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Features of the formation of ice creations on a symmetrical and asymmetrical airfoil and their influence on aerodynamic characteristic of the wing

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The results of numerical investigations ice formations on the wing with symmetrical and asymmetrical airfoil. Numerical studies ice creations were carried out on straight wing in the range of angles of attack from -20 degrees to 20 degrees in conditions of experiment in aerodynamic tube with number Mach $\mathrm{M} = 0.12$ and Reynolds $\mathrm{Re} = 0.7 \cdot 10^6$ million. Compare aerodynamic characteristic of the wing without ice, obtain in calculations with experimental results are presented. Analysis of the results of ice formations is performed.

Keywords: aerodynamic characteristic, symmetrical and asymmetrical airfoil, ice formations.

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Determination of aerodynamic characteristics, as well as stability and controllability parameters of an aircraft taking into account possible ice growth on its surface is an urgent task of designing aircraft, in particular, small aviation objects, seaplanes and screen-planes. The experience of calculations of ice growth shapes and aerodynamic characteristics of symmetric and asymmetric profiles based on the results of numerical modelling based on the control volume method indicates significant differences in the scenarios of ice growth formation and, consequently, the influence of ice on aerodynamic characteristics. The aim of the present work is to investigate the peculiarities of ice buildup on the wing depending on the symmetry of the profile shape. These differences may be related to the fact that the deviation from the shape symmetry during the droplets' approach to the streamlined body favors their inertial deposition in regions where the distance from the droplet trajectory to the streamlined body is small. In addition, increasing the curvature of the streamline profile in the lower region increases the boundary layer thickness and the residence time of droplets in it. In this case, due to the inertia of droplets when they get into the boundary layer, their velocity will exceed the flow velocity in the vicinity of the droplets and, as a consequence, the Saffman force will act on the droplets, directed towards the streamlined body due to the negative velocity difference between the flow and droplets during their movement in the boundary layer.

In the present work, parametric studies of ice formation on a straight wing with a symmetric profile NACA 642A015 and an asymmetric profile NACA 642A615 have been carried out using numerical modelling techniques. The computational models of straight wings (Fig. 1) with relative elongation of 2.8 and different profiles were constructed according to the geometrical data of the models under the conditions of aerodynamic experiment in the tube [1].

The calculations of icing effects were carried out in a three-dimensional formulation of the problem on a straight wing whose leading edge is perpendicular to the flow around it, so three-dimensional effects were minimized. The equation of motion of individual droplets has the form

$$\frac{d\mathbf{V}_p}{dt} = \mathbf{g}\left(1-\frac{\rho}{\rho_p}\right) + \frac{9\mu}{2\rho_p a_p^2}\,\frac{C_D}{C_D^{\mathrm{Stk}}} \times \left[\mathbf{V}-\mathbf{V}_p + 0.343\,a_p\sqrt{\frac{\rho}{\mu}\left|\frac{\partial \mathbf{V}_\tau}{\partial \mathbf{n}}\right|}\left(\mathbf{V}-\mathbf{V}_p\right)_\tau \mathbf{n}\right],$$

where $\mathbf{V}_p$ — the velocity of the drop, $\mathbf{g}$ — the free-fall acceleration of the drop, ρ — the density of air, ρ_p — the density of a water drop, a_p — the radius of the drop, μ — the dynamic viscosity of air. The second summand in the right-hand side — the sum of the aerodynamic force and the Saffman force favoring droplet deposition in the boundary layer of the streamlined body, $\mathbf{n}$ — the unit vector of the normal, τ — the tangent, C_D — the drag coefficient, $C_D^{\mathrm{Stk}} = 24/\mathrm{Re}_p$ (Re_p — the Reynolds number of droplet motion relative to the flow carrying them), the index p stands for particle. When decimated by the characteristic flow velocity and streamline size, the value in front of the first summand will be the inverse of the Froude number $(1/\mathrm{Fr} = gL/V^2 \approx 10^{-4} \ll 1)$, and the value in front of the second — the inverse of the Stokes number $(1/\mathrm{Stk} = 9\mu L/2\rho_p a_p^2 V \approx 2)$. Thus, the influence of gravity is negligible and the droplet impact area on the wing is comparable to the thickness of the wing profile. The equations of change of momentum and energy of the

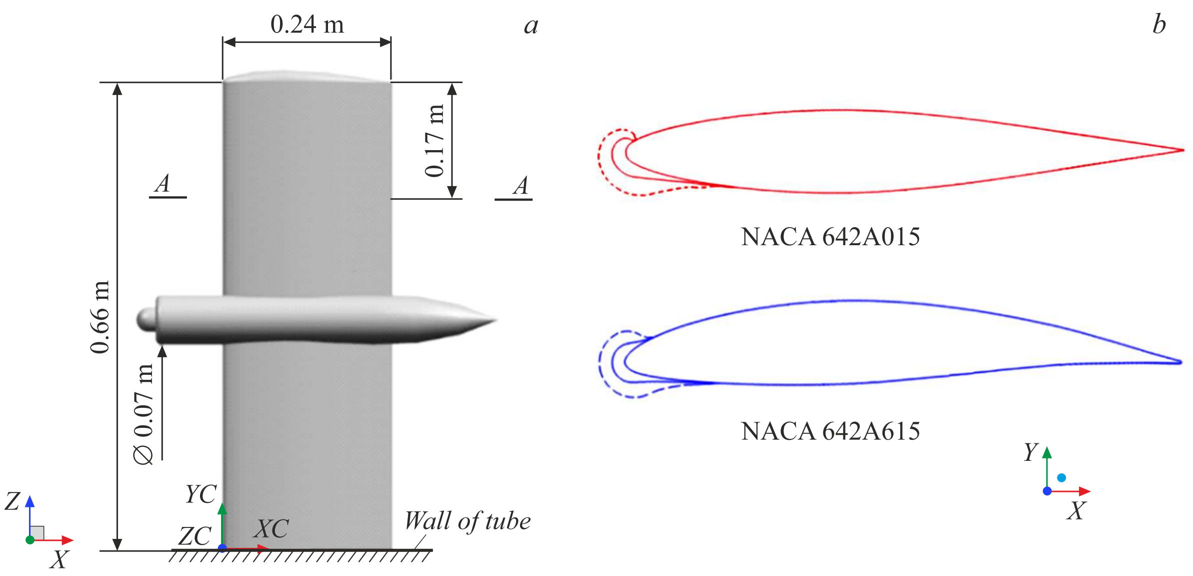


Figure 1. Computational model of the wing. a — general view; b — ice shapes formed at angle of attack $\alpha = 5^\circ$ in the wing section A–A. $t_{ice} = 10$ min (solid lines) and 30 min (dashed lines).

particle-carrying gas have the following form:

$$\rho\frac{d\mathbf{V}}{dt}=\overline{\nabla}\widehat{\mathbf{P}}-\mathbf{f},\rho\frac{de}{dt}=\overline{\nabla}\widehat{\mathbf{P}}\mathbf{V}-\overline{\nabla}\left(-\lambda\overline{\nabla}T\right)-\varepsilon,$$

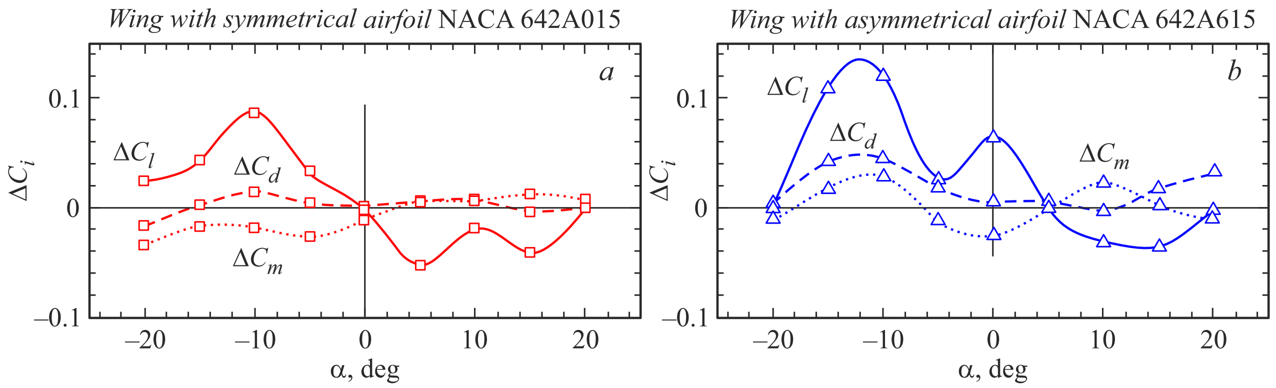
where $\mathbf{f}$ and ε — the momentum flux densities and interfacial interaction energy, $\widehat{\mathbf{P}}$, e and λ — the stress tensor, internal energy density and thermal conductivity coefficient of the carrier phase.

The ANSYS FENSAP-ICE program was used to calculate the ice accretion. The calculation of the motion and deposition of aqueous droplets in an air current is performed in this software package using the DROP3D module in the Eulerian formulation. The thermodynamic Messinger model was used as the basis for calculating the shape of ice formation in ANSYS FENSAP-ICE. The calculation of loose ice formation on the wing was carried out at an ambient temperature of 268 K (-5°C) with the content in the air of the liquid phase of water LWC=0.005 kg/m^3 at a constant arithmetic mean value of the droplet diameter of 20 μm. In the present paper, the formation of smooth ice is considered. The ice shapes formed at angle of attack $\alpha = 5^\circ$ for 10 and 30 min on the symmetric and asymmetric wing profiles are shown in Fig. 1, b.

For the calculations, a structured mesh containing about 10^7 cells, of which 100 cells along the chord and the same number along the wingspan, was constructed in the ICEM CFD program. To resolve the boundary layer, a special o-grid, constructed along the normal to the surface and containing 20 cells in height, was created. A one-parameter turbulence model adapted to flows with low Reynolds numbers was used in the wall region. studies of the influence of ice growths on the aerodynamic characteristics of the wing were carried out in the ANSYS FLUENT program using the k–ω SST turbulence model. The equations solved in the calculation process were approximated using finite-volume schemes of the second order of accuracy. in the range of angles of attack $-20 \leqslant \alpha \leqslant 20^\circ$ at Mach numbers $\mathrm{M} = 0.12$ and Reynolds numbers $\mathrm{Re} = 0.7 \cdot 10^6$ in this paper are given for an icing time of 10 min.

The increments of aerodynamic characteristics were obtained as the difference between the force and moment coefficients of the wing with ice ($t = 10$ min) and without ice: $\Delta C_l = C_{l\ ice} - C_{l\ without\ ice}$, $\Delta C_d = C_{d\ ice} - C_{d\ without\ ice}$, $\Delta C_m = C_{m\ ice} - C_{m\ without\ ice}$, where C_l — wing lift coefficient, $C_{l\ ice}$ — with ice, $C_{l\ without\ ice}$ — without ice, C_d — wing drag coefficient, C_m — pitching moment coefficient. The calculation results show that the presence of ice increases the lift force of the wing in the range of angles of attack $-15^\circ \leqslant \alpha \leqslant 0$, but on a wing with a symmetrical profile to a lesser extent (Fig. 2, a), and at positive angles of attack ice on the wing, regardless of its profiling, slightly reduces the lift force. A significant increase in drag is observed mainly on the wing with asymmetric profile NACA 642A615 (Fig. 2, b) in the range of angles of attack $-15 \leqslant \alpha \leqslant 5^\circ$ and at $\alpha > 15^\circ$. The effect of icing on the pitching moment as a function of the angle of attack is particularly strong for a wing with an asymmetric profile (Fig. 2, b). The cause of several maxima and minima, especially for an asymmetric profile, is the breakaway flow from the formed ice ($\alpha = -10^\circ$, $\alpha = 15^\circ$)and the increase in the height of the breakaway zone, as well as the flow breakaway from the ice outgrowth ($\alpha = 0$) attached to the wing. Aerodynamic characteristics at some angles of attack are shown in the table.

Analysis of the calculated data showed that the aerodynamic characteristics of the wing with symmetric profile NACA 642A015 are less affected by icing and their


Wing with symmetrical airfoil NACA 642A015

Wing with asymmetrical airfoil NACA 642A615

Figure 2. Dependences of the increment of aerodynamic coefficients due to aircraft icing on the angle of attack. *a* — wing with symmetrical profile; *b* — wing with asymmetrical profile.

Aerodynamic coefficients of the wing

Angle of attack, deg	Symmetrical wing profile				Unsymmetrical wing profile			
	without ice		with ice		without ice		with ice	
	C_y	C_x	$C_{y\,ice}$	$C_{x\,ice}$	C_y	C_x	$C_{y\,ice}$	$C_{x\,ice}$
−10	−0.557	0.096	−0.469	0.110	−0.353	0.078	−0.232	0.123
0	0.007	0.029	0.007	0.031	0.145	0.0389	0.209	0.044
15	0.534	0.189	0.494	0.186	0.833	0.183	0.799	0.199

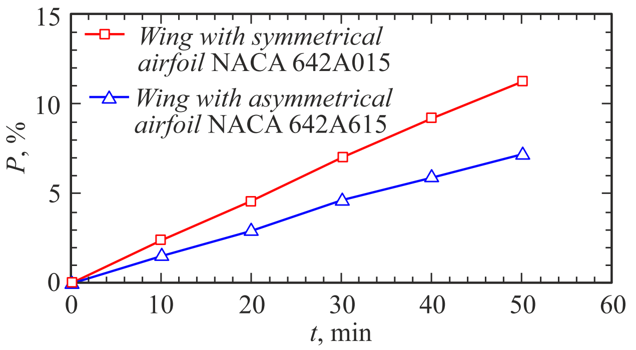


Figure 3. Weight increment of ice accretion as a function of time.

increments due to icing are closer to a linear relationship at $\alpha > 0$. The results of the ice accretion weight as a function of time are shown in Fig. 3, where the ice accretion weight increment shows by how many per cent the wing weight increases over time as ice accretions form. These dependencies are linear in nature. On a wing with a symmetrical profile, significantly more ice builds up over time than on a wing with an asymmetrical profile. It should be noted that the derivative of the ice increment function from time on the wing with a symmetric profile NACA 642A015 is 1.6 times larger than that of the wing with an asymmetric profile.

Numerical studies of the influence of ice growths on the aerodynamic characteristics of the wing have shown that at a relatively short icing time (10 min) ice on a wing with a symmetrical profile has a smaller influence on the aerodynamic characteristics of the wing than on a wing with an asymmetrical profile. It can be seen that on the wing with a symmetrical profile the ice growth rate is much higher, which may be due to the fact that at the angle of attack the inertially deposited droplets on the wing have less time to acquire the velocity of the flow carrying them. This leads to higher values of droplet impact velocity (compared to the case of asymmetric profile) and, as a consequence, to an increase in the mass flux density of crystallizing liquid particles.

Conflict of interest

The authors declare that they have no conflict of interest.

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