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COMPUTATIONAL GLAZE ICE ACCRETION PREDICTION

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Summary: *The paper presents the main problem of the wing airfoil glaze ice accretion prediction: theoretical solution of the flow of a thin water layer on a cold surface and gradual freezing. There are formally arranged the conservative equations using for the solution of water flow in open channels. The flux terms are evaluated using a discontinuous Galerkin method, which could be considered as a generalized finite volumes classical method.*

There are presented some results of the glaze ice accretion simulation in comparison with published experiments and those predicted by current ice accretion prediction codes.

1. Introduction

The paper is a follow-up to the authors' previous contribution to the IM 2006 conference about the wing airfoil *rime ice* accretion computational prediction [1].

The rime ice forms when small supercooled droplets hit the surface of the airfoil and freezes instantly upon impact. It tends to form at combinations of low ambient temperature, low speed and a low value of cloud water content.

In contrast, the second main type of aircraft icing – *glaze ice* – creates at combinations of temperature close to freezing, high speed or high cloud liquid water content, not all of the impinging water freezes on impact, the thin layer of remainder water is flowing along the surface and freezes at other locations.

The performance degradation of aircraft in icing conditions can be assessed theoretically using computational codes. Computational simulation of ice accretion is an essential tool in design, development and certification of aircraft for flight into known icing conditions. Currently exist several internationally approved ice accretion codes, LEWICE (LEWis ICE accretion program) is software developed by the Icing Branch at NASA Glenn Research

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Center, 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, CANICE code developed at the Ecole Polytechnique de Montreal and CIRA code from Italian Aerospace Research Center.

Generally, current ice accretion codes give satisfied results of the rime ice simulation, but glaze icing cases are the most difficult to predict. There is still room for improvement in the quality of ice-accretion-space predictions [2].

One of possibilities could be using so called a shallow water theory [3] for the solution of the flow of a thin water layer on the airfoil surface and gradual freezing. The problem can be solved by a discontinuous Galerkin method, which could be considered as a generalized finite volumes classical method [4].

2. Thin liquid layer flow with heat transfer and phase changes

We do apply conventional approximate assumption of a hydrostatic pressure distribution for the one-dimensional flow solution. In compare to standard methods, we moreover try to include approximate influence of a velocity profile shape on the momentum equation by means of a coefficient β in a form

$$\beta(\overline{v}, h, \ldots) = \frac{1}{h}\int_0^h \left(v(y)/\overline{v}\right)^2 \,\mathrm{d}\,y\,. \tag{1}$$

Where v is the velocity, h is the surface height and $\overline{v}$ is the average velocity. Usual two equations describing momentum and mass conservation are completed by the third equation qualifying energy balance.

Following relationships are formally arranged to the form analogous to the conservative equations using for the solution of water flow in open channels.

Conservative equations could be written in the general form

$$\frac{\partial \boldsymbol{Q}}{\partial t} + \frac{\partial \boldsymbol{F}}{\partial x} = \boldsymbol{S} + \boldsymbol{S}_q\,. \tag{2}$$

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

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

$$\boldsymbol{S} = \begin{pmatrix} 0 \\ g_n I_2 + g_t A - (dp/dx)A/\rho - o_w \tau_w/\rho + o_e \tau_e/\rho \\ o_w \alpha_w (T_w - T)/\rho + o_e \alpha_e (T_e - T)/\rho + o_e q_p c T_p \end{pmatrix}, \tag{3}$$

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

Where g represents acceleration due to gravity with components g_n (positive in direction to the channel bed) and g_t (positive in direction of increasing x coordinate). Rather unusual orientation of g_n was chosen with regard to the keeping of the analogy with usually using equations of shallow water derived for low-slope channels, where $g_n \approx g$. The quantity ρ is the liquid density, the liquid temperature is denoted by T, channel wall temperature is T_w and the ambient temperature above water level is T_e.

Integrals I_1 and I_2 are given by the shape of the channel cross-section

$$I_1 = \int_0^h (h-\eta)\, b(x,\eta)\,\mathrm{d}\eta, \quad I_2 = \int_0^h (h-\eta) \frac{\mathrm{d}\, b(x,\eta)}{\mathrm{d}\, x} \mathrm{d}\eta\,. \tag{4}$$

The coordinate η is measured upwards from the lowest point of channel bed level in the section x = const. and $b\ (x, \eta)$ is the channel width. For the section of unitary width will be $I_1 = h^2/2$, $I_2 = 0$. The channel geometry description is complemented by the wetted perimeter o_w and the level width o_e.

Variable quantities: $Q_1 = A$ represents the local flow cross-section, $Q_2 = Q = A\,\overline{v}$ is the flow volume and $Q_3 = E = A\,c\,T$ expresses the thermal energy of liquid having specific heat capacity c. Quantities: F_1 is the mass flux, F_2 is the momentum flux and F_3 is the flux of energy.

Vector $\boldsymbol{S}$ includes sources of mass, momentum and energy. Certain liquid volume inflows from external sources S_{q1} (flux of impacting droplets) with the area intensity q_p [$\mathrm{m^3 s^{-1} m^{-2}}$]. Some water can freezes, the freezing fraction could be expressed from the heat balance like the area intensity q_{fr}. Similarly, the area intensity q_{ev} represents the quantity of evaporating water, which is determined by the vapours diffusion from the surface. Source of momentum S_2 includes: hydrostatic pressure (effect of the cross-section change $\mathrm{d}A/\mathrm{d}x$), tangential component of gravity force g_t (generally external volume forces), friction on the channel bed τ_w and on the liquid surface τ_e and the momentum component supplying from external sources with the radial velocity v_{px}. Finally, the source of energy S_3 constitutes heat transfer on the channel wetted perimeter, heat transfer on the liquid level (coefficients α_w and α_e), the heat supplied from external sources by means of liquid and the thermal influence of freezing and evaporating process, where L_{fr} is the latent heat of fusion and L_{ev} is the latent heat of evaporation.

There are many cases solving the liquid layer flow considering – with sufficient accuracy – the shear stress in the air boundary layer as neglectable, so $\tau_e \approx 0$. However, in the case of high velocity air flow, the shear stress on the level remarkably affects results of solution. Complete solution of the flow of water layer and surrounding air is rather complicated in the common case. It is necessary to solve simultaneously the flow profile in the water layer and the flow profile in the air boundary layer above the water level either. During the glaze ice accretion, the water flow layer on the wing is very thin, in the order of tenth of millimeters, and the water flow velocity is very small in compare to the velocity of surrounding air. Therefore, for the further solution of the problem, the following simplified assumptions are made:

- the flow in the thin water layer is assumed to be laminar
- the air flow round the body is not affected by the slowly flowing water layer
- process of the ice accretion is assumed to be slow, mutual coincidence of the water layer and surrounding air can be considered as the pseudo-stationary problem.

Then can be performed the simplified solution according to the scheme:

- evaluation of the air boundary layer on the profile with a fixed wall and determination of the shear stress τ_e on the level
- solution of the stationary velocity profile within the water layer at defined τ_e and the determination of shear stress τ_w on the wall.

Using the conventional assumption that the pressure gradient d*p*/d*x* is in the section x = const independent on the point position in the crosswise section. Then dependency of the shear stress τ on coordinate y must be linear, so dτ /dy = const, as to be ensured the force equilibrium in the direction of coordinate x on every elemental thickness dy.

With regard to the above outlined assumptions we receive relation for the shear stress on the wall

$$\tau_w = 3\frac{\mu\,\overline{v}}{h} - \frac{1}{2}\tau_e \tag{5}$$

and the β coefficient in form

$$\beta = \frac{1}{h}\int_0^h \left(v(y)/\overline{v}\right)^2 \,\mathrm{d}\,y = \int_0^1 \left(v(\overline{y})/\overline{v}\right)^2 \,\mathrm{d}\,\overline{y} = \frac{3}{5}\,\frac{8+9\overline{\tau}+3\overline{\tau}^2}{4+4\overline{\tau}+\overline{\tau}^2}\,. \tag{6}$$

The special case is the laminar flow for τ_e = 0. Resulting classical relations for the flow within the thin liquid layer are

$$\tau_w = 3\,\mu\,\overline{v}/h\,,\; v(\overline{y}) = 3\overline{v}/2\left(2\overline{y}-\overline{y}^2\right),\; v_{\max} = 3\overline{v}/2 \text{ and } \beta = 1.2\,. \tag{7}$$

Another special case responds to $\overline{\tau} = 1$, so τ_w = τ_e, when we receive resulting linear velocity profile and value of coefficient β = 4/3 ≈ 1.33.

The formulated problem of the thin liquid layer flow solution was solved by a discontinuous Galerkin method, which could be considered as a generalized finite volumes classical method. For the full discretization of the problem, the basis set contains as spatial functions as functions of time. The problem leads to the solution of the system of ordinary differential equations in the final phase. Principles of the Galerkin method, applied to the solution of the flow of a thin water layer and gradual freezing, are closely described in [5].

3. Presentation of results

There are presented some computational results of the wing airfoil NACA 0012 glaze ice accretion prediction in Fig. 1 and Fig. 2. Figures show appropriate published experimental ice shapes [2] outlined with a red line either.

Input data of the solution are airfoil chord b = 0.45 m, free stream velocity v_∞ = 77.2 m s^{-1}, angle of attack α = 0º, cloud liquid water content LWC = 0.32 g m^{-3}, droplets median volume diameter MVD = 18 µm, ambient air temperature T_e = 270.5 K and wing surface temperature T_w = 273.0 K. Total icing duration time is 300 s.

Results of the glaze ice accretion prediction for the icing duration time 150 and 300 seconds are outlined in Fig. 1.

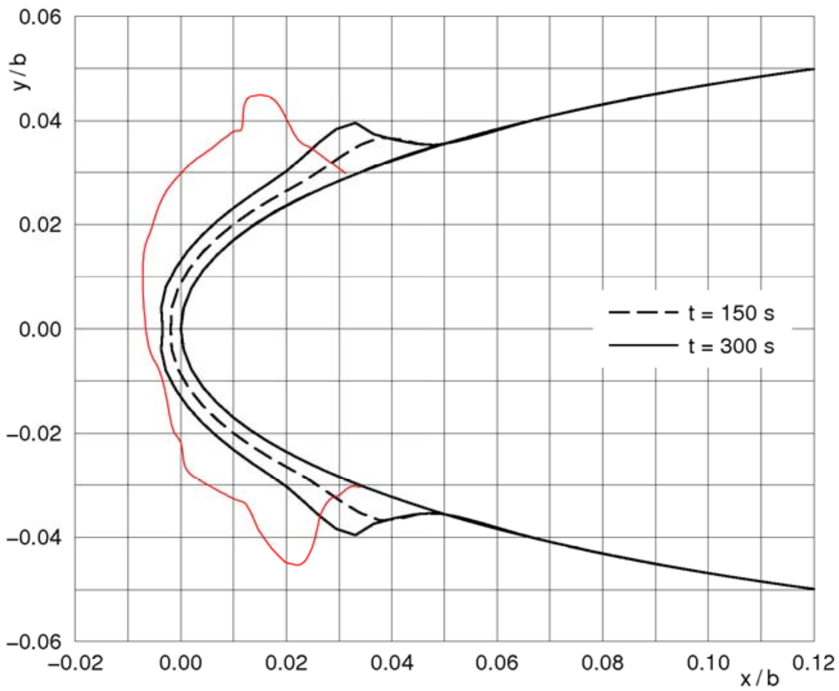

Fig. 1. Successive glaze ice accretion for icing duration time 150 s and 300 s and comparison with experimental ice shape.

Process of glaze ice accretion is strongly related to the heat transfer between water layer and wing surface. Results of solution are therefore substantially influenced by the wall temperature T_w. Fig. 2 shows the effect of wall temperature on glaze ice accretion prediction.

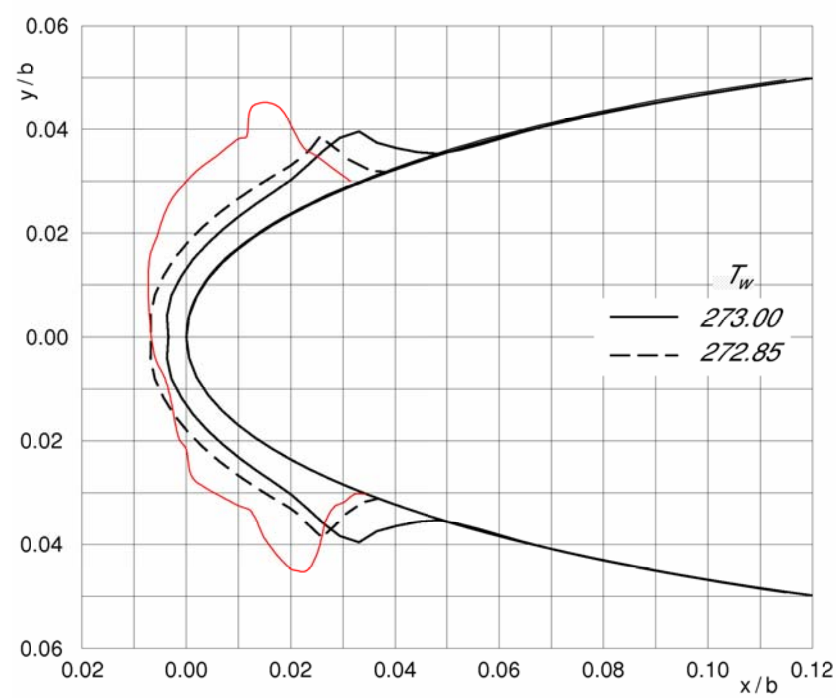

Fig. 2. Effect of wall temperature on glaze ice shapes and comparison with experiment.

4. Conclusions

It could be noted that the results outlined above qualitatively correspond to the experimental observations of glaze ice shapes.

Comparison in Fig. 3 acknowledges that the presented solution could be considered at least as a fully comparable with the current ice accretion prediction codes.

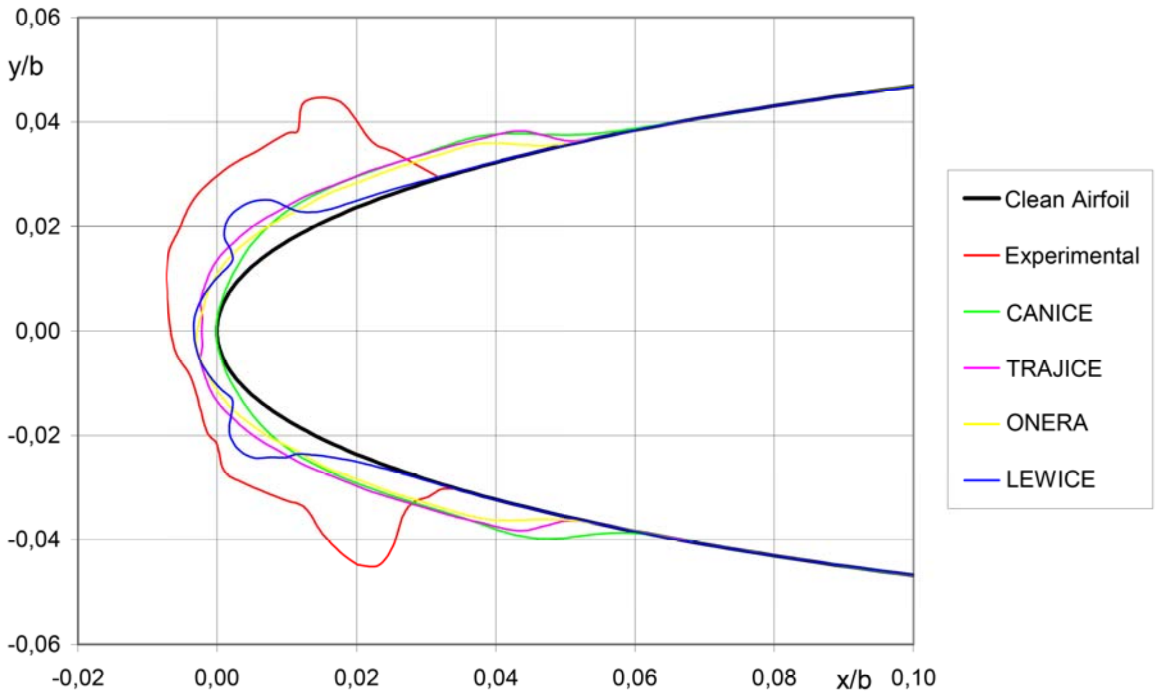

Fig. 3. Quantitative comparison of current computational ice-accretion simulation methods from [2].

Generally, glaze ice shapes are the more difficult cases to predict due to the complex thermodynamic, fluid motion and heat transfer processes involved in ice growth. Used assumption of steady-state heat transfer is rather simplified, especially for thick ice layers and their complicated relief, where the very ice thickness definition is problematic. In real conditions, the real wing structure would affect the ice accretion either.

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