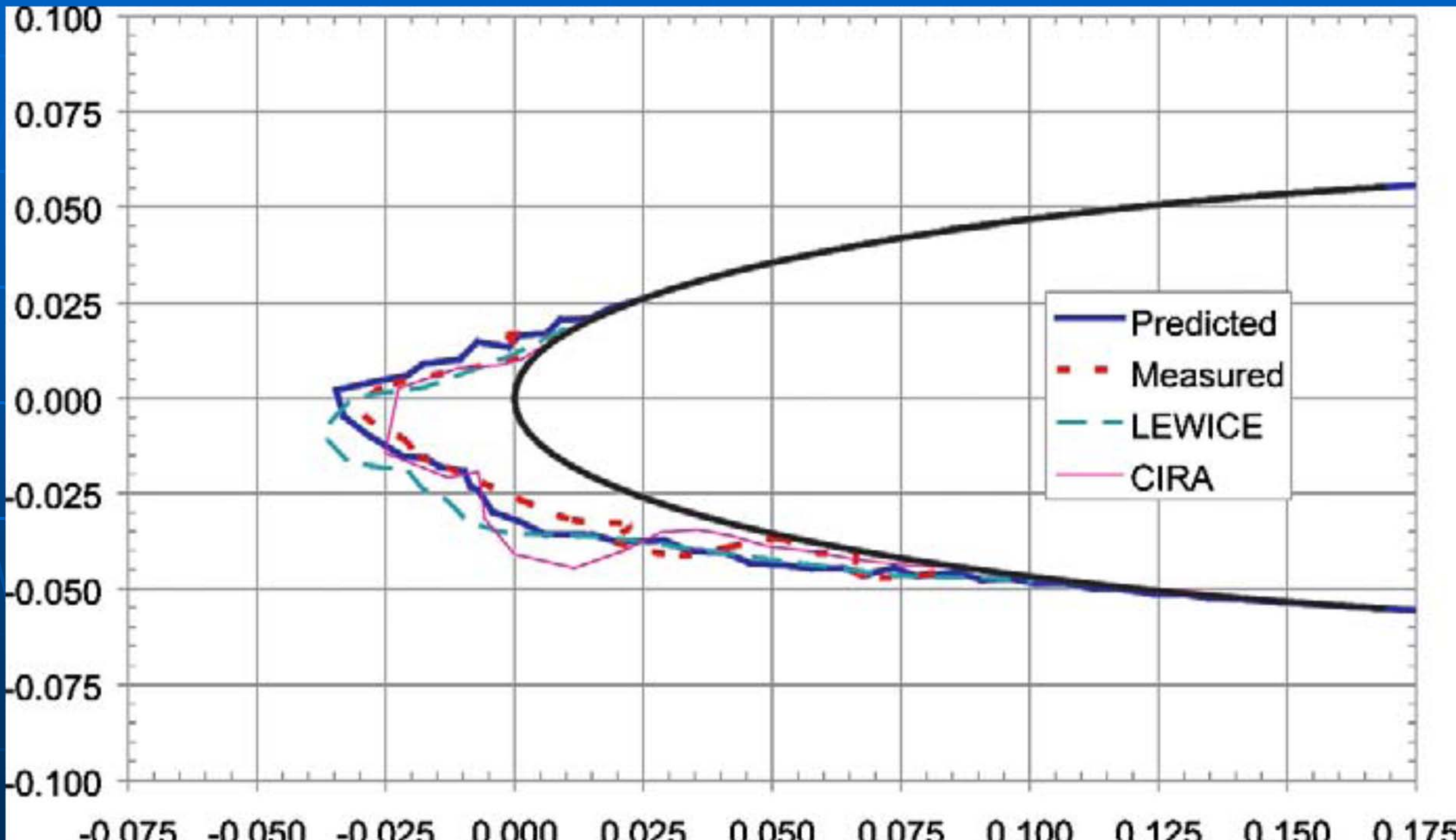
Ice Shape at -28.3C: Fortin and Laforte (2006)



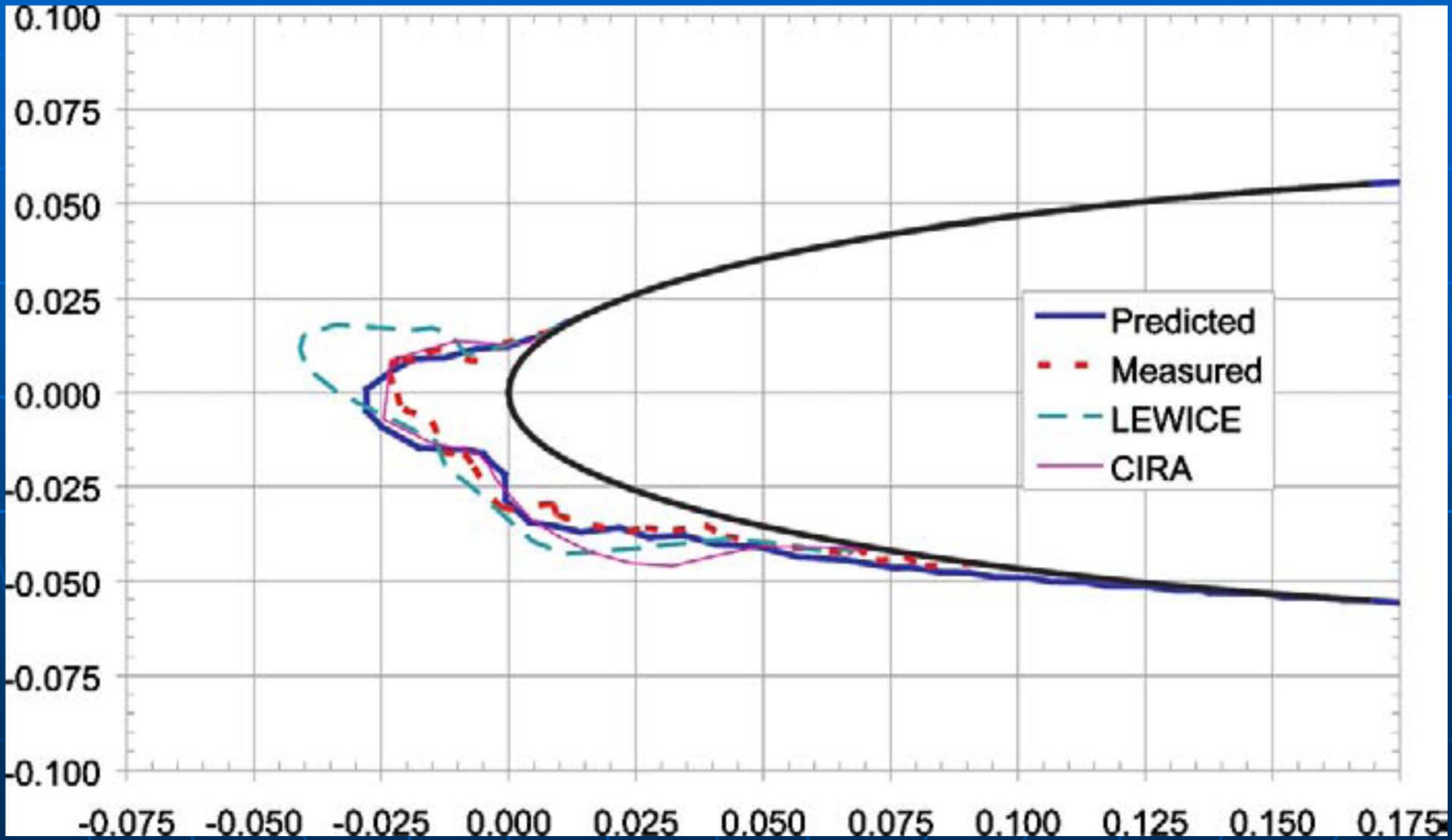
Ice Shape at -19.4C: Fortin and Laforte (2006)



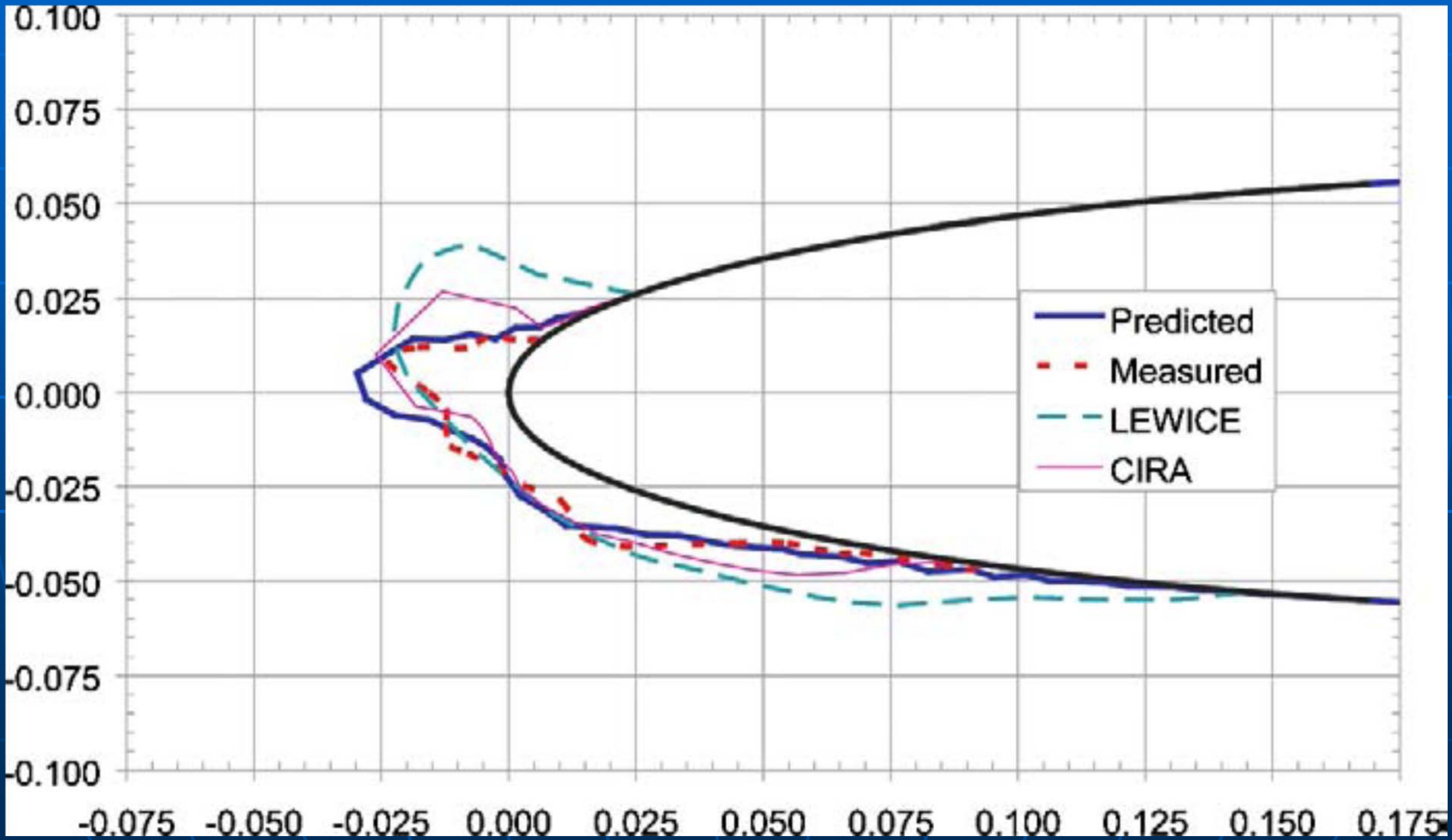
Ice Shape at -13.3C: Fortin and Laforte (2006)



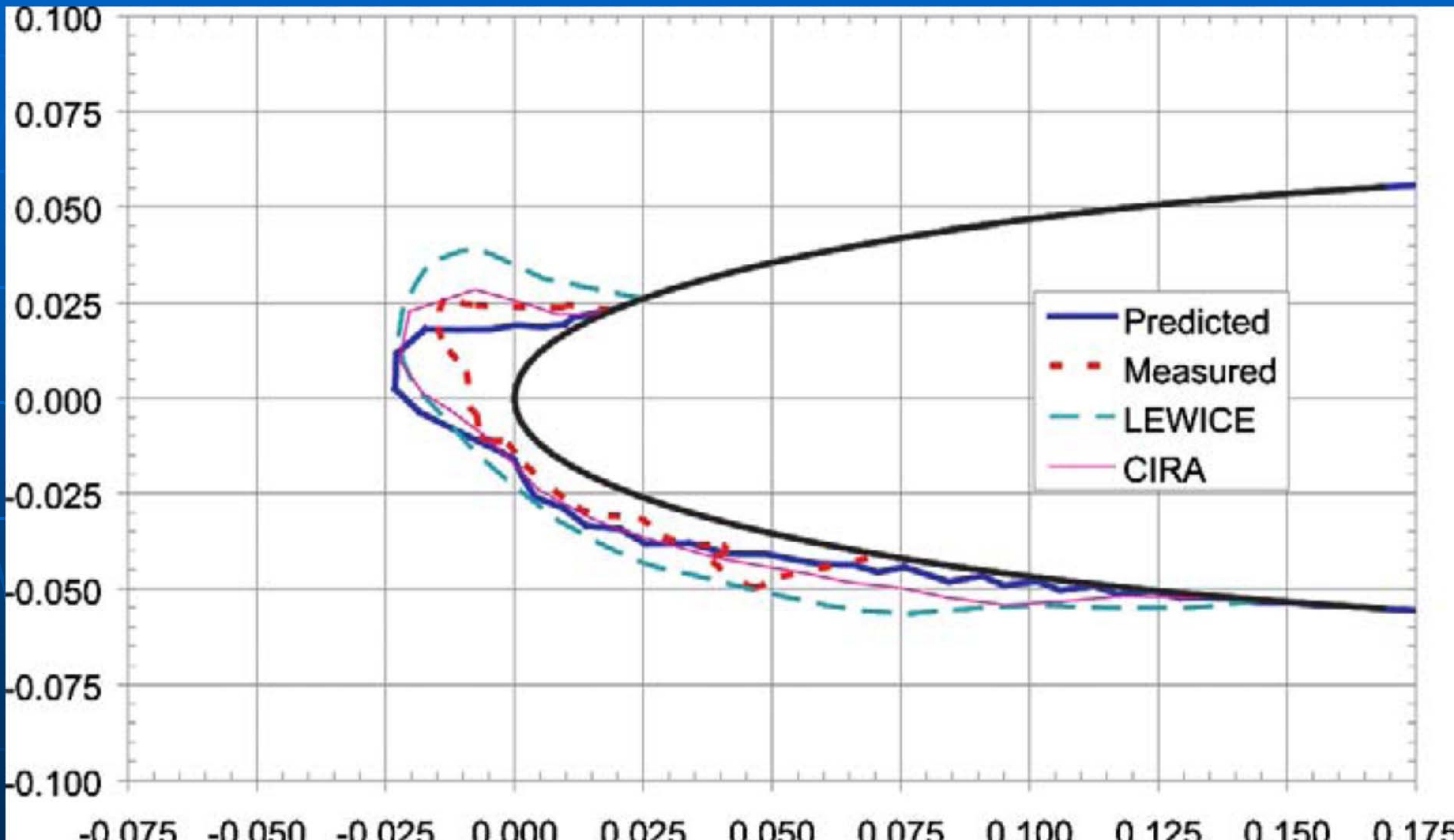
Ice Shape at -10C: Fortin and Laforte (2006)



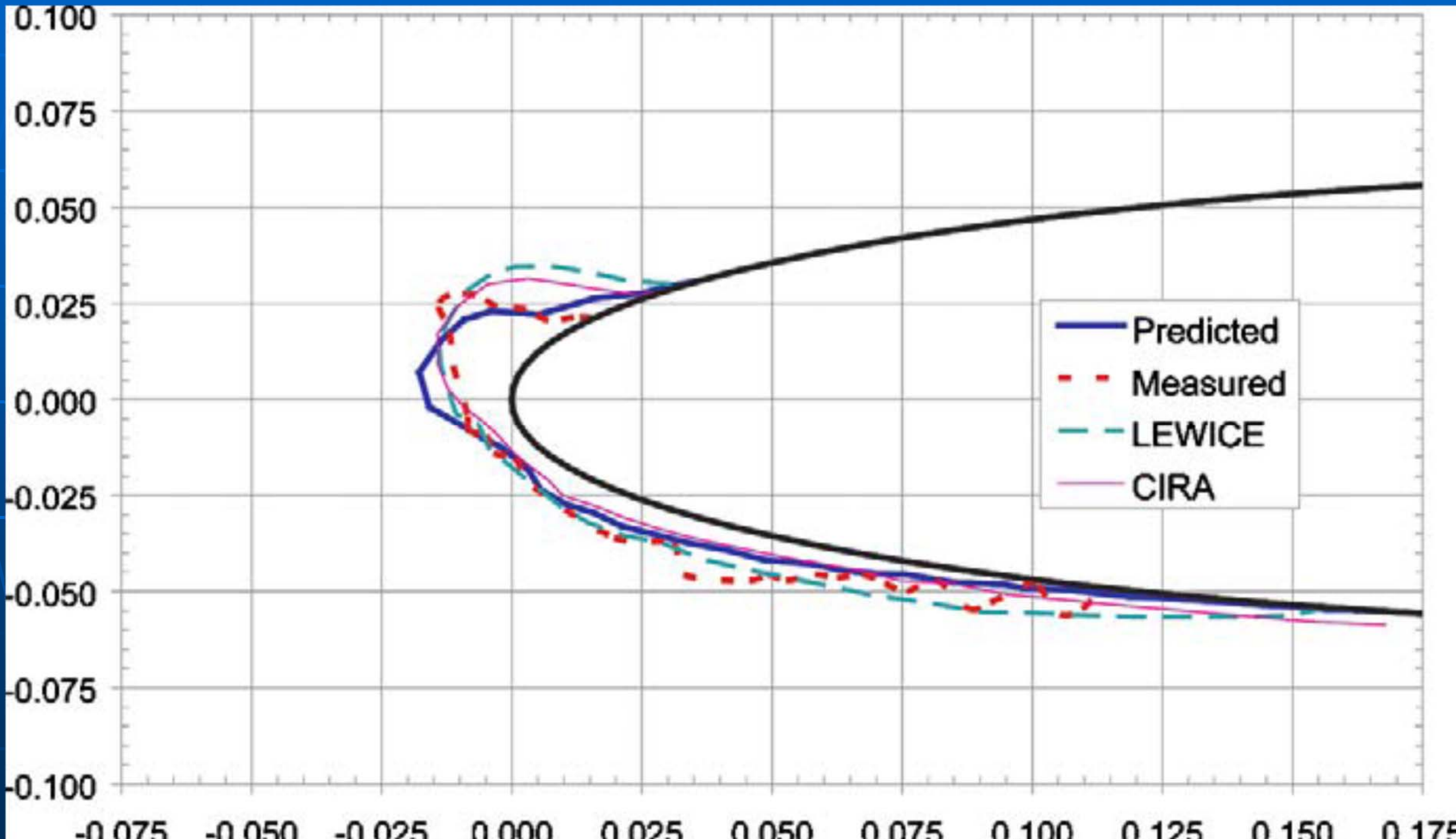
Ice Shape at -7.8C: Fortin and Laforte (2006)



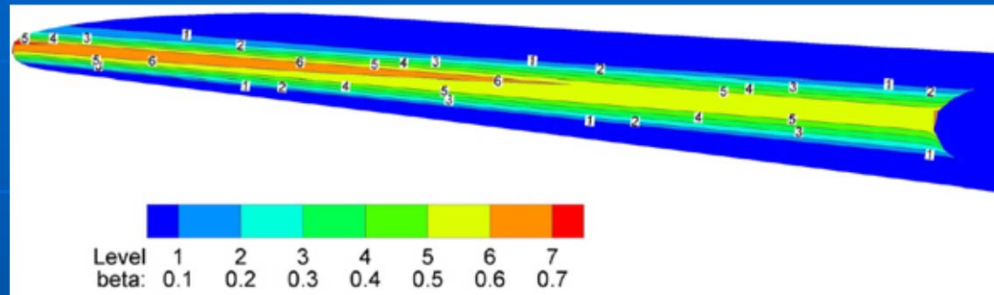
Ice Shape at -6.1C: Fortin and Laforte (2006)



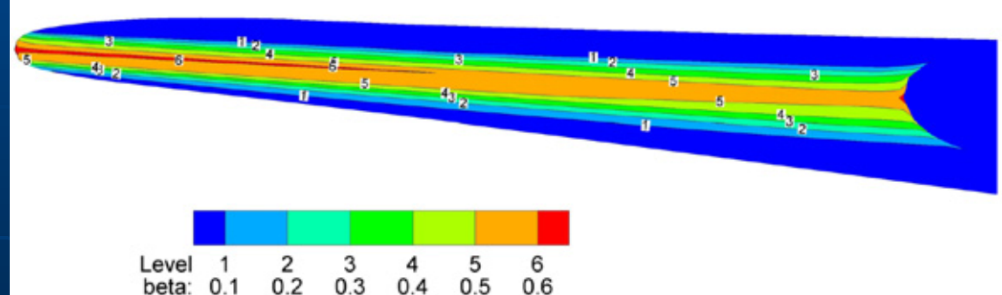
Ice Shape at -4.4C: Fortin and Laforte (2006)



Local collection efficiency at 0◦ and 6◦ angle of attack, Y. Cao, C. Ma, Q. Zhang, J. Sheridan, Aerospace Science and Technology (2012)



(a) 0° angle of attack.



(b) 6° angle of attack.

Typical Input Parameters Required for Modeling

- In order to be able to model icing on a surface in flight, we typically need the following variables *a priori*:
  - altitude
  - flight speed V_∞ or the Mach number M_∞
  - volume median droplet diameter d_{drop}
  - equilibrium surface temperature t_s
  - surface configuration
  - angle of attack

Free stream Physical Properties

- For a given altitude, the freestream physical properties can be evaluated:
  - pressure p_∞
  - temperature t_∞
  - density ρ_∞
  - kinematic viscosity v_∞
  - thermal conductivity k_∞

Boundary Layer Edge Velocity V_1/V_∞ vs. x/L

- Knowing the surface configuration and angle of attack we can determine the ratio of the boundary layer edge velocity to the freestream velocity, V_1/V_∞, as a function of the nondimensional streamwise or chordwise distance, x/L (Abbott et al., 1946)

Boundary Layer Edge Pressure and temperature

- Knowledge of V_1/V_∞ enables computing the pressure and temperature at the outer edge of the boundary layer:

$$\frac{p_1}{p_\infty} = \left[1 + \sqrt{\frac{\gamma - 1}{2}} M_\infty \left\{ \sqrt{\frac{\gamma - 1}{2}} M_\infty - \left(\frac{V_1}{V_\infty} \right) \right\} \right]^{\frac{\gamma - 1}{\gamma}}$$

$$\frac{T_1}{T_\infty} = \left(\frac{p_1}{p_\infty} \right)^{\frac{\gamma - 1}{\gamma}}$$

Boundary Layer Edge Pressure when the Coefficient of Pressure is given

- For some surfaces, the coefficient of pressure C_P along the surface may be available in lieu of the velocity ratio V_1/V_∞. In this case the pressure ratio should first be computed using the following expression:

$$\frac{p_1}{p_\infty} = 1 + \frac{\gamma}{2} M_\infty^2 C_P$$

Boundary Layer Edge Velocity

- The velocity at the outer edge of the boundary layer should then be found using the equation:

$$\frac{V_1}{V_\infty} = \sqrt{\frac{2}{\gamma - 1}\frac{1}{M_\infty}\left[1 + \left(\frac{\gamma - 1}{2}\right)M_\infty^2 - \left(\frac{p_1}{p_\infty}\right)^{\frac{\gamma - 1}{\nu}}\right]}$$

Modified Inertia Parameter

The modified inertia parameter, $K_{T,o}$, can be obtained from the following equation (Bowden et al. 1964):

$$K_{T,o} = 1.87x10^{-7}\left[\frac{1.15V_{\infty}}{\mu g}\right]^{0.6}\left[\frac{d_{drop}^{1.6}}{12\rho_{\infty}^{0.4}L}\right]$$

where the units are knots for V_{∞}, $lb_f.s/ft^2$ for μ, ft for the chord length, lb_m/ft^3 for ρ_{∞}, and ft/s^2 for g. The equation gives values within ±5% for droplet Reynolds numbers ranging from 25 to 1000.

The Local Collection Efficiency

- The local collection efficiency β is computed employing the graphical relationships given in several references for a number of surfaces at different angles or simply computing the term dy/ds
- The local collection efficiency, β, is defined as the ratio between the locally impinging droplet flux and the free stream droplet flux

Local Collection Efficiency

- This efficiency is governed by the ratio of the inertia of the impinging droplets and their aerodynamic drag.
- It is primarily a function of the droplet size and distribution, water density and viscosity, freestream velocity, wing geometry, and angle of attack.

Local Mass Flux Impinging on the Surface

- The local mass flux impinging on the surface may be computed from:

$$\dot{m}_i'' = \beta W V_\infty$$

Here W is the cloud liquid water content (g/m^3)

Compute h_c

- The heat transfer coefficient, h_c, should be computed based on the geometry of the surface
- For example, at the leading edge of an airfoil, it can be evaluated using the following equation:

$$Nu_L = \mathrm{Re}_L^{0.5}\,\mathrm{Pr}^{0.4}\left[1.14\left(\frac{L}{d}\right)^{0.5} - 2.353072\left(\frac{L}{d}\right)^{3.5}\left(\frac{s}{L}\right)^{3}\right]$$

Heat Transfer Coefficient h_c in the Aft Region (Laminar Regime)

- As another example, the after region of the wing, two possibilities exist depending on the flow regime. For laminar flow, Martinelli et al. (1943) proposed the following equation:

$$Nu_L = 0.286\,\mathrm{Re}_L^{0.5}\left(\frac{V_1}{V_\infty}\right)^{0.5}\left(\frac{L}{s}\right)^{0.5}$$

h_c in the Aft Region (Turbulent Regime)

- For turbulent flow, the Nussett number expression in the after region may be written as:

$$Nu_L = 0.0296\,\Pr^{1/3}\,\mathrm{Re}_L^{0.8}\left(\frac{V_1}{V_\infty}\right)^{0.8}\left(\frac{L}{s}\right)^{0.2}$$

Air Thermal Conductivity and h_c

- Once the Nusselt number has been computed, the convective heat transfer coefficient may be determined for a given air thermal conductivity. Bowden et al. (1964) gave the following for the thermal conductivity:
  - T is in °R
  - k is in Btu/hr.ft.°F

$$k = \frac{0.001533\left(\frac{T}{1.8}\right)^{1.5}}{\frac{T}{1.8} + 245.4\left(10^{-12/\left(\frac{T}{1.8}\right)}\right)}$$

Relative Heat Factor

- The relative heat factor, b, was originally introduced by Tribus (1949) and can be expressed as a nondimensional quantity of the impinging flux, the specific heat of liquid water, and the convective heat transfer coefficient:

$$b = \frac{m_i'' c_w}{h_c}$$

Mass Flux of the Fraction of Water impinging on the surface and Freezing into Ice m''_f

- m''_f is the mass flux of the fraction of water impinging on the surface and freezing into ice and is given by:

$$m''_f = n_f m''_i$$

- where n_f is the freezing fraction

Heat Flux to the Surface due to Freezing q_f

- The heat flux to the surface due to the freezing of the impinging water may be computed from:

$$q_f = m''_f \left[\lambda_f + c_i \left(t_{fz} - t_s \right) \right]$$

- where t_{fz} is the freezing temperature of water

Boundary Layer Recovery Factor

- Compute the boundary layer recovery factor, r, as given by Hardy (1946):

$$r = \left[1 - \frac{V_1^2}{V_\infty^2} \left(1 - \Pr^{n_1} \right) \right]$$

- where n_1 is ½ for laminar boundary layers and 1/3 for turbulent boundary layers

Heat Flux due to Aerodynamic Heating q_{aero}

- The heat flux to the surface due to aerodynamic heating may be computed from:

$$q_{aero} = \frac{r h_c V_1^2}{2 g J c_P}$$

- where J is the mechanical equivalent of heat 778.26 ft.lb_f/Btu and c_P is the specific heat at constant pressure

Heat Flux to the Surface due to Droplet Kinetic Energy q_{drop}

- Compute the heat flux to the surface due to droplet kinetic energy from:

$$q_{drop} = \frac{m_i'' V_\infty^2}{2gJ}$$

Convective Heat Flux from the Surface q_c

- The convective heat flux from the surface may be computed from:

$$q_c = h_c(t_s - t_1)$$

Evaporation Potential

- The maximum amount of water that can be evaporated (or the evaporation potential) can be computed from the following equation according to Sogin (1954):

$$m''_{e,\max} = \frac{h_v p_1}{R_a T_f}\left[\frac{M_v}{M_a}\left\{\frac{p_{v,w}}{p_1 - p_{v,w}} - \frac{p_{v,\infty}}{p_\infty}\left(\frac{p_1}{p_1 - p_{v,w}}\right)\right\}\right]$$

- We allow the densities of the water vapor at the surface and the boundary layer edge to be evaluated in terms of the partial pressures of the vapor
- We allow for the influence of induced convection

Vapor Pressure

- Compute the water vapor pressure using empirical correlations. For the temperature range 492 ≤T≤ 672°R, Pelton and Willbanks (1972) provided the following equation:

$$p_{v,w} = 2117\left(\frac{672}{T}\right)^{5.19} \exp\left[-9.06\left(\frac{\lambda_e}{T} - 1.4525\right)\right]$$

- where T is in °R, $p_{v,w}$ is in lb_f/ft^2 absolute

Latent Heat of Vaporization

$$\lambda_e = 1352.3 - 0.5696T + 0.0839x10^{-3}T^2 + 0.0927x10^{-7}T^3$$

Vapor Pressure for a Supercooled Liquid

- For a supercooled liquid at a temperature less than 492°R, Dorsey (1940) provided this correlation:

$$p_{v,w} = 2117\exp\left[2.3\left\{A_1 + \frac{A_2}{\left(\frac{T}{1.8}\right)} + \frac{A_3\left(\left(\frac{T}{1.8}\right)^2 - A_7\right)}{\left(\frac{T}{1.8}\right)}\left(10^{\left[A_4\left(\left(\frac{T}{1.8}\right)^2 - A_7\right)^2\right]} - 1\right) + A_5\left(10^{\left[A_6\left(374.11 - \left(\frac{T}{1.8}\right)\right)^{5/4}\right]}\right)\right\}\right]$$

- where $A_1 = 5.4266514$, $A_2 = -2005.1$, $A_3 = 1.3869 \times 10^{-4}$, $A_4 = 1.1965 \times 10^{-11}$, $A_5 = -4.4 \times 10^{-3}$, $A_6 = -5.7148 \times 10^{-3}$, and $A_7 = 2.937 \times 10^{5}$.

Mass Transfer Coefficient

- Compute the mass transfer coefficient, h_v, which may be related to the heat transfer coefficient, h_c, employing the Lewis analogy:

$$h_v = \frac{h_c}{\rho c_P Le^{2/3}} = \frac{h_c}{\rho c_P \left(\frac{\alpha}{D} \right)^{2/3}}$$

Coefficient of Mass Diffusion

- Compute the coefficient of mass diffusion of water vapor in air, D, using the following empirical relationship (ASHRAE 2009):

$$D = \frac{0.00215}{p}\left(\frac{T^{2.5}}{T+441}\right)$$

- where the pressure is in psia, the temperature is in °R, and the diffusion coefficient is in ft^2/hr.

Sublimation Potential

- Compute the maximum amount of ice that can be sublimated (or the sublimation potential) from:

$$m''_{s,\max} = \frac{h_v p_1}{R_a T_f}\left[\frac{M_v}{M_a}\left\{\frac{p_{v,i}}{p_1 - p_{v,i}} - \left(\frac{p_{v,\infty}}{p_\infty}\right)\frac{p_1}{p_1 - p_{v,i}}\right\}\right]$$

- Compute the vapor pressure over ice using Dorsey's correlation

Additional Calculations

- When the surface temperature is in the vicinity of the freezing point, some of the liquid present on the surface would evaporate, while some of the ice would sublimate.

- In order to account for these two possibilities, two additional quantities should be defined; an evaporation fraction n_e and a sublimation fraction n_s.

Additional Calculations (Cont.)

- With the knowledge of the evaporation and sublimation fractions, the rate of liquid runoff from the surface, and the mass flux of ice accreting on the surface, can both be calculated (see Sherif et al. 1997)

Additional Calculations (Cont.)

- The heat flux leaving the surface due to evaporation as well as that due to sublimation can now be calculated (see Sherif et al. 1997)

- Similarly, the heat flux leaving the surface due to droplet warming can be calculated (see Sherif et al 1997)

Conclusions

- We have presented a summary of some results from the literature for heat transfer and icing accretion in aeronautical structures, a highly complex problem
- The accuracy of predicting the heat transfer rate is among other things dependent on the local roughness height and liquid water mass
- The local roughness is directly dependent on the skin friction coefficient and indirectly dependent on the heat transfer coefficient