The influence of ice crystals on the evolution of run-back ice in mixed icing conditions

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Abstract. In the framework of the development of physical and mathematical models of icing in crystalline and mixed conditions and their verification, the effect of ice crystals in the airflow on the evolution of run-back ice on the surface of a wing model for tests in icing facility is numerically studied. The results confirm that the experimentally observed change in the mass of ice deposits with the introduction of crystals into the flow is associated with the absorption of a part of the mass of crystals by the film at low flow rates and with the film splashing at higher speeds.

Recently, the regime of icing, which was not taken into account previously, has been actively studied [1–6]. It is due to ice crystals, which poses a threat to the stable operation of the aircraft engine. In one of the scenarios of the ice accumulation in the engine path, the crystals melt upon contact with a warm surface and form a moving water film that freezes due to crystal bombardment, turning into run-back ice. When flying in a crystalline or mixed (consisting of droplets and crystals) cloud, a blockage of the channel of the Pitot tube can occur. Thus, icing in the presence of crystals in the atmosphere is a very dangerous process in internal flows, since in this case zones of accumulation of crystals can form.

The arrangement of the icing experiment inside the channel is difficult in terms of providing the necessary measurements and observations. Therefore, it is reasonable to validate computing programs in the case of an external flow around the model. In this paper, we consider an example of parameter adjustment based on a comparison with experiment for a simplified physical model of run-back ice formation when crystals get to a wing profile model with a heated leading edge.

The model was placed in the working part of the icing wind tunnel. A nozzle provided the flow of the water film on the model surface. The nozzle was located upstream and below the model in such a way that it provided uniform distribution of the film thickness over the span at the leading edge, while not interfering the flow with crystals. In experiments, crystals with the given sizes, shapes, and mass contents per unit volume (IWC – Ice Water Content) flowed onto the model. They interacted with the film on the surface and cooled it. As a result, run-back ice was formed on the upper removable plate of the model. The ice mass was measured. Another measured parameter was the distance \(L\) from the beginning of the flat portion of the model to the front of the run-back ice.

A typical form of run-back ice obtained on the wing model as a result of experiments [7] in an icing wind tunnel is shown in figure 1. The wing model profile (chord 205 mm, wingspan 150 mm)
had a cylindrical leading edge with a radius of \( R = 15 \text{ mm} \). Inside the model, an Ohmic heater was installed in the form of a spiral wound on a cylindrical tube. The center of the tube was at a distance \( r_0 = 9 \text{ mm} \) from the leading edge of the model.

The experiments were carried out in pairs. In the first experiment of each pair, the mass of run-back ice was measured, which was formed due to film freezing in 60 s after the start of the test in the absence of crystals in the air stream. The second experiment was carried out under the same conditions, but with the addition of crystals to the stream. This led to an increase in the mass of ice deposits at a flow velocity of \( V_\infty = 20 \text{ m/s} \) and to a decrease at \( V_\infty = 80 \text{ m/s} \). This behavior of run-back ice is confirmed below on the basis of numerical studies carried out in the framework of the developed physical and mathematical model.

The model is based on the equations of the boundary layer averaged over the thickness of the film. The previously developed physical and mathematical model [7, 8] made it possible to trace the evolution of run-back ice in the absence of crystals in the flow. In the present work, the theoretical model [8] is supplemented by taking into account the bombardment of the film by crystals. Under the assumption that the crystal causes splashing of the film and a small part of its mass penetrates inside, the system of equations has the form:

\[
\begin{align*}
\rho \partial \langle u_i \rangle / \partial s &= -\rho \partial \langle h_i \rangle (s,t) / \partial t - \dot{m}_s + \dot{m}_t + \dot{m}_m - \dot{m}_w, \\
0 &= -h_1 \dot{p} / \partial s + \tau_a - \tau_s + \dot{m}_p \rho_\text{pl} + (\dot{m}_1 - \dot{m}_w) \rho_\text{pl}, \\
\rho c_1 \partial \langle u_i \rangle (s,T)/ \partial s &= q_i^* - q_i - \dot{m}_s L_s - c_T \rho_\text{pl} \partial \langle h_i \rangle (s,t) / \partial t + \dot{m}_1 (V_\text{pl}^2 / 2 + c_i T_\text{pl}) + \dot{m}_1 (V_\text{pl}^2 / 2 + c_i T_\text{pl}) - \dot{m}_w c_i T_i^\infty, \\
\partial \langle h_i \rangle (s,t) / \partial t &= \begin{cases} 0, & T_1^- > T_f, \\
(\rho_1 |q_i^+| + |q_i^-|) / \rho_1 L_i, & T_1^- = T_f \end{cases}
\end{align*}
\]
\[ h_i(s) = \frac{\partial h_i(s,t)}{\partial t} \int_{s_i}^{s} \frac{ds}{\langle u_i \rangle} \]

Here \( \rho_i, \rho_l \) are the densities of liquid (water) and ice; \( h_i, h_j \) are film and ice thicknesses; \( \langle u_i \rangle \) is average film speed; \( s \) is the curvilinear coordinate along the surface of the streamlined body; \( t \) is the time; \( m_v, m_h, m_{sp} \) (index \( sp \) means splash) are the densities, respectively: of the flows of the evaporating mass of the film, droplets arriving in the film, fragments of ice crystals penetrating into it, and ablation of the film mass due to splashing by the crystals. Next, \( p \) is the pressure in the film; \( \tau_n, \tau_s \) are shear stresses at the upper and lower boundaries of the film; \( u_{pl}, u_{pi} \) (index \( p \) means particle) tangential to the surface components of the velocity of droplets and crystals incident on the body; \( c_l, c_i \) are heat capacity of water and ice; \( \langle u_i T_i \rangle \) is the product of the film velocity and temperature \( T_i \) averaged over the film thickness; \( q_{sl}, q_i^l, q_i^r \) are the densities of heat fluxes into the air from the upper boundary of the film, from the surface of the body (or ice) into the film and from the film into the forming ice layer; \( L_v, L_l \) – heats of the water – steam and water – ice phase transitions; \( V_{pl}, V_{pi} \) are velocity moduli of water and ice particles upon impact on the film; \( T_{pl}, T_{pi}, T_i, T_i^f, T_i^r \) are the temperatures of the corresponding particles, freezing of water, the upper and lower boundaries of the film; \( s_i \) is the coordinate at which film freezing begins.

When determining the flux density \( m_{hi} \) of droplets near the model and crystal fragments that have invaded the film. The flux densities of the sprayed mass \( m_{sp} \) and introduced into the film \( m_i \) were supposed to be proportional to each other (\( m_{sp} = k m_i \)). It was assumed that the temperature of the crystals \( T_{pi} \) is equal to the temperature of the incoming air flow \( T_\alpha \).

The method for solving the above system of equations is described in detail in [8]. Calculations of the evolution of run-back ice were performed for experimental conditions [7]. First, we stop at a mode with a speed of \( V_\infty = 80 \text{ m/s} \) for one of the runs without crystals in the flow. It was characterized by the following parameters: airflow temperature \( T_\infty = -9.9^\circ \text{C} \), surface temperature of the model measured by thermocouples \( T_s = 12.7^\circ \text{C} \), distance from the beginning of the flat section of the model to the front boundary of the run-back ice \( L = 55 \text{ mm} \), mass of the run-back ice \( G = 2.9 \text{ g} \).

Calculations of run-back ice were performed at the indicated \( T_\alpha \) value. At that, the quantities \( \rho_{pl}, T_{pl}, \) and \( q_{io} \), which were not measured in the experiment, were selected so that as a result of the calculations, the values of \( G, T_\alpha, \) and \( L \) recorded in the experiment were obtained. Note that the interaction of droplets with a heated surface is a complex physical phenomenon. Here, \( T_{pl} \) should be considered as some fictitious quantity that allows one to control the film temperature. The distribution of the heat flux from the heater \( q_i^r(s) \) along the profile contour was set according to the law

\[ q_i^r(s) = Q_0 \cdot (r, \mathbf{n}) / r^2 \sim 1 / r, \]

where \( r \) is the radius vector drawn from the center of the heater to the contour of the wing model, \( \mathbf{n} \) is the normal to its surface, the value \( Q_0 \) of the power of the heater per unit of its length was selected in the calculation. The initial value \( T_i^f \) in the theoretical model corresponded to the temperature \( T_s \).
As a result of fitting, it was found that $\rho_{\text{pl}} = 1.3 \text{ g/m}^3$, $T_{\text{pl}} = 12.2^\circ \text{C}$, and $q_{\text{lo}}^+ = 1.05 \text{ W/cm}^2$. After the values of $T_{\text{pl}}$ and $q_{\text{lo}}^+$ in the run without crystals were found, the run-back ice of the second experiment of the pair with crystals in the flow was calculated at these values. The crystals had an irregular shape with an average diameter of the sphere of the same volume equal to 0.99 mm. The value of water content in crystals was $\text{IWC} = 11 \text{ g/m}^3$. The ambient temperature at this run slightly decreased and was equal to $T_{\infty} = -11.2^\circ \text{C}$. The presence of crystals in the flow resulted in a decrease in the temperature of the leading edge to $T_s = 6.2^\circ \text{C}$ and a shift of the ice barrier forward, $L = 26 \text{ mm}$. The mass of frozen ice decreased to $G = 1.2 \text{ g}$.

In this calculation, the concentration of crystals embedded in the film was selected so that the calculated temperature $T_s$ was equal to the measured temperature. The selection gave a value of $\rho_{\text{pi}} = 0.11 \text{ g/m}^3$, i.e. only 0.1% of the incident mass of crystals was introduced into the film.

Then, the film splashing coefficient $\kappa$ was selected so that the experimental and calculated values of $L$ coincided. In the absence of splashing ($\kappa = 0$), the calculated distance $L$ turned out to be greater than in the experiment. An increase in the coefficient $\kappa$ led to a forward displacement of the barrier. As a result, it was found that $\kappa = 9.1$. The calculated mass of run-back ice was $G = 1.1 \text{ g}$ and was close to that experimentally measured.

A similar procedure was carried out for a pair of runs at $V_{\infty} = 20 \text{ m/s}$. In the absence of crystals, the experiment was characterized by the values $T_{\infty} = -13.7^\circ \text{C}$, $T_s = 6.4^\circ \text{C}$, $L = 43 \text{ mm}$, $G = 4.2 \text{ g}$. The fitted values in the calculation were $\rho_{\text{pl}} = 9.1 \text{ g/m}^3$, $T_{\text{pl}} = 11.1^\circ \text{C}$, and $q_{\text{lo}}^+ = 0.07 \text{ W/cm}^2$. In the second experiment with crystals ($\text{IWC} = 5 \text{ g/m}^3$) $T_{\infty} = -13.6^\circ \text{C}$, $T_s = 3.8^\circ \text{C}$, $L = 32 \text{ mm}$, $G = 7.5 \text{ g}$ were measured.

When calculating the run-back ice with crystals in the flow in this case, even at $\kappa = 0$, the ice barrier shifted markedly forward and the calculated value of $L$ is less than the experimental one. A downward movement of the barrier can be achieved by increasing the temperature $T_{\text{pl}}$ while increasing the concentration $\rho_{\text{pi}}$, so that the temperature $T_s$ remains unchanged. In this case, the mass of ice deposits $G$ increases. It was found that $G = 5.2 \text{ g}$, $\rho_{\text{pi}} = 2.41 \text{ g/m}^3$. The calculated profiles of run-back ice are presented in figure 2.

![Figure 2](image_url)

Figure 2. The thickness of the ice layer on the model surface at $V_{\infty} = 80 \text{ m/s}$ (left) and $20 \text{ m/s}$ (right): curves 1 – without crystals, 2 – with crystals. The coordinate $s$ is calculated from the beginning of the flat section of the wing model.

Thus, the calculations showed that at a relatively high flow velocity, only a small fraction of the mass of crystals is introduced into the film, and its splashing is large. At low speeds, the film splashing practically disappears, and a significantly larger mass of crystals can penetrate the film. This can be
explained by its greater thickness. According to the calculation results, the thickness is on average 60 µm at \( V_\infty = 20 \text{ m/s} \) and 10 µm at 80 m/s in the front semi-cylindrical part of the model.

Note that with a large mass of crystal fragments that have invaded the, which occurs at low airflow velocities, the film flow should already be considered as a two-phase flow with melting ice particles, as in [9]. This will require complication of the theoretical model used in this work.

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References
[1] Villedieu P, Trontin P, Aouizerate G, Bansmer S, Vanacore P, Roisman I and Tropea C 2019 MUSIC-Haic: 3D multidisciplinary tools for the simulation of in-flight icing due to high altitude ice crystals (SAE Techn. Pap.) 2019-01-1962.
[2] Bucknell A, McGilvray M, Gillespie D, Jones G and Collier B 2019 A three-layer thermodynamic model for ice crystal accretion on warm surfaces: EMM-C (SAE Techn. Pap.) 2019-01-1963.
[3] Bartkus T P, Tsao J C, Struk P M 2019 Analysis of experimental ice accretion data and assessment of a thermodynamic model during ice crystal icing (SAE Techn. Pap.) 2019-01-1963.
[4] Nilamdeen S, Rao V S, Switchenko D, Selvanayagam J, Ozcer I and Baruzzi G S 2019 Numerical simulation of ice crystal accretion inside an engine core stator. (SAE Techn. Pap.) 2019-01-1963.
[5] Trontin P and Villedieu P 2018 Intern. J. Multiphase Flow 108 105.
[6] Norde E, van der Weide E T A and Hoeijmakers H W M 2018 AIAA J. 56 222.
[7] Kashevarov A V, Levchenko V S, Miller A B, Potapov Yu F and Stasenko A L 2018 Techn. Phys. 63 782.
[8] Kashevarov A V and Stasenko A L 2019 Thermophys. and Aeromech. 26 237.
[9] Kashevarov A V and Stasenko A L 2017 J. Appl. Mech. Techn. Phys. 58 275.