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WING AIRFOIL RIME ICE ACCRETION PREDICTION

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Summary: *The paper presents the wing airfoil rime ice accretion prediction code R-ICE 1.1. The rime ice accretion model includes the calculation of a velocity distribution round a wing airfoil. The resulting flow field is used to an aerodynamic forces acting on water droplets determination. The set of differential equations describing particle trajectories through the local flow field is derived from the spherical shape droplet motion equations. Results of the droplets trajectories solution are used for the determination of a water mass flux impacting on the wing airfoil surface.*

There are presented some computational results of the volume median diameter droplets influence on the airfoil droplet collection efficiency. The impacting rime ice accretion changing the airfoil shape is illustrated in compare of experimental results.

1. Introduction

The formation of ice on wings occurs when the aircraft flies at a level where temperature is at, or below freezing point and hits supercooled water droplets. Two basic kinds of ice can be formed [1]. The *rime ice* if all the impinging water droplets freeze immediately upon impact. It tends to form at combinations of low ambient temperature, low speed (low kinetic heating) and a low value of cloud water concentration. In contrast, the *glaze ice* creates at combinations of temperature close to freezing, high speed or high cloud liquid water concentration, not all of the impinging water freezes on impact, the remainder is running aft along the surface.

There is described the first period of a wing airfoil ice accretion theoretical solution – the rime ice accretion prediction code R-ICE [2] in the paper.

The overall rime ice simulation involves:

- flow field calculation
- water droplets trajectory calculation
- ice accretion prediction.

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2. Flow field calculation

The most essential part in the process of icing simulation is the solution of a velocity distribution round a wing airfoil. Since the velocity of ice accretion is neglectable in compare to air speed, it is possible to solve the steady state of flow field in one step of computation. The used method enables to solve the unsteady state flow too. Naturally demands on the efficient hardware and the computer time substantially increase indeed.

The flow around the prismatic bodies could be modeled like a two-dimensional problem. In that case the relation for any point inside the control area is in form

$$2\pi \operatorname{grad}\varphi = \int_S \operatorname{grad}\left(\ln\frac{1}{r}\right)\frac{\partial\varphi}{\partial n}\,\mathrm{d}S + \int_S \varphi \operatorname{grad}\left(\frac{\mathbf{r}\circ\mathbf{n}}{r^2}\right)\mathrm{d}S\,. \tag{1}$$

The searching solution has to respect the boundary area condition $\operatorname{grad}\varphi\circ\mathbf{n} = v_n$, where v_n is the normal direction velocity component on the boundary. It is possible to approximate the velocity potential φ, or the $\partial\varphi/\partial n$ value respectively, on the body surface and on the flow field potential discontinuity surfaces by a linear combination of an appropriate function class. If we choose the needed quantity of control points on the boundary in which we require to fulfill the integral equation for the gradient of potential and boundary conditions, the method leads to the set of linear equations solution for unknown coefficients of functions linear combination that approximate the solution in the end.

3. Trajectory of water droplets

The water droplet is considered as a mass point with a mass m on that the resultant force $\mathbf{F}$ is acting. Its acceleration and position vector $\mathbf{r}$ are given by relations

$$\frac{\mathrm{d}\mathbf{v}_p}{\mathrm{d}t} = \frac{\mathbf{F}}{m},\quad \frac{\mathrm{d}\mathbf{r}}{\mathrm{d}t} = \mathbf{v}_p\,. \tag{2}$$

Currently the water droplet passing through the atmosphere is considered as a spherical shape element on that the surrounding fluid forces (aerodynamic and aerostatic) and gravitation act.

Specifying to components relations (2) create the set of ordinary differential equations for the trajectory $\mathbf{r}(t)$ solution. That equation system can be solved numerically. Typical results of trajectories solution near an airfoil are presented in Fig. 1. It is perceptible that the small water droplets have trajectories similar to streamlines, vice versa the large water droplets trajectories are affected by the airfoil inherency only slightly.

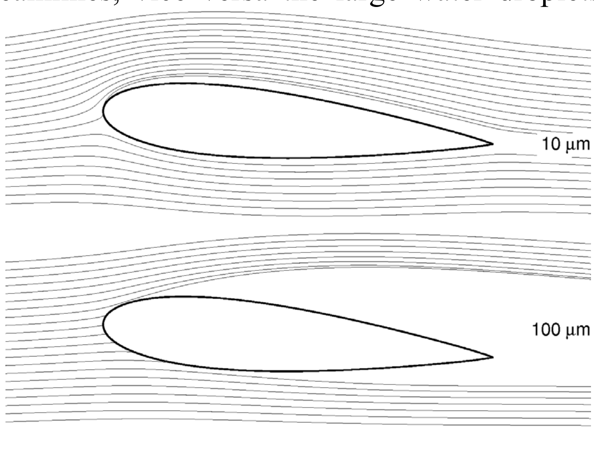

Fig. 1. Influence of the water droplets diameter on their trajectories. Airfoil NACA 0018, chord is 1 m, free stream velocity is 50 ms^{-1} and angle of attack is 5°.

4. Water droplets collection efficiency

Let is presumed the known water droplets distribution in a space far in front of a streamed body. Then may be calculated droplets trajectories and select those of which intersect an airfoil surface. Finally can be determined the quantity of catch water and its distribution along a body surface.

That problem is solved by means of various codes differently. Some of them [3] locate droplets to nodal points of rectangular net at the beginning of solution and solve trajectories of each one. This approach is considerably general and enable to every droplet allocate a different diameter, but it presents an extreme requirements on the used hardware.

Other methods are limited to the single diameter droplets trajectories computation [4, 5]. Together with a droplet trajectory are solved two secondary droplets trajectories located symmetrically to the main "droplet" apart from in a distance δy at the beginning of solution. Secondary droplets impinge the airfoil surface in a distance δs, where s is the coordinate measured along an airfoil shape (see Fig. 2). Values of δy and δs determine a quantity β expressed as the water droplets local collection efficiency by means of relation

$$\beta = \frac{\delta y}{\delta s}. \tag{3}$$

Codes using quantity β for a given droplet diameter are expeditious and enable to extend them easily for an event of any droplet diameter distribution function.

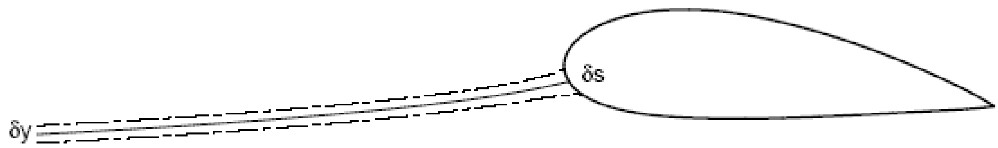

Fig. 2. Definition of the local catch efficiency

Collection efficiency is simply physically defined as the ratio of the masse of droplets impinging on an airfoil, in unit time to the mass of droplets which would impinges if the droplets were following strait line trajectories

$$\beta = \frac{m_e}{m_\infty} = \frac{m_e}{v_\infty c_\infty}, \tag{4}$$

where c_∞ kg.m^{-3} is a liquid water concentration in an undisturbed flow with a velocity v_∞.

There are presented some example results of the local values collection efficiency β solution. The results in Fig. 3 show the effect of a wing angle of attack α and Fig. 4 effect of a water droplets diameter D on the collection efficiency.

Values of the collection efficiency β are predominant for the rime ice accretion prediction presuming an immediate freeze of the impinging water droplets upon an impact location.

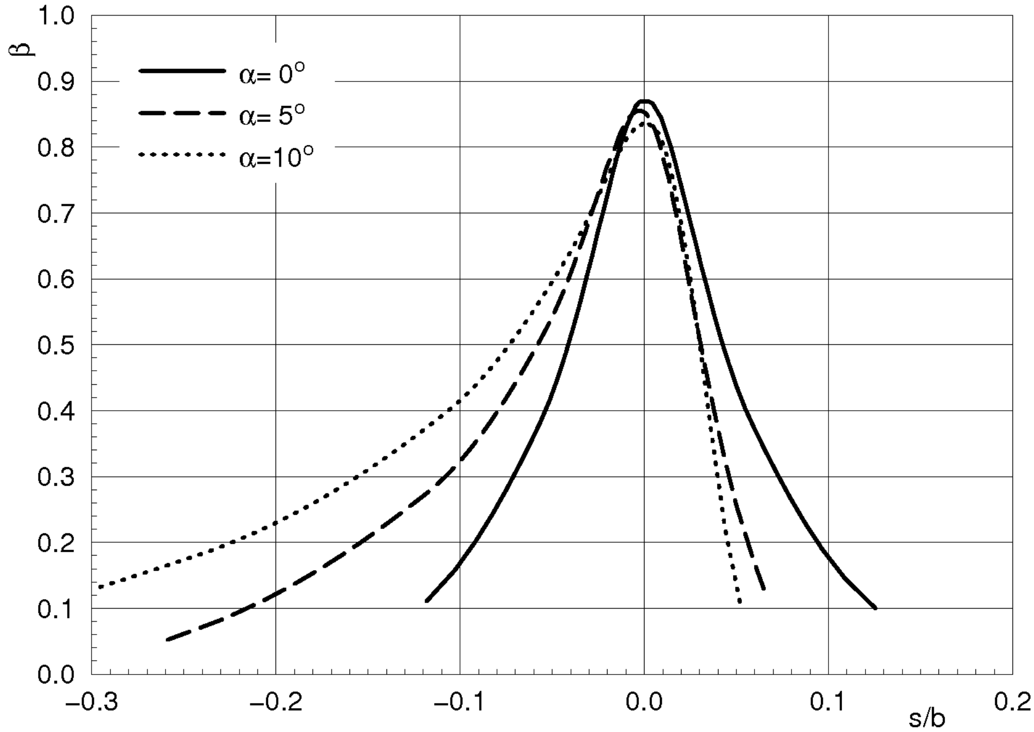

Fig. 3. Illustration of the effect of the wing angle of attack on the local collection efficiency in dependence of a surface position. Airfoil NACA 0018, chord is 1 m, free stream velocity is 50 ms^{-1} and droplets diameter is 100 μm.

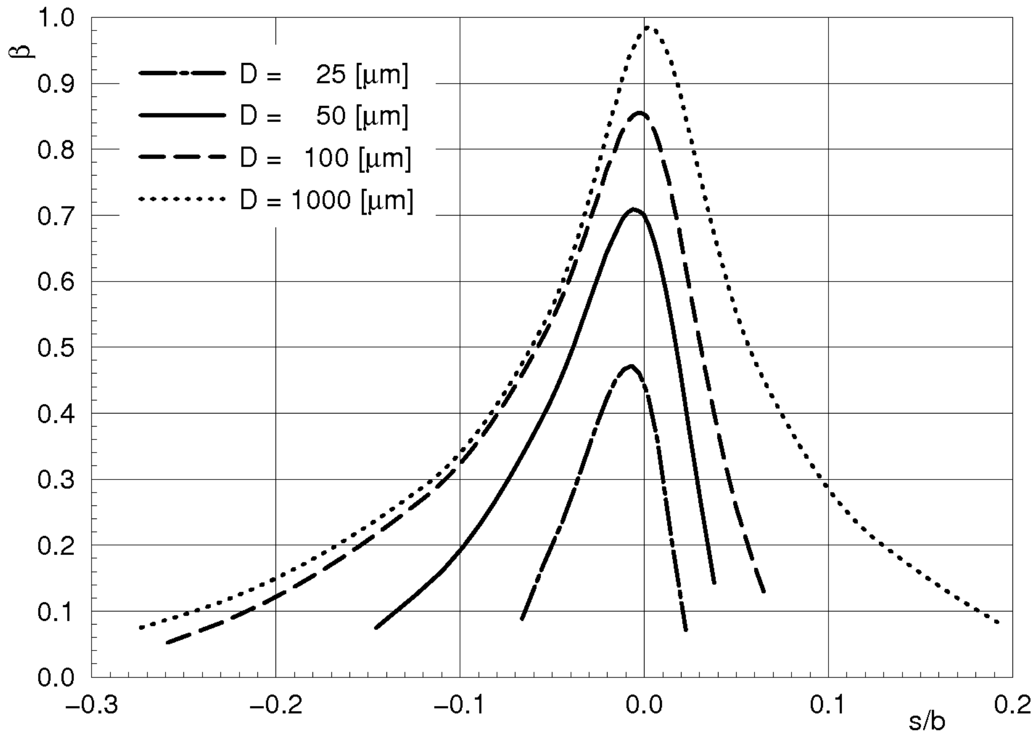

Fig. 4. Illustration of the effect of the droplets diameter on the local collection efficiency in dependence of a surface position. Airfoil NACA

5. Ice accretion prediction

For illustration, the ice accretion shapes in rime ice conditions after the first time step of numerical solution are outlined in Fig. 5 (the layer thickness is manifold increased). The angle of attack is respectively 0º, 5º and 10º.

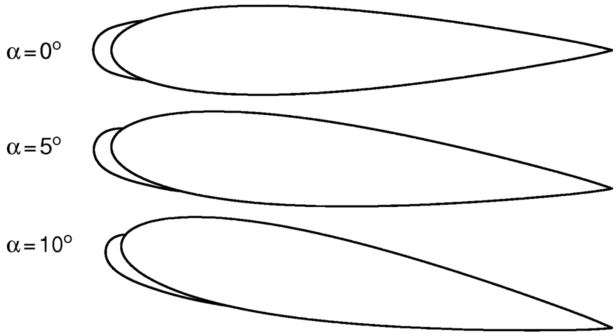

Fig. 5. Illustration of the rime ice accretion shapes for three values of angle of attack (the layer thickness is increased). Airfoil NACA 0018, chord is 1 m, free stream velocity is 50 ms^{-1} and droplets diameter is 50 μm.

A time stepping procedure is used with successive thin ice layers followed by a new flow field and droplet impingement recalculations. This procedure is repeated until the desired icing time is reached. Presented results of the rime ice successive accretion shapes for a different accretion times are illustrated in Fig. 6 and Fig. 7.

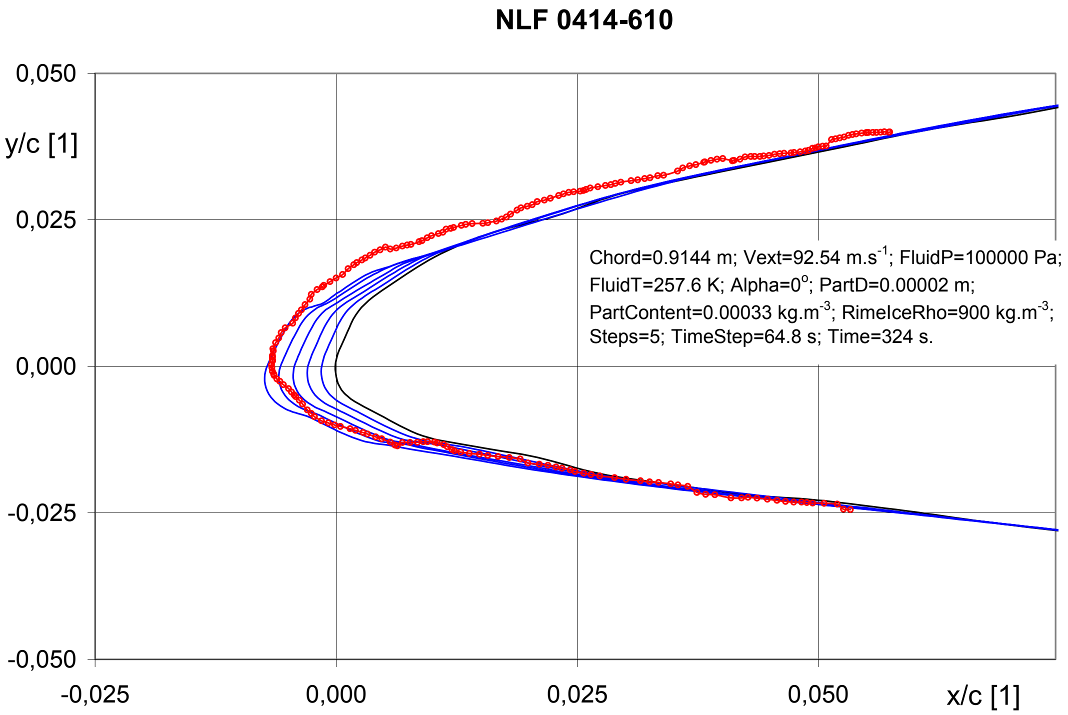

Fig. 6. Illustration of the successive rime ice accretion for the icing duration time 324 sec.

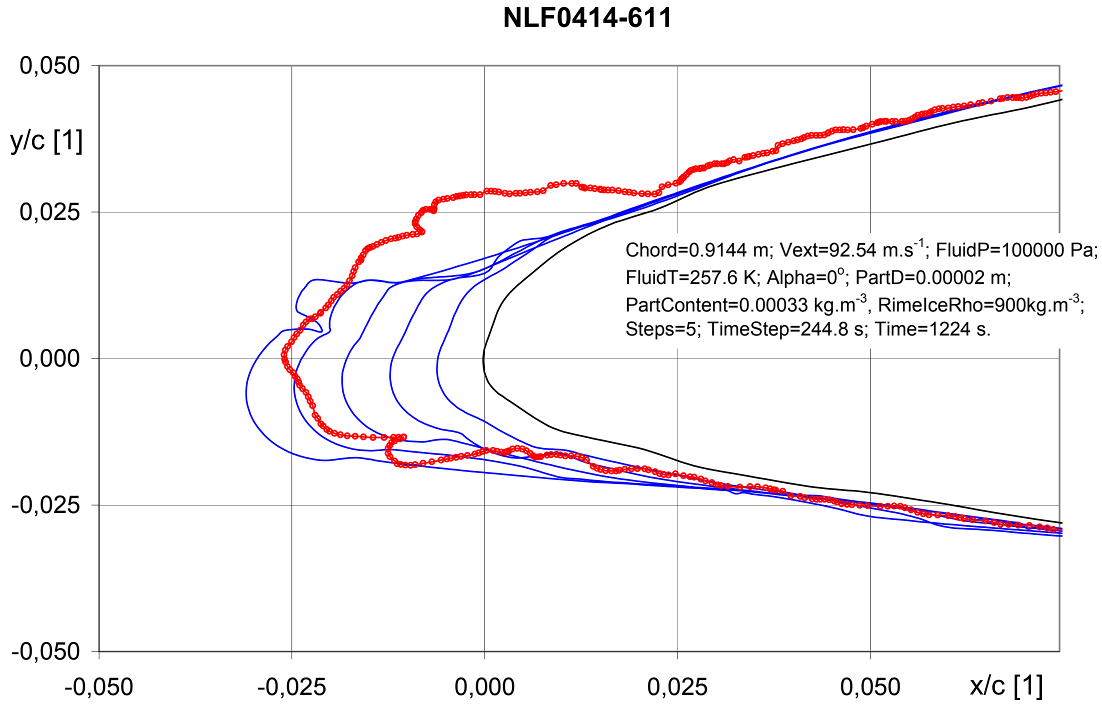

Fig. 7. Illustration of the successive rime ice accretion for the icing duration time 1224 sec.

Results of the airfoil NFL0414 ice accretion prediction for the total icing duration time 324 seconds in five time steps of solution are outlined in Fig. 6. Similarly results of the same NFL0414 airfoil ice accretion prediction solution for the icing duration time 1224 seconds are presented in Fig. 7. There are presented icing parameters (the R-ICE code incoming data) in appropriate figures either.

Figures 6 and 7 also show the final ice shape from the in-flight icing experiment [6] at the same conditions by a red color line. By comparing the results with the experiment, in spite of a good agreement in the first mentioned test (Fig. 6), in the second case (Fig. 7) it seems that the higher icing duration requires a finer step division of the total ice accretion time.

6. Concluding remarks

Computational simulation of ice accretion is an essential tool in design, development and certification of aircraft for flight into known icing conditions. Presented icing code R-ICE [2] enables to predict the location, size and shape of rime ice accretion.

Ice accretion prediction code R-ICE provides the comparable results like other current computational ice-accretion simulation methods [6]. It is evident from the quantitative comparison plotted in figures 8 and 9. Icing parameters of solutions are the same as those outlined in the previous paragraph.

Although the icing code R-ICE provides a number of satisfied results of the rime ice simulation it is necessary to be considered as a product in the phase of further development and improvement.

The second period of a wing airfoil icing theoretical solution the glaze ice accretion prediction is in the phase of implementation to the program code and testing now.

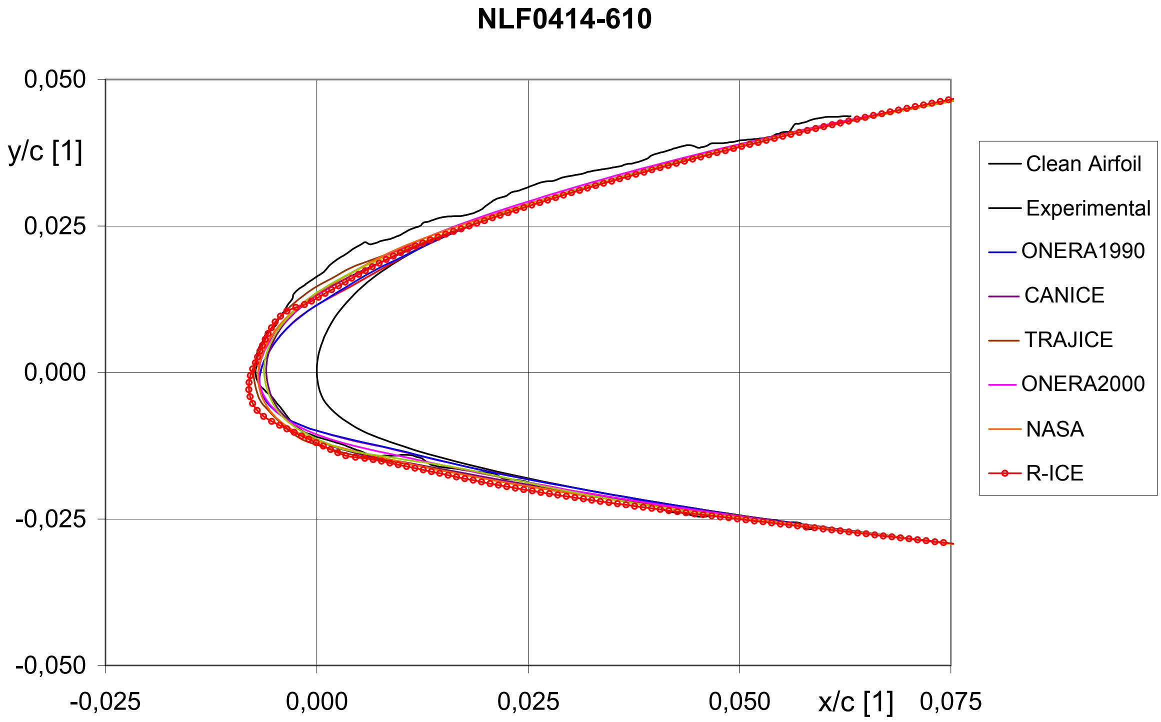

Fig. 8. Quantitative comparison of current computational ice-accretion simulation methods for the icing duration time 324 sec.

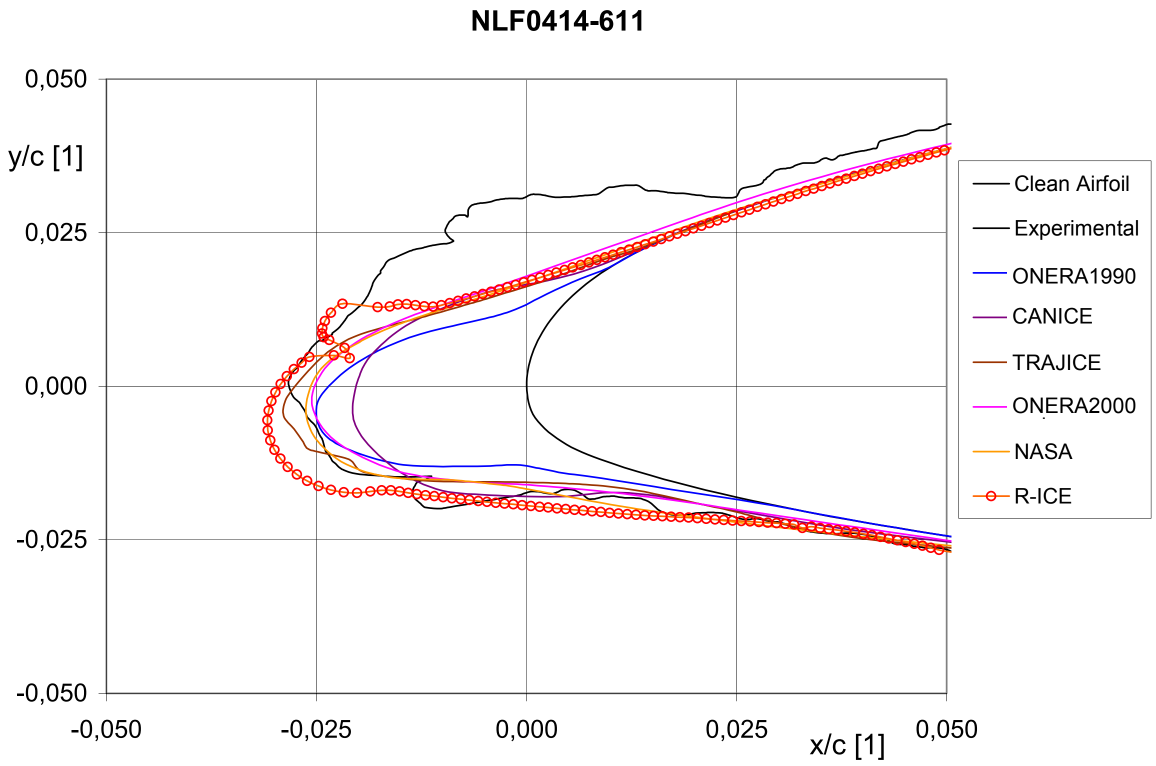

Fig. 8. Quantitative comparison of current computational ice-accretion simulation methods for the icing duration time 1224 sec.

7. Acknowledgement

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