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EXPERIMENTAL INVESTIGATION, NUMERICAL AND MATHEMATICAL SIMULATION OF DISPERSE FLOWS IMPINGING ON AIRCRAFT SURFACE

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Abstract

Numerical algorithms of particles and droplets’ interaction with a nanostructured solid surface are developed using smoothed particles hydrodynamics and molecular dynamics methods, results of parametric investigation of particles’ interaction with liquid films are obtained. The experimental work was devoted to investigation of runback ice accretion on the airfoil model with electrically heated leading edge in fully glaciated and mixed icing conditions. The ice mass was obtained as a function of the flow parameters (temperature, velocity, IWC, LWC) and the surface temperature. These experimental and theoretical efforts concern the modelling of single drops and crystals as well as thermodynamics of fluid film moving along a profile and solidifying (runback ice accretion). Instead of widely exploited conception of the “instantaneous freezing down” of a high-speed droplet impingement upon a solid body surface, a new physico-mathematical model is suggested. This model is based on theoretical and experimental results which are obtained in previous studies.

Keywords: aircraft icing, icefobic coatings, supercooled droplets, nonspherical particles stochastic motion

1. General Introduction

Investigations of disperse flows interaction with solid surfaces is of great interest in a wide range of areas of human practice in particular in aircraft icing problem [1–5]. In a mathematical formulation of two-phase flow interaction with aircraft surface a principal question arises concerning macroscopic characteristics of impinging particles and substrate (heat capacity, elastic moduli, etc.). The matter is that numerical values of these characteristics may differ significantly during short impact time interval from those measured in quasistationary conditions. This fact was emphasized for example in [4] and taken in account in [6]. There are five physical problems of aircraft icing physics: first one is icing control via surfaces with special micro and nano relief configurations and material properties, the second is connected with supercolled droplets’ stability crystallization models when they impinge upon aircraft’s surface, third one is models of icing erosion and ablation in aerosol flow, forth one is connected with complex motion of nonspherical ice crystals and their impingement on aircraft surface which may be covered by liquid film, ice or have special properties, which are connected with flow and particles’ iteration, finally the fifth physical problem is rheology of liquid film which contains ice crystals after supercooled droplets’ crystallization and ice crystals’ impingement.

2. Supercooled droplets’ on aircraft surface simulation

The use of hydrophobic and ice-phobic coatings is of interest in the problems of counteracting icing of aircraft [1–3]. In present work, on the basis of the developed mathematical models of impact / rebound and sliding of supercooled drops on a hydrophobic surface, dimensionless parameters and characteristics of hydrophobic coatings are formulated. Such coverings work effectively at small values of the Weber numbers $\mathrm{We} = H\rho V^2/\sigma$ for droplets which interact with circumfluent body surface (H – period of roughness, ρ – droplets’ density, σ – surface tension, V – normal component of droplets’ impingement velocity).

However, in the case of dynamic action of a liquid, the ice-phobic properties may lead to the opposite effects due to penetration of liquid into cavities and solidification in them. The hydrophobic properties of coatings are determined by the contact angle θ and effective slip length tensor $\hat{\boldsymbol{b}}(\theta, \varphi, L)$, which is used for the following surface velocity slip condition: $\boldsymbol{V}_{\mathrm{Slip}} = \hat{\boldsymbol{b}}(\theta, L, \varphi)\dfrac{\partial \boldsymbol{U}}{\partial n}$; here $\boldsymbol{U}$

– gas velocity vector near the surface, n – normal direction, φ – the proportion of the wetted surface, L is the width of the cavity (Figure 1, left). Among with the parameters described above, anti-icing coatings should be characterized by the following restitution parameter, which takes into account the speed of collision of supercooled droplet:

$$a_s(\mathrm{We},\theta,\varphi,L)=\frac{2}{\pi}\int_0^{\pi/2}\sqrt{a_n^2(\mathrm{We},\theta,\varphi,L,\beta)+a_\tau^2(\mathrm{We},\theta,\varphi,L,\beta)}\,d\beta$$

and adhesion forces' tension which arise during the solidification of supercooled droplets. Here a_n and a_τ are the recovery coefficients of the normal and tangential velocity components, respectively, β is the angle of incidence. Another control parameter is the fraction of the initial droplet mass md that remains on the surface after its impact. In addition, if the normal component of the impact velocity of drops on the surface ($V^{\max}=V_\infty\exp(-1/4\mathrm{Stk})$ [7], here $\mathrm{Stk}_\infty=\frac{2}{9}\frac{\rho_l V_\infty a^2}{\mu_g R}$ – Stokes number) is less than the characteristic temperature-dependent value $V^{\max}<V_0^*(1-T/T_f)^{-7/10}$, the drops will remain in a liquid state and will move along the surface of the streamlined body without freezing. Here Stk is the Stokes number, V_∞ is the flight speed, V_0^* = 8.9 sm/s, and T_f is the freezing point. Fig. 1 on the right shows the dependence of the size of the of the streaky roughness of the surface of a hydrophobic body on the parameters of the aerosol flow in terms of the Weber and Stokes numbers. In present paper expressions are obtained for the forces acting on the droplets sliding over the surface, taking into account their rotation, and the criteria for the transition from the rolling mode to the sliding mode, depending on the integral moment of the aerodynamic forces in the boundary layer near the surface.

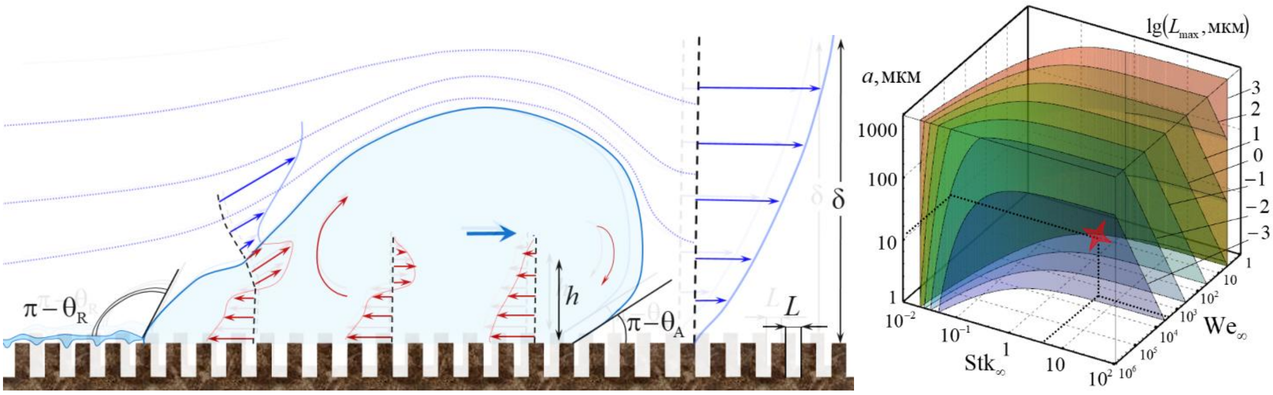

Figure 1 – On the left is the diagram of the droplet movement over the surface; on the right is the dependence of the maximum distance between the protrusions on the Weber and Stokes numbers and the radius of the drop a.

The results of calculations of the effect of droplet crushing on the icing of aircraft are presented, taking into account the hydrophobic properties of a solid. Upon impact, the droplet decreases in diameter according to the following expression [5]: $\kappa=\frac{d}{d_0}=8.72\exp[-0.0281K]$, $\kappa\in[0.05,1]$ – the ratio of the diameters after and before colliding with the surface, $K=\frac{\sqrt[5]{\mathrm{Oh}^2}}{\mathrm{We}_n}$ – Cossali parameter. Investigations of the effect of crushing of supercooled droplets upon impact on the surface of an aircraft with varying degrees of hydrophobicity have been carried out. $\mathrm{We}_n=\frac{\rho d\cdot V_n^2}{\sigma}$, $\mathrm{Oh}=\frac{\cdot\mu}{\sqrt{\rho\sigma d}}$ – Weber's number calculated from the normal component of the impact velocity, Oh is the Ohnesorge number, μ is the viscosity of the liquid.

Maximum normal component of droplet impingement speed $V_{in}^{\max}$ is connected with Stokes number as was mentioned above, R – characteristic size of a circumfluent body's front part. Thus using droplet atomization criterion [8] one get $\kappa=2.84\sqrt{\mathrm{We}/\mathrm{Re}}=2.84\sqrt{\mathrm{Ca}}$ the following criterion for atomization taking in account droplets' inertia in terms of Stokes number:

$$\kappa_{\max} = 2.84\sqrt{\frac{\mu V_n^{\max}}{\sigma}} \cong \frac{17}{6}\sqrt{\frac{\mu V_\infty}{\sigma}\sqrt[8\mathrm{Stk}_\infty]{e}}\,.$$

Here $K_{\mathrm{W}} = \mathrm{K}\cdot\mathrm{e}^{0.859}\left(\frac{\rho_l}{\mathrm{LWC}}\right)^{0.125}$ – Cossali's parameter which was modified by Wright [8]. Here ρ_l – water density, LWC – liquid water content. After surface impingement, droplets atomize when $\psi = \frac{K_{\mathrm{W}}}{(\sin\beta)^{1.25}} \geq 200$ [9], and splashing mass could be defined from the following equation $\frac{m_{\mathrm{Splash}}}{m_0} \cong 0.7(1-\sin\beta)\left[1-e^{0.092026(\psi-200)}\right]$. Another Droplets' atomization Criterion is as follows: $\frac{P}{\tau_{\mathrm{ST}}}\sqrt{\gamma\mu_m}\,p\sqrt{\frac{2aV}{4R_0T}}\frac{\sqrt{\eta}}{\sigma} > S_{Critical} \cong 0.45$ – one may use this equation to predict splashing threshold taking in account impingement velocity' dependence on Stokes number; $\tau_{\mathrm{ST}} = \sigma/\sqrt{\eta t}$ – the stress which is cased by the surface tension, η – kinematic viscosity of liquid.

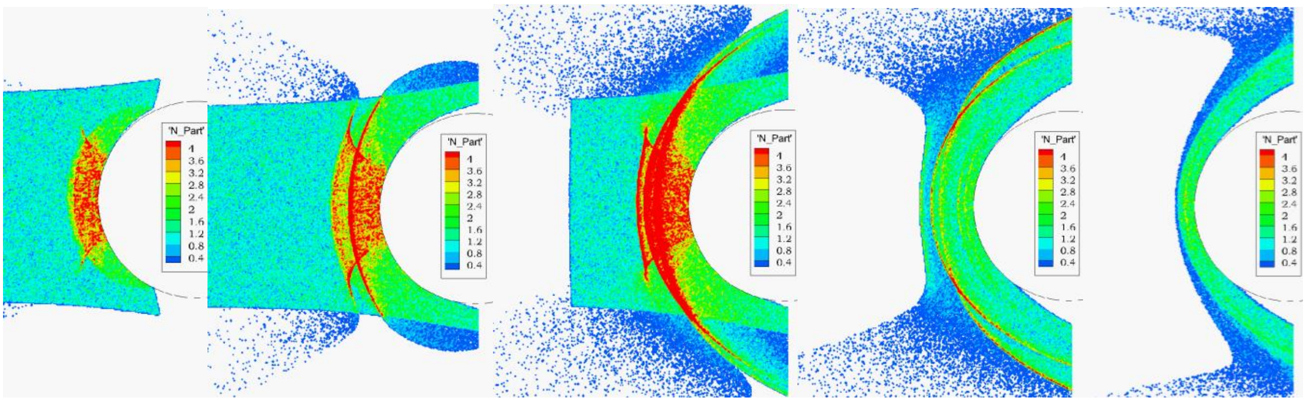

Figure 2 – Numerical concentration of droplets distribution in aerosol flow near the cylinder using splashing model [9]. The concentration values are referred to the concentration of the undisturbed flow. Initial droplet size 30 mcm, unperturbed flow velocity 6 m/s, temperature does not change and is equal to 0 o C, atmospheric pressure; the radius of the cylinder used to simulate the leading edge (characteristic size is 12.5 mm) of the wing model in the TsAGI air-cooling wind tunnel [2,10].

3. Nonspherical ice crystals' simulation

Influence of crystals' shape on disperse flow interaction with solid body was taken in account. The complexity of mathematical modelling of non-spherical shape ice crystals' dynamics led to the construction of original approaches in mathematical and numerical modelling of corresponding processes. Different types of particles' stochastic motion mechanisms are simulated and compared. A system of equations for the motion of a gas of non-spherical bodies and particles of natural origin in gradient media is constructed, taking into account their scattering due to nonspherical shape. Dimensionless control parameters characterizing the physical features of such flows are determined. Experimental data on spheroid particles' scattering are obtained. The results of the influence of the shape of particles on the features of their movement and interaction with a streamlined body in gradient flows are presented in terms of dimensionless control parameters. Methods of pressure, temperature and density parameters determination are developed in order to improve precision and amount of information from experimental investigations; influence of particles' parameters including shape factor on carrying gas parameters' determination is taken in account.

For each type of physical mechanism, stochastics diffusion coefficients are calculated and inserted into the last formula. At each time step, random numbers are generated and additional movement speed caused by stochastics is added. Another way to calculate stochastic motion of particles is to use characteristic velocities for each type of particles' stochastic motion:

$$\mathbf{V}_p = \mathbf{V}_p^{\mathbf{0}} + \frac{|\mathbf{V}'|}{\sqrt{1+t/\tau_R}} \cdot \mathbf{\Xi}_{\mathbf{Turb}} + \sqrt{\frac{8\mathrm{k_B}T}{\pi m_1 N}} \cdot \mathbf{\Xi}_{\mathbf{Br}} + V_{\mathrm{NS}} \cdot \mathbf{\Xi}_{\mathbf{NS}} + V_{\mathrm{BIO}} \cdot \mathbf{\Xi}_{\mathbf{BIO}} + V_{\mathrm{EM}} \cdot \mathbf{\Xi}_{\mathbf{EM}}$$

Orientational force F_χ which acts on particle could be described by the following equation: $F_\chi(\mathrm{Re}, E) = 3\pi \frac{\mu^2}{\rho} \mathrm{Re}_p \left| 1 - \frac{1}{E^{1/3}} \sqrt{\frac{E^2+4E+5}{10}} \right|$ for small Reynolds number (Re << 1), which is based on the difference between particles' and gas velocity. Equation for nonspherical particles' stochastic and deterministic motion is the following:

$$m_p \frac{\mathrm{d}\boldsymbol{V}_p}{\mathrm{d}t} = \sum \boldsymbol{F}_{\mathbf{Det}} - \Gamma_{\mathrm{NS}} \boldsymbol{V}_p + \delta(t) \mathbf{\Xi}_\chi F_\chi \cdot \xi_\chi .$$

Research has been carried out using the equations of stochastic dynamics of non-spherical particles, modified equations of the dynamics of a continuous medium for two-phase media containing non-spherical particles of complex shape, modeling the dynamics of a set of individual non-spherical particles in three-dimensional flows.

Table 1 – Mechanisms of stochastic motion of bodies of nonuniform medias

№	Stochastic mechanism	Scattering coefficient	'Friction' coefficient Γ	Characteristic speed
1	Brownian motion	$\frac{\mathrm{k_B}T}{\mu a_p}$	$\frac{\pi}{\mu}\sqrt{\frac{\mathrm{k_B}T\rho_p a_p}{6}}$	$\sqrt{\frac{8\mathrm{k_B}T}{\pi m_1 N}}$
2	Turbulent pulsations	$\frac{0.19k^2}{\varepsilon}$	–	$\frac{|\mathbf{V}'|}{\sqrt{1+t/\tau_R}}$.
3	Nonuniform distribution of flow parameters	$\sqrt{\frac{\delta\rho}{\rho_p}\frac{\pi a^2}{2}C_D(\mathrm{Re},\mathrm{M})V_0^2}$	$\sqrt{\left(\frac{\pi}{18}\right)^{1/3}\frac{1}{4}\delta\rho C_D \pi a^2 V_0}$	$\left(\frac{F_\chi S_\chi}{m_p}\right)^{1/3} = V_0\sqrt{\frac{\delta\rho}{\rho_p}C_D(\mathrm{Re},\mathrm{M})\left[\frac{9\pi}{128}\right]^{1/6}}$
4	Nonspherical shape	$\sqrt{\frac{F_\chi}{\rho_p}} = \frac{\mu\sqrt{3\pi\,\mathrm{Re}_p\,\varphi}}{\sqrt{\rho\rho_p}}$	$(48\pi^5)^{1/6} a_p \mu \sqrt{\frac{\rho_p}{\rho}\mathrm{Re}_p\,\varphi}$	$\left(\frac{F_\chi S_\chi}{m_p}\right)^{1/3} = \mathrm{Re}_\infty \frac{LV_\infty}{a_p}\sqrt{\frac{\rho}{\rho_p}}\sqrt{\mathrm{Re}_p\,\varphi}\left(\frac{243}{16}\pi\right)^{1/6}$
5	Elemagnetic field fluctuations	$\sqrt{\delta F/\rho_p}$	$\frac{F_\chi}{V_\chi} = \frac{a_p\sqrt{\rho_p \delta F}}{\sqrt[3]{3/4\pi}}$	$\left(\frac{\delta FS}{m_p}\right)^{1/3} = \frac{\sqrt[3]{3/4\pi}}{a_p}\sqrt{\frac{\delta F}{\rho_p}}$
6	Fluctuations of decisions of living organisms	$\sqrt{\frac{F_{\mathrm{Drag}}\psi}{\rho_p}}$	$\approx 6\pi\mu a_p$	$\frac{\sqrt[3]{3/4\pi}}{a_p}\sqrt{\frac{F_{\mathrm{Drag}}\psi}{\rho_p}}$
7	Errors of collisions' models	–	$\approx 6\pi\mu a_p$	$\sqrt{\delta a_n^2 + \delta a_\tau^2}V_0$

4. Practical recommendations for aircraft icing simulation

Based on recent investigations, following peculiarities should be taken in account in icing simulations.

I. For crystallization initiation, specific kinetic energy should be higher than $L_b(T)$:

$$L_b(T) = L_b^0 \left(1 - \frac{T}{T_f}\right)^{-7/5}$$

Here $L_b^0 \cong 4 \cdot 10^{-3}$ J/kg, T – temperature which is below zero, T_f – freezing temperature. This result was obtained empirically and interpolated in [4].

II. The expression for the crystallization front velocity of supercooled water has the form:

$$u = \psi(T_f - T)^2,$$

here $\psi = (3.75 \pm 0.4) \cdot 10^{-3}$ m/(s·K^2);

III. Supercooled water turns into a mixture of liquid with crystals, the mass fraction of which is determined by the expression:

$$\alpha_m(T) \cong \varsigma\sqrt{1-\frac{T}{T_f}}$$, here $\varsigma = (1.98 \pm 0.50)\,^\circ\,\mathrm{K}^{-1/2}$ [4];

IV. The distance *L* between the protrusions should not exceed $L_{\max}$. *R* – radius of curvature of the leading edge of the wing. Droplet diameter $D >> L$.

$$\frac{L_{\max}}{D} = 2\frac{\sqrt[4\mathrm{Stk}]{e}}{\mathrm{We}_\infty},$$

where $\mathrm{Stk} = \frac{2}{9}\frac{\rho_l V_\infty a^2}{\mu_g R}$, $\mathrm{We}_\infty = \frac{D\rho_l V_\infty^2}{\sigma_l}$.

V. Expressions for the forces which act on moving droplets

$$m_d\frac{\mathrm{d}V_d}{\mathrm{d}t} = m_d\,g\sin\alpha - \frac{1}{2}\xi_\sigma\,\pi b\sigma_l\,(1+\cos\theta) + C_g\left(\mathrm{Re},\frac{\delta^{**}}{a}\right)\cdot\mu\frac{h}{2}(V-V_d) - F_\omega + \psi\frac{\mathrm{d}m_d}{\mathrm{d}t}V_d$$

In the right part of this equation first term is gravitational force, the second one is retarding force which is caused by surface energy, third one describes droplet's interaction with surrounding flowm the last but one is retarding force which is due to liquid rotation inside droplet ($F^\omega = k_\omega m_d\varsigma^3\sqrt{\frac{8}{\mathrm{Re}^3}}\frac{\mathrm{d}V_d}{\mathrm{d}t}$ $k_\omega = \varsigma^3\sqrt{8} \cong 0.24$)and the last one describes the loss of momentum when droplet moves along surface.

VI. Expression for the heat flux at the interface during crystallization is as follows:

$$q = \rho_l u\big(C(T_f - T) - L\alpha_m\big).$$

This equation was obtained theoretically [6] taking in account previously obtained experimental results [4].

VII. In order to prevent aircraft icing in aerosol cloud with supercooled droplets using icefobic coatings' following physical consideration should be as follows:

1. Contact angle θ is usually measured to characterize hydrophobic properties at low Weber number – when droplets' velocity is not enough to penetrate inside micro and nanorelief. It depends on surface structure in terms of *f* (part of the projection of the wetted area onto the substrate surface, taking into account the partial filling of the pores) and *r* (roughness factor – which equals ratio of projection of surface to the plane which is parallel to the surfaces to surface area) and surface energy and other properties of materials in terms of contact angle of a droplet on flat surface θ_0. Expression for contact angle dependence on surface properties and material is as follows:

$$\cos\theta = f\left(r\cdot\cos\theta_0 + 1\right) - 1;$$

2. Slipping length *b* (which is tensor in general case)

$$u_{\mathrm{slip}} = b\partial V_z/\partial z;$$

3. Droplets' velocity recovery coefficient depend on Weber number We and should be averaged as follows to it's dependence on angle of impingement β:

$$a(\mathrm{We}) = \frac{2}{\pi}\int_0^{\pi/2}\sqrt{a_n^2(\mathrm{We},\beta) + a_\tau^2(\mathrm{We},\beta)}\,\mathrm{d}\beta;$$

4. Mass recovery coefficient when droplet impinges at surface takes in account droplets' restitution coefficients when they interact with hydrophobic surface:

$$\varepsilon = m_d / m_d^0$$

– ratio of droplet's mass after and before the collision;

5. Maximum size between protrusions of structured surface depends on Weber and Stokes number describes regimes which are similar to Wenzel and Cassi-Baxter regimes of droplet behavior when it impinges upon hydrophobic surface:

$$\frac{L_{\max}}{D} = 2\frac{\sqrt[4\mathrm{Stk}]{e}}{\mathrm{We}_{\infty}};$$

6. The effect of coatings is temperature dependent:

$$V_0^*\left(1 - T/T_f\right)^{-7/10} < V_{\infty}\exp\left(-1/4\mathrm{Stk}_{\infty}\right).$$

Critical impingement speed when droplet begins to crystallize should be higher than a value which depends on droplet's temperature and Stokes number.

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6. Copyright Statement

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References

[1] Roisman I and Tropea C Impact of a crushing ice particle onto a dry solid wall. *Proc. Roy Soc. A.* 215 Vol. 471, No. 20150525, 2015.

[2] Kashevarov A, Levchenko V, Miller A, Potapov Yu and Stasenko A On the hydrothermodynamics of the icing of a wing profile in the air-crystalline flow. *Tech. Physics*, Vol. 03, No. 6, pp 782–788, 2018.

[3] Kashevarov A and Stasenko A Modeling of ice accretion on the aircraft surface in an air flow containing ice particles. *J. Appl. Mechanics and Technical Physics*, Vol. 59. No. 4, pp 645–652, 2018.

[4] Amelyushkin I and Stasenko A Interaction of supercooled droplets and nonspherical ice crystals with a solid body in a mixed cloud // *CEAS Aeronautics Journal*, Vol. 9, No. 4, pp 711–720, 2018.

[5] Amelyushkin I, Stasenko A and Zhbanov V Experimental investigation, mathematical and numerical simulation of aircraft icing phenomena. *Proceedings from the 31th Congress of the International Council of the Aeronautical Sciences ICAS-2018 9th–14th September 2018. Belo-Horizonte, Brazil*, Paper number ICAS2018_0741, pp 1–9, 2018.

[6] Amelyushkin I, Kudrov M, Morozov A, Shcheglov A and Stasenko A Models of processes accompanying crystallization of supercooled droplets. *Trudy ISP RAN/Proc. ISP RAS*, Vol. 1, No. 2, pp 15–21, 2020.

[7] Amelyushkin I, Miller A and Stasenko A Estimation of the period of roughness of anti-icing coatings of the body in an air stream with supercooled drops // *Bulletin of the Moscow State Regional University*. Series: Physics and Mathematics. DOI: 10.18384/2310-7251-2021-1-54-63, No. 1. pp 54–63, 2021.

[8] Liu J, Vu H, Yoon S, Jepsen R and Aguilar G Splashing phenomena during liquid droplet impact // Atomization and sprays. Vol. 20, No. 4, pp 297–310, 2010.

[9] Bilodeau D, Habashi W and Fossati M An Eulerian re-impingement model of splashing and bouncing supercooled large droplets // Conference DOI: 10.2514/6.2013-3058. pp 1–14, 2013

[10] Kashevarov A, Miller A, Potapov Yu, Stasenko A and Zhbanov V Droplet dynamics on a body surface in a gas flow. *High Temperature*, Vol. 57, No. 2, pp 222–227, 2019.

[11] Xie J, Xu J, Shang W and Kai Zhang Mode selection between sliding and rolling for droplet on inclined surface: Effect of surface wettability // *Int. J. Heat and Mass Transfer*. Vol. 122, pp 45–58, 2018.