Ice Accretion Prediction Code

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Dedicated to the memory of

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Motivation

The in-flight icing may affect all types of aircraft.

Presence of ice on an aircraft surface can lead to a number of performance degradations:

- changes in pressure distribution
- decreased maximum lift and increased drag
- stall occurring at lower angles of attack and increased stall speed
- reduced controllability

It is important to understand how the different ice shapes affect aircraft aerodynamics.

It can be studied by flight tests, wind tunnel measurements, and computational simulations.

Computational simulation of ice accretion is an essential tool in design, development and certification of aircraft for flight into icing conditions.

Currently, there exist several approved ice accretion codes:

- **LEWICE** (LEWis ICE accretion program) is software developed by the Icing Branch at NASA Glenn Research Center
- **CANICE** code developed at the Ecole Polytechnique de Montreal
- **ONERA** (Office National d'Etudes et de Recherches Aérospatiales) code in France
- **TRAJICE** code which was developed by DERA (Defence Evaluation and Research Agency) in United Kingdom
- **CIRA** code from Italian Aerospace Research Center.

Ice Accretion Prediction Code

Code was developed as a tool for simulating flight into icing conditions

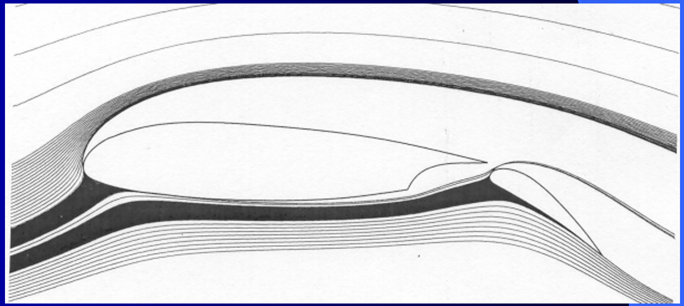
Presented software was subsequently developed and improved.

There are three main code versions:

R-Ice 1.1 Rime ice accretion prediction

Ice 3.1 Glaze ice accretion prediction

Ice 4.1 Multi-element airfoils icing



Trajectory of water droplets

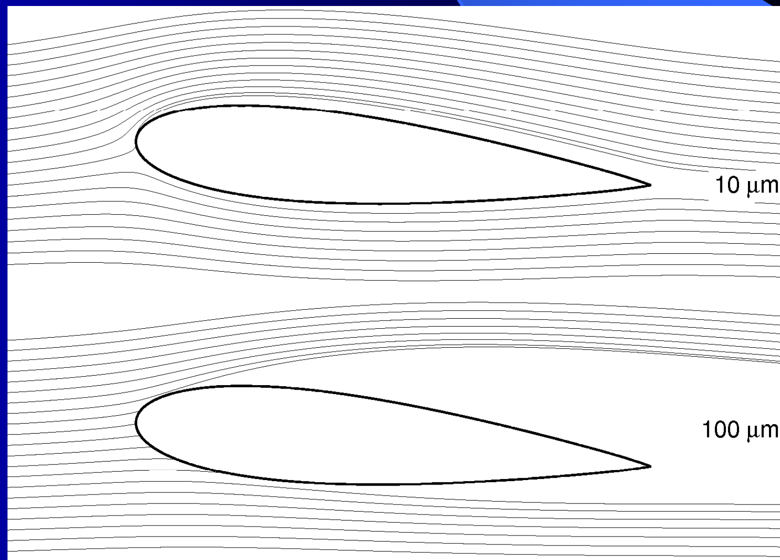
The potential flow field is calculated using 2-D panel method. The relation for any point inside the control area is in form

[illegible]

Potential flow field is then used to determine the trajectories of water droplets and the impingement points on the body.

Droplets passing through the atmosphere are considered as spherical elements on that the surrounding fluid forces and gravitation act.

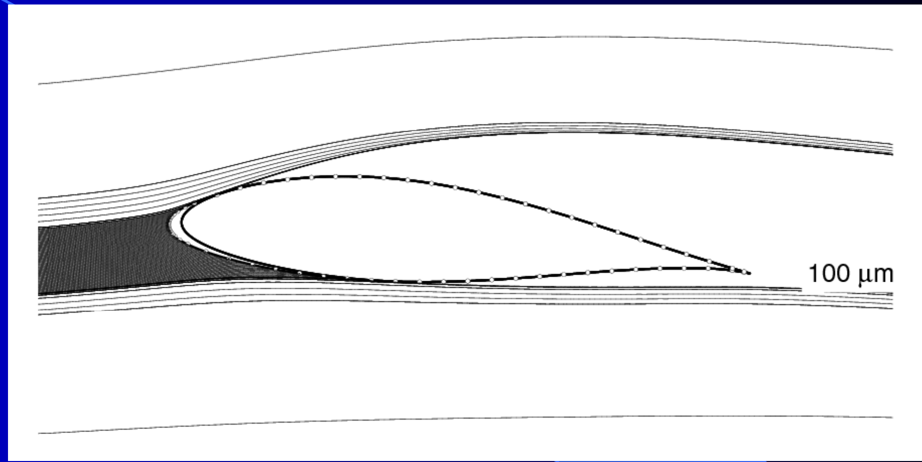
Small water droplets have trajectories similar to streamlines, vice versa large water droplets trajectories are affected by the airfoil inherency only slightly.

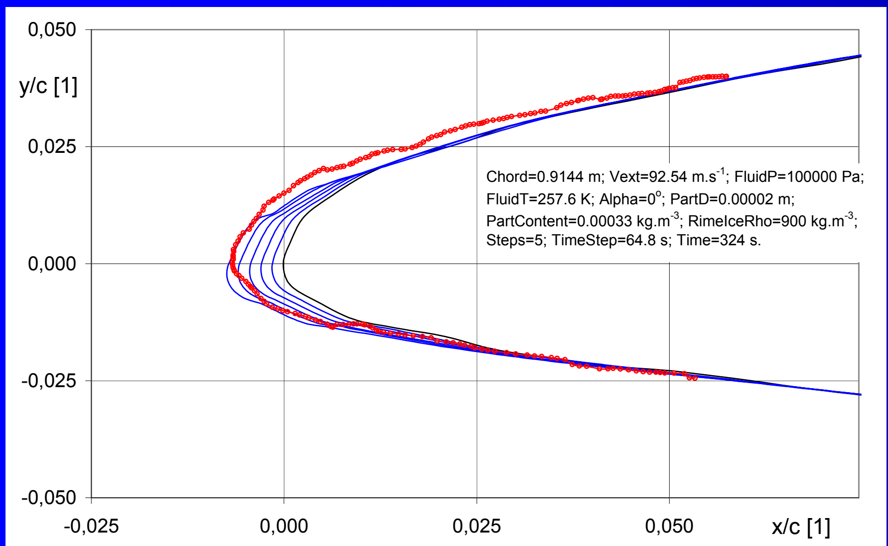


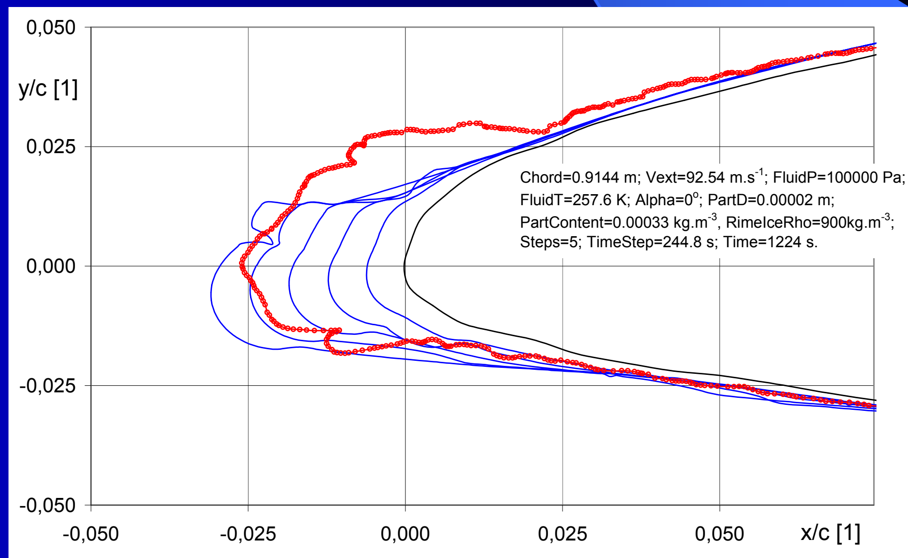
Version 1.1 – Airfoil *rime ice* accretion prediction

Impinging super-cooled water droplets freeze immediately upon impact.

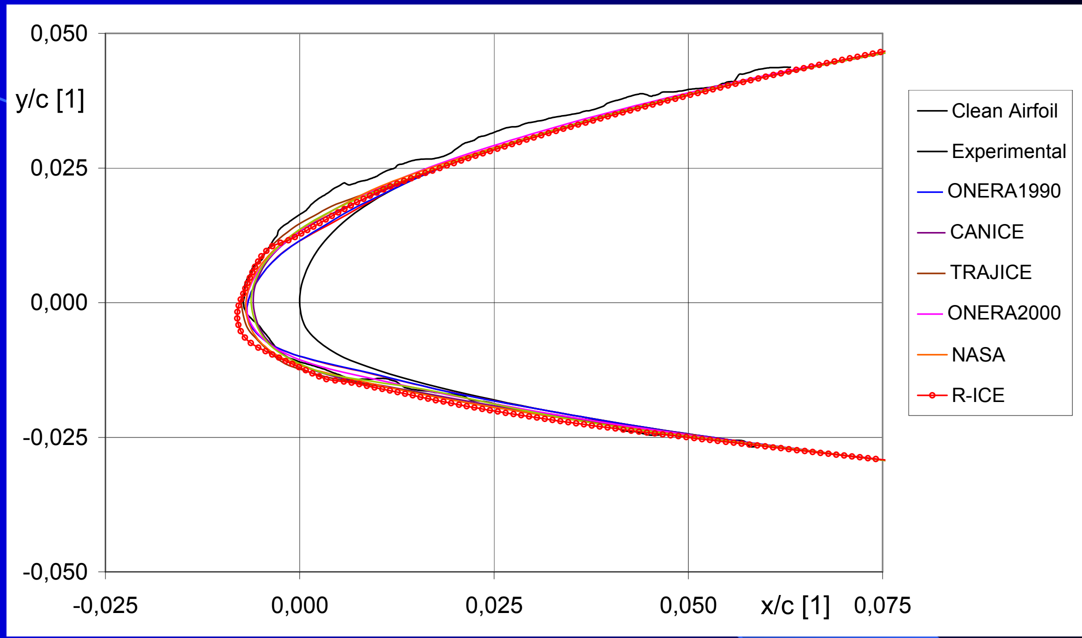
Code applies a time-stepping procedure to calculate the shape of an ice accretion.



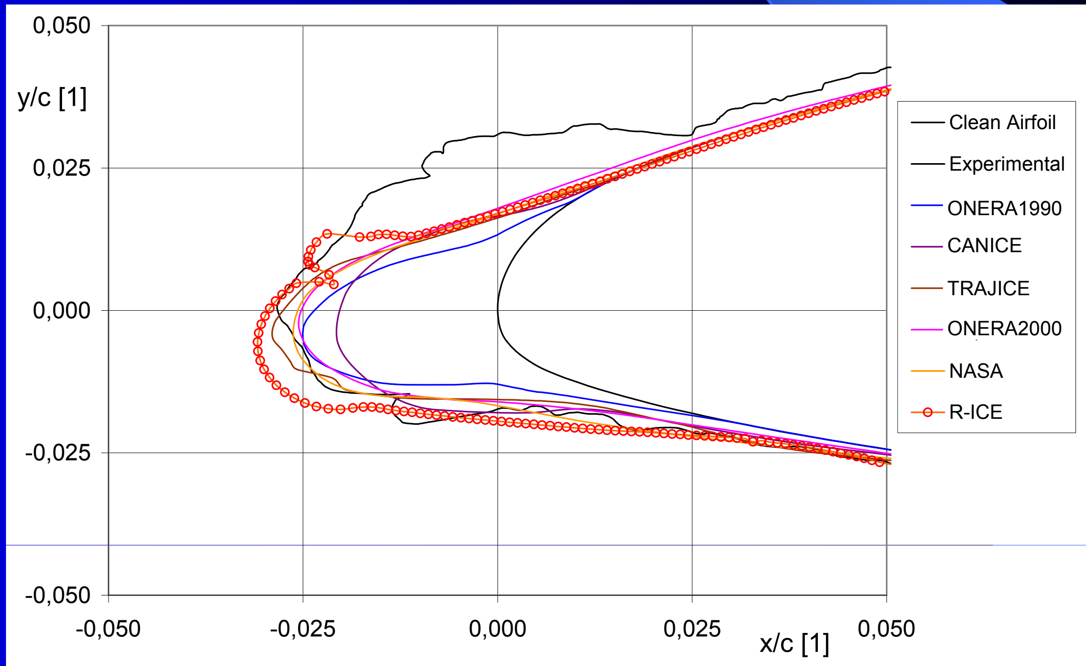




Quantitative comparison of using the current computational ice-accretion simulation methods.



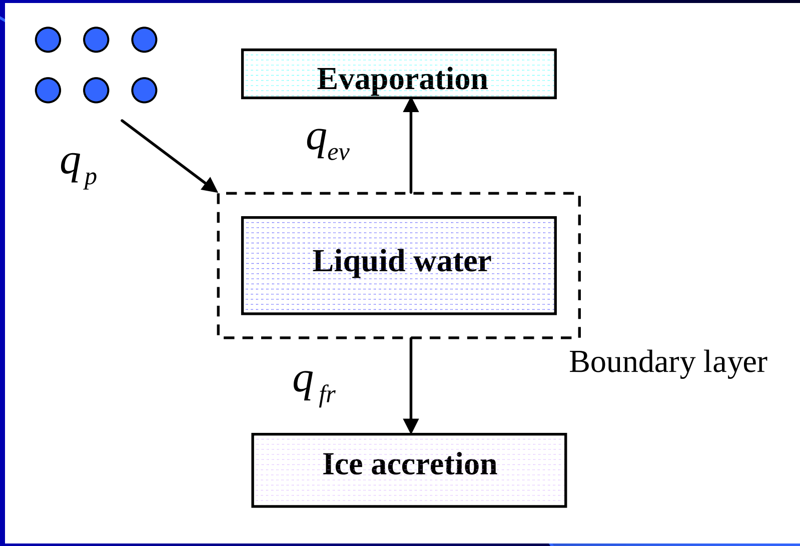
Generally, current ice accretion codes give satisfied results of the rime ice simulation.



Version 3.1 – Airfoil *glaze ice* accretion prediction

Glaze ice creates at combinations of temperature close to freezing. In that case, not all of the impinging water freezes on impact.

Thin layer of water is flowing very slowly along the surface and freeze at other locations.



There are used theoretical approaches are generally called as a shallow water theory.

The conservative equations using for the solution of water flow in open channels are formally arranged.

The flux terms are evaluated using a discontinuous Galerkin method based on finite-volume formulation.

Mass, motion, and energy conservative equations could be written in the general form

$$\frac{\partial \boldsymbol{Q}}{\partial t} + \frac{\partial \boldsymbol{F}}{\partial x} = \boldsymbol{S} + \boldsymbol{S}_q$$

Vectors of variables $\boldsymbol{Q}$, flow $\boldsymbol{F}$ and sources $\boldsymbol{S}$, $\boldsymbol{S}_q$ are given by relations:

$$\boldsymbol{Q} = \begin{pmatrix} A \\ Q \\ E \end{pmatrix}, \quad \boldsymbol{F} = \begin{pmatrix} Q \\ \beta Q^2/A + g_n I_1 \\ EQ/A \end{pmatrix}$$

A – flow cross-section, Q – flow volume, E – thermal energy; components of $\boldsymbol{F}$: mass flux, momentum flux, flux of energy

Internal sources:

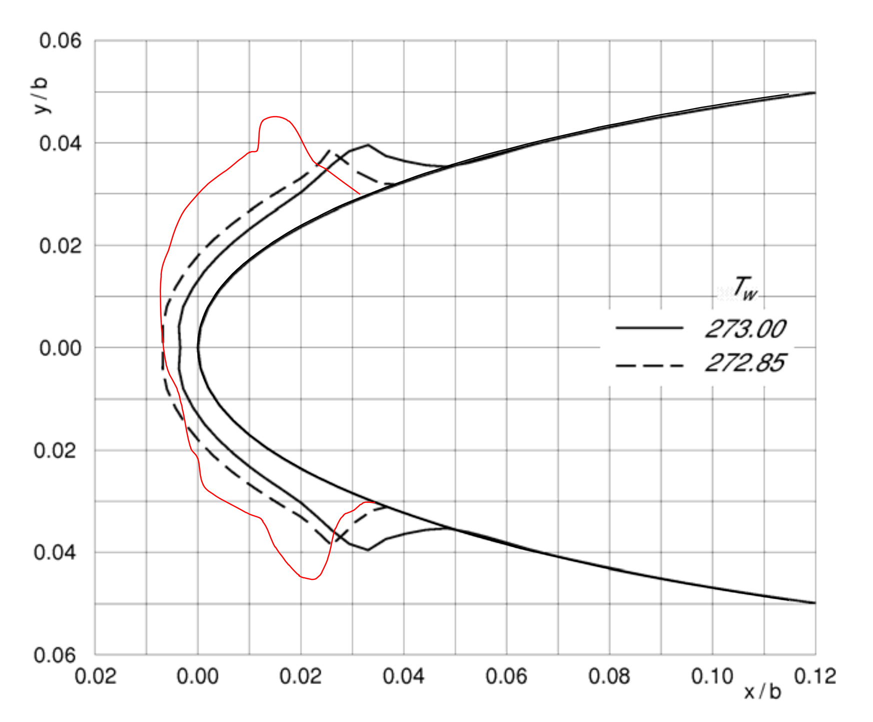
$$\boldsymbol{S} = \begin{pmatrix} 0 \\ g_n I_2 + g_t A - (dp/dx)A/\rho - o_w \tau_w/\rho + o_e \tau_e/\rho \\ o_w \alpha_w (T_w - T)/\rho + o_e \alpha_e (T_e - T)/\rho \end{pmatrix}$$

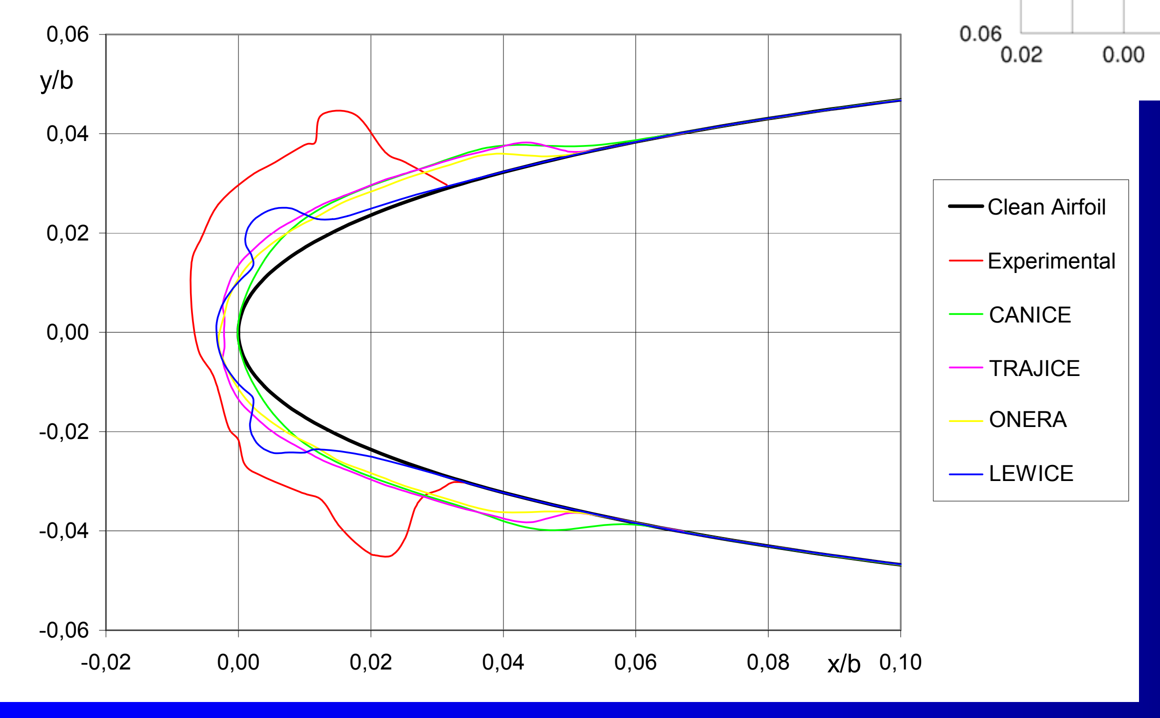
External sources:

$$\boldsymbol{S}_q = \begin{pmatrix} o_e q_p - o_w q_{fr} - o_w q_{ev} \\ o_e q_p v_{px} - o_w q_{fr} v - o_w q_{ev} v \\ o_e q_p c T_p - o_w q_{fr} (cT + L_{fr}) - o_w q_{ev} (cT + L_{ev}) \end{pmatrix}$$

Example of glaze ice-accretion simulation.

Airfoil NAC 0012, chord 0.45 m, angle of attack α = 0°, velocity v_∞ = 77.2 m s^{-1}, MVD = 18 μm, LWC = 0.32 g m^{-3}, air temperature T = 270.5 K, icing exposition 300 s.

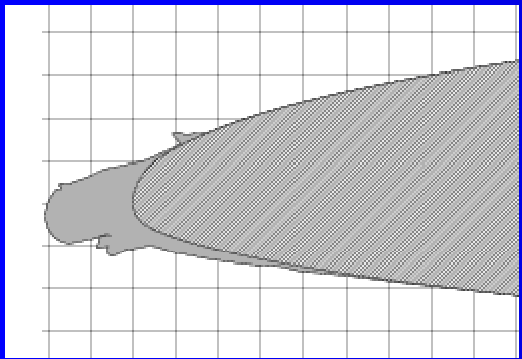




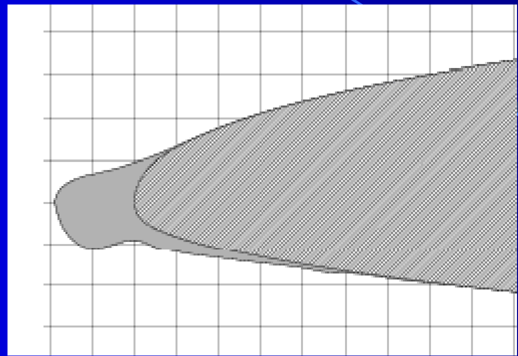
Comparison of current ice-accretion codes shows ➡ there is still room for improvement in the quality of predictions.

Air temperature influence on iced airfoil shapes

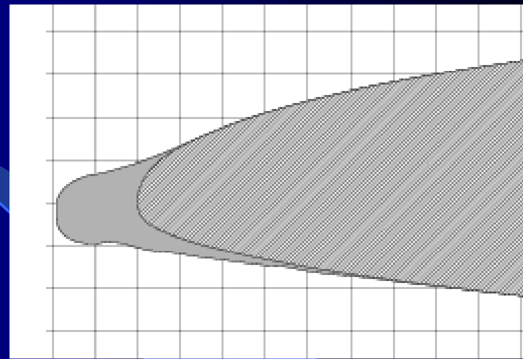
Stream-wise shape (b), (c) Double-horn shape (d), (e) Span-wise ridge shape (f)



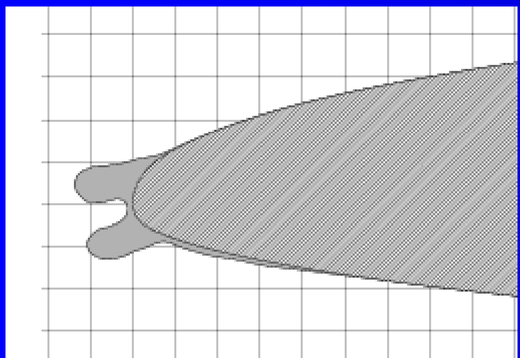
(a) Rime ice



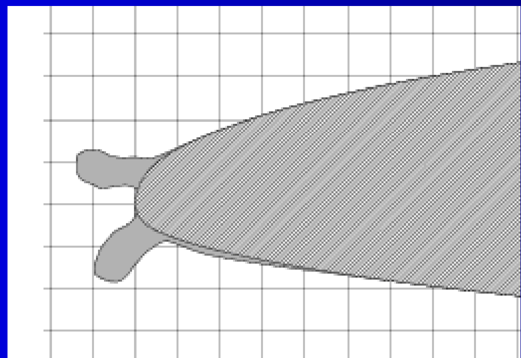
(b) T = 269.65 K



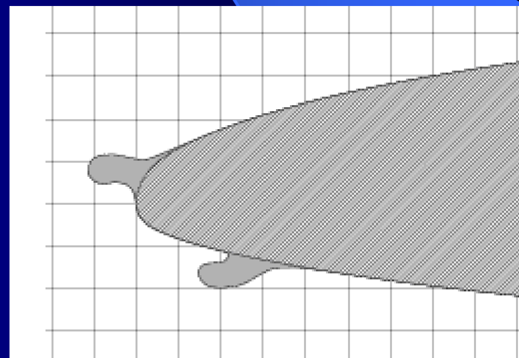
(c) T = 270.15 K



(d) T = 270.65 K



(e) T = 271.65 K



(f) T = 272.65 K

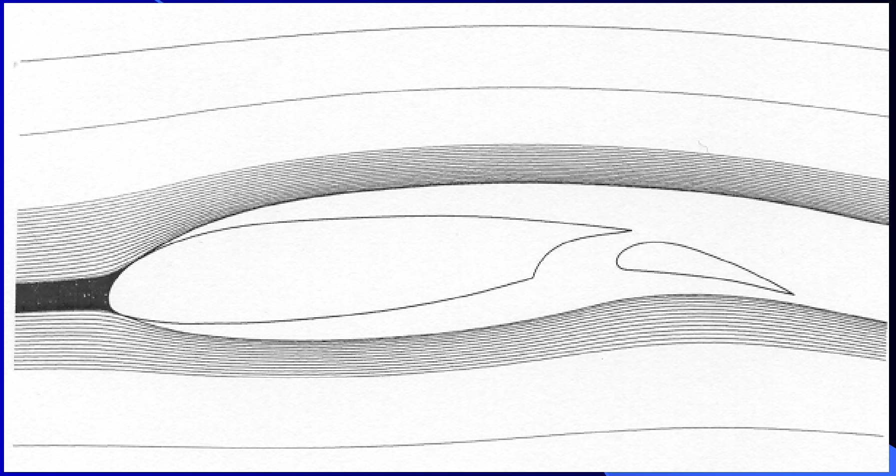
Airfoil NFL0414, chord 0.45 m, angle of attack $\alpha = 0^{o}$, velocity $v_{\infty} = 77.2$ m s^{-1},
MVD = 18 μm, LWC = 0.32 g m^{-3}, icing exposition 900 s.

Version 4.1 – Multi-element airfoils icing

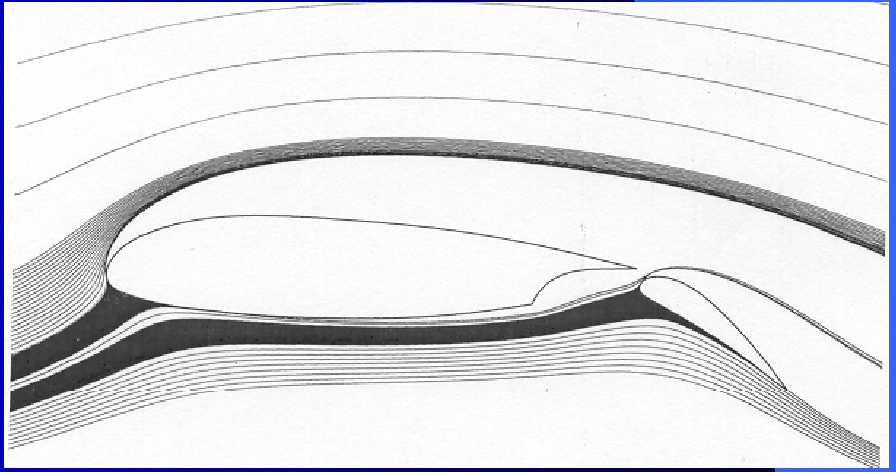
The latest code version enables solution of multi-element airfoils up to eight separate parts.

Mutual flow overlap of circumfluent bodies occurs.

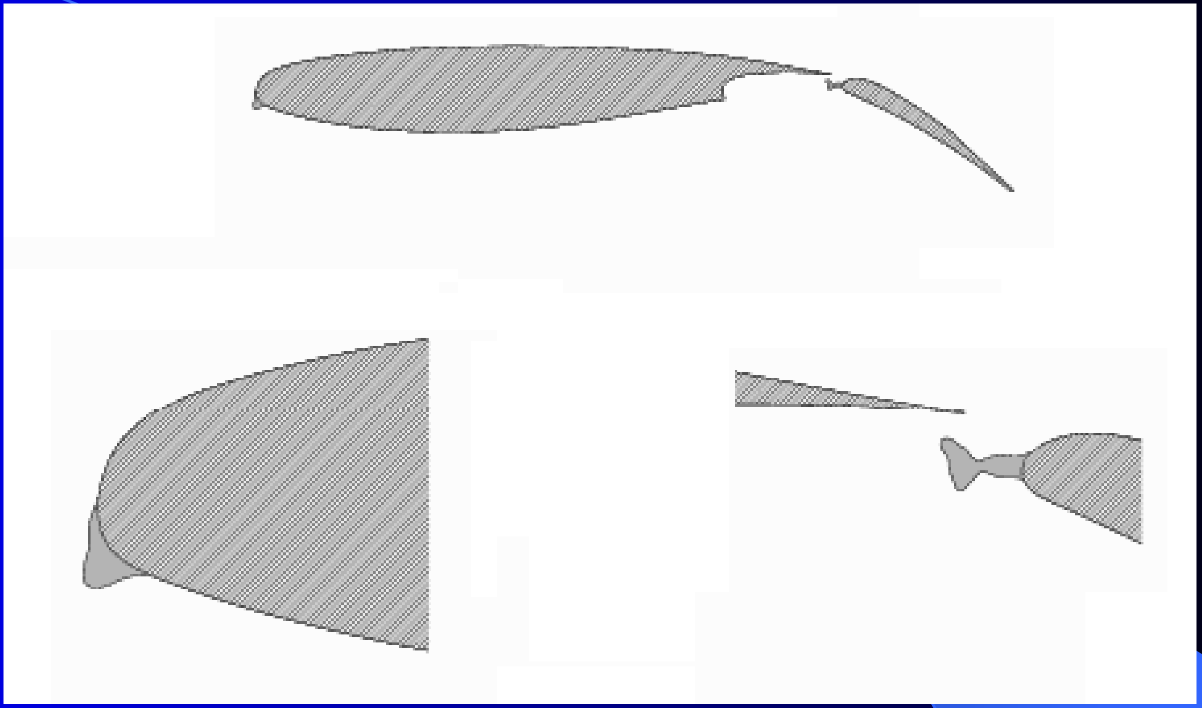
Droplet trajectories near an airfoil with a slotted flap



Droplet trajectories near an airfoil with a slotted flap in landing position



Example of flapped airfoil icing



Ice accretion on the flap causes the reduction of the gap size between main element and flap.

Consequently, it can have a large impact on the performance degradation of iced multi-element airfoils.

There is a potential mechanical problem in the elevator mechanism itself.

Input file

Configuration file: **`_ice.cfg`**

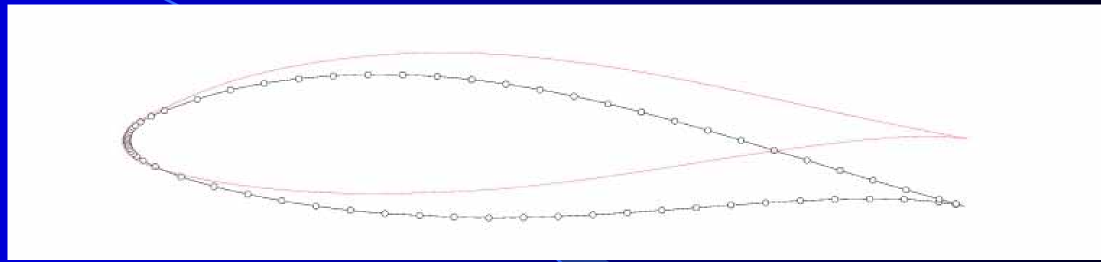
Icing parameters

```
# configuration file
# ------------------
ProfDta=NACA0018                  # NACA0018
Chord=1                           # 1.0;<0.1,10>
Vext=50                           # 50.0;<10,200>
Alpha=5                           # 5.0;<-20,20>
FluidP=100000                     # 1.e5;<0.1e5,1.2e5>
FluidT=263                        # 263;<200,300>
PartContent=0.001                 # 1.e-3;<0.05e-3,5.e-3>
PartD=0.0001                      # 100e-6;<5.e-6,5000.e-6>
PartT=274.15                      # 274.15;<200,300>
BodyT=263.15                      # 263.15;<200,300>
RimeIceRho=900                    # 900;<700,1000>
GlaseIceRho=917                    # 917;<700,1000>
# ------------------
TimeStep=120                      # 120;<1,600>
Steps=5                           # 5;<1,1000>
MinBodyPoints=50                  # 50;<20,500>
```

Graphical output files

Airfoil geometry

`geom004.eps`

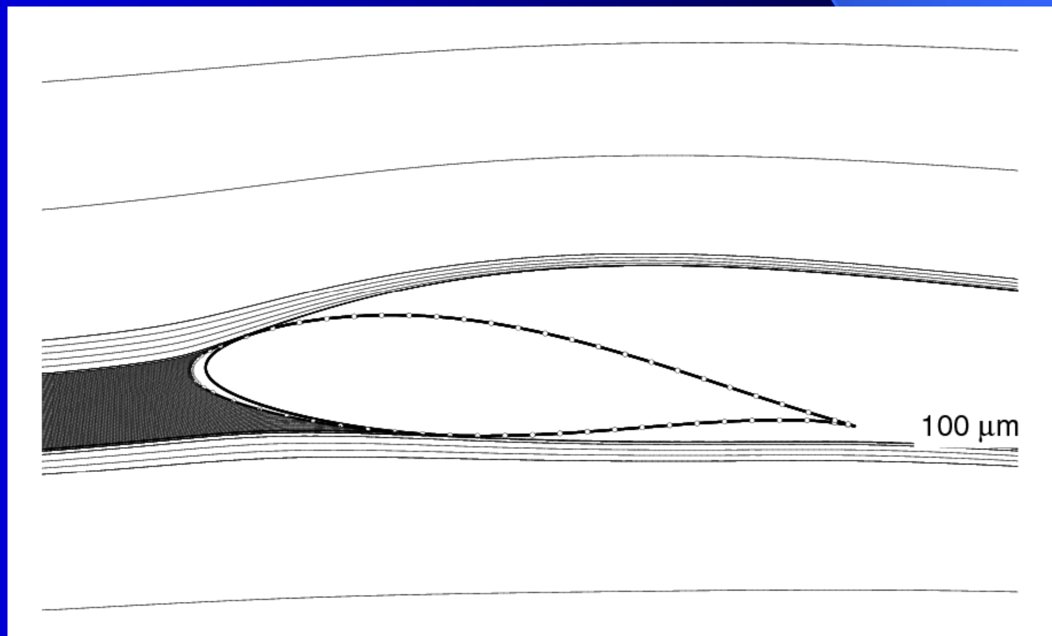


Successive ice accretion by steps

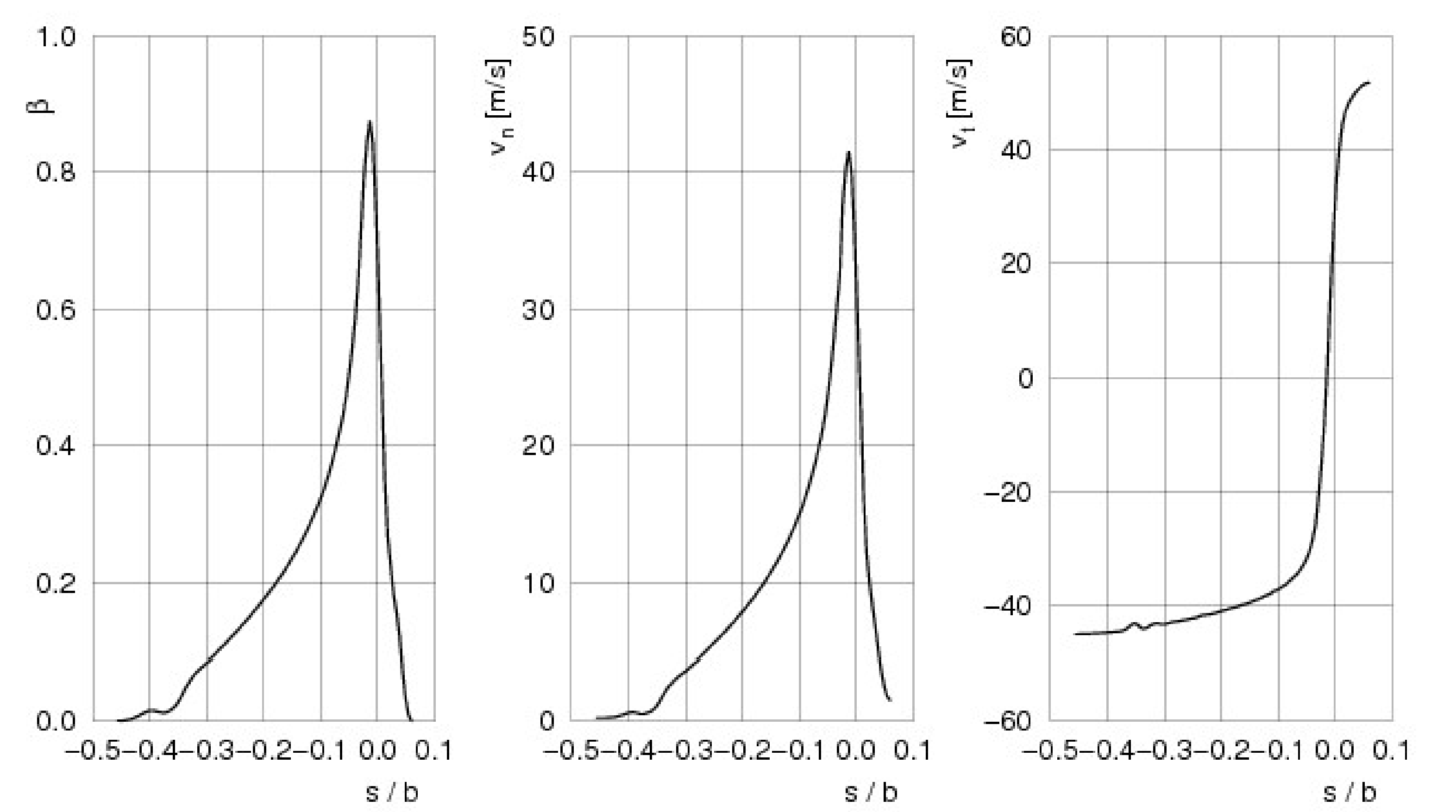
`modif004.eps`

Droplet trajectories near iced airfoil

`part004.eps`

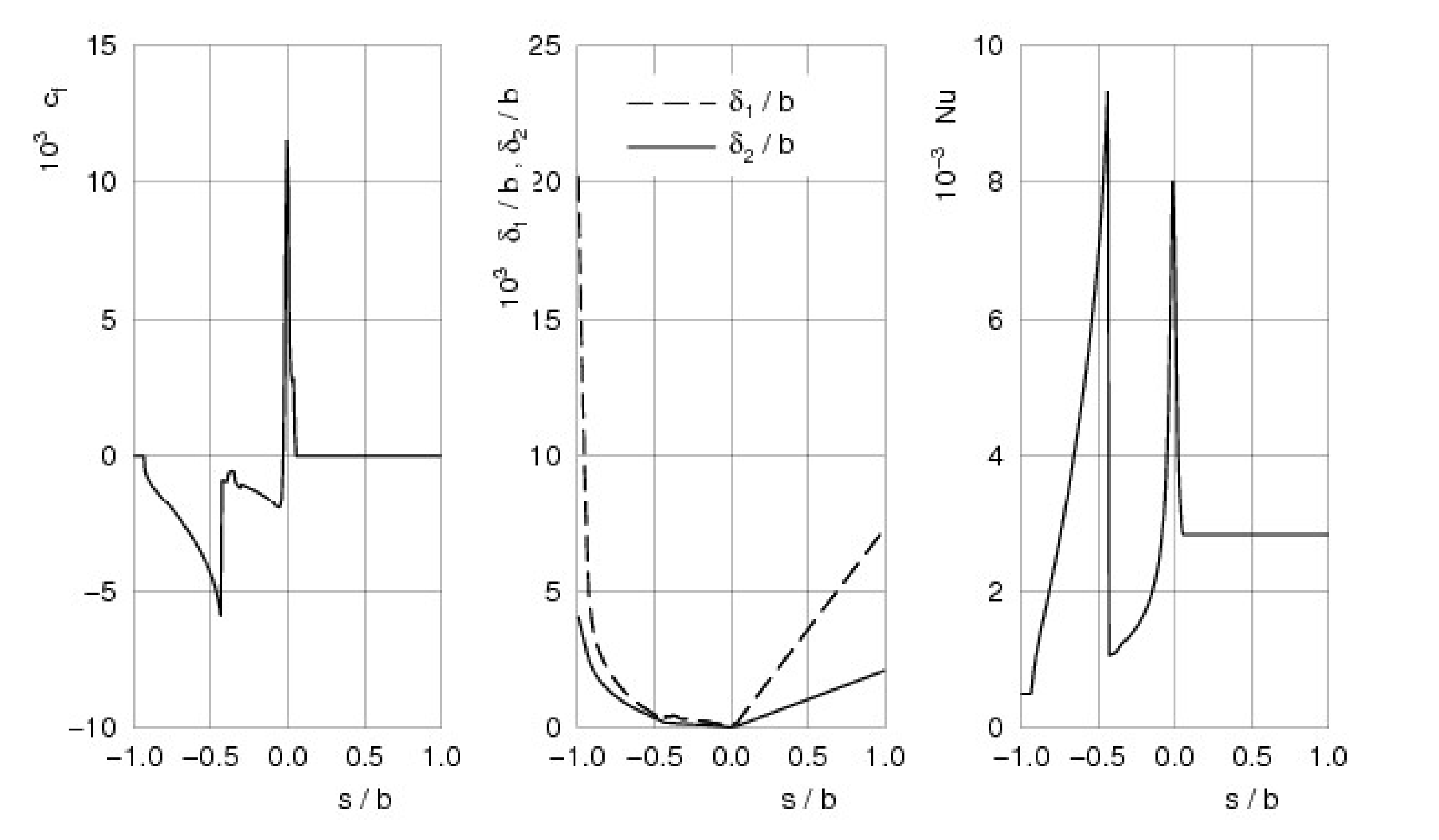


beta004.eps



Water droplets local collection efficiency β,
normal v_n and tangential v_t velocity with regard to the airfoil surface at impact location

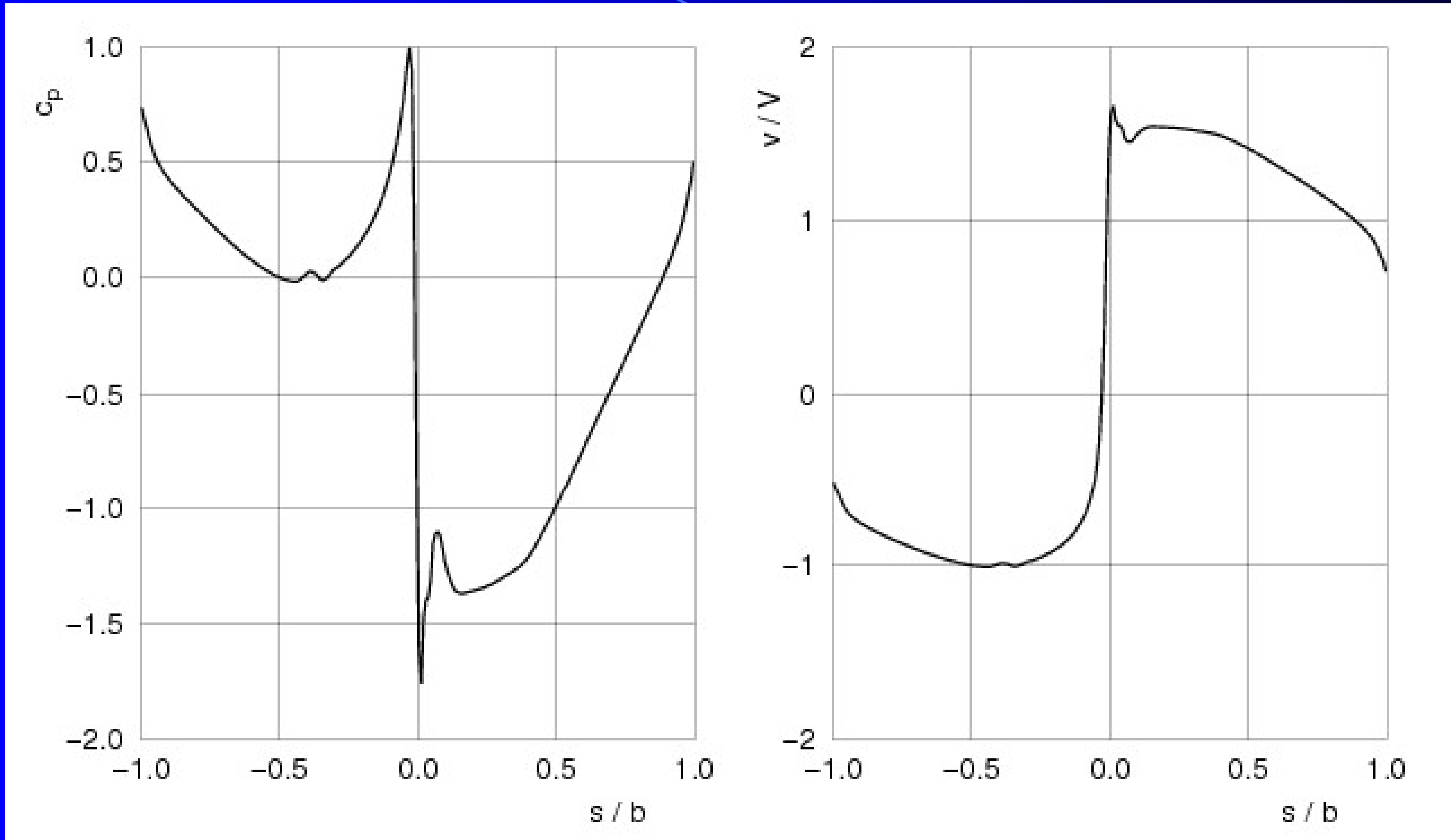
blay004.eps



Parameters of boundary layer:

Local friction coefficient c_f, displacement boundary layer thickness δ_1 (mass) and δ_2 (impulse), and Nusselt number Nu

flow004.eps



Distribution of pressure coefficient c_p and relative velocity v/v_∞

Text output file

flow005.dta

```
 1.000000        Chord        [m]
 2.087219        Length       [m]
 5.000000        Alpha        [st]
 50.000000       Vext         [m/s]
 1.000000e+005   FluidP       [Pa]
 263.000000      FluidT       [K]
 1.324643        FluidRho     [kg/m^3]
 1.246121e-005   FluidNu      [m^2/s]
 1.000000e-004   PartD        [m]
 274.150000      PartT        [K]
 1.000000e-003   PartContent  [kg/m^3]
 1000.000000     PartRho      [kg/m^3]
 263.150000      BodyT        [K]
#  s[m]        x[m]         y[m]         v[m/s]       beta[-]     vn[m/s]      vt[m/s]      cp[-]        cf[-]        Nu[-]
-1.0395e+000 +9.9210e-001 -8.7863e-002 -3.2739e+001 0.0000e+000 +0.0000e+000 +0.0000e+000 +5.7127e-001 +0.0000e+000 6.7548e+002
-1.0353e+000 +9.8800e-001 -8.8559e-002 -3.2634e+001 0.0000e+000 +0.0000e+000 +0.0000e+000 +5.7400e-001 +0.0000e+000 6.7548e+002
-1.0311e+000 +9.8390e-001 -8.9234e-002 -3.4098e+001 0.0000e+000 +0.0000e+000 +0.0000e+000 +5.3493e-001 +0.0000e+000 6.7548e+002
-1.0270e+000 +9.7979e-001 -8.9889e-002 -3.6759e+001 0.0000e+000 +0.0000e+000 +0.0000e+000 +4.5952e-001 +0.0000e+000 6.7548e+002
-1.0228e+000 +9.7568e-001 -9.0526e-002 -3.8835e+001 0.0000e+000 +0.0000e+000 +0.0000e+000 +3.9672e-001 +0.0000e+000 6.7548e+002
-1.0187e+000 +9.7157e-001 -9.1144e-002 -4.0328e+001 0.0000e+000 +0.0000e+000 +0.0000e+000 +3.4946e-001 +0.0000e+000 6.7548e+002
..........................................................................................................................
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+1.0187e+000 +9.7264e-001 -7.8940e-002 +4.1296e+001 0.0000e+000 +0.0000e+000 +0.0000e+000 +3.1785e-001 +0.0000e+000 3.2149e+003
+1.0228e+000 +9.7658e-001 -8.0263e-002 +3.9687e+001 0.0000e+000 +0.0000e+000 +0.0000e+000 +3.6997e-001 +0.0000e+000 3.2149e+003
+1.0270e+000 +9.8052e-001 -8.1603e-002 +3.7486e+001 0.0000e+000 +0.0000e+000 +0.0000e+000 +4.3793e-001 +0.0000e+000 3.2149e+003
+1.0311e+000 +9.8445e-001 -8.2961e-002 +3.4692e+001 0.0000e+000 +0.0000e+000 +0.0000e+000 +5.1859e-001 +0.0000e+000 3.2149e+003
+1.0353e+000 +9.8837e-001 -8.4338e-002 +3.3053e+001 0.0000e+000 +0.0000e+000 +0.0000e+000 +5.6299e-001 +0.0000e+000 3.2149e+003
+1.0395e+000 +9.9229e-001 -8.5735e-002 +3.2948e+001 0.0000e+000 +0.0000e+000 +0.0000e+000 +5.6577e-001 +0.0000e+000 3.2149e+003
#end
```

Closing remarks

ICE code enables computational rime ice and glaze ice accretion prediction on single and multi-element airfoils in acceptable time of solution.

Mathematical model has recently been modified for variable wall temperature along the airfoil surface.

The code was also improved for the better approximation of transition boundary layer location.

Presented code could be considered at least as a fully comparable with the current ice accretion prediction codes.

Thank you for your attention