ФИЗИКО-МАТЕМАТИЧЕСКИЕ И ТЕХНИЧЕСКИЕ НАУКИ

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CONDITIONS FOR THE OCCURRENCE OF ICING ON AERODYNAMIC PROFILES AND METHODS OF THEIR CALCULATION

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Abstract. *This article analyzes the methods and models suitable for studying the icing of the aerodynamic surface (wing). Systems to counteract the unifying effect are considered. Methods and models for calculating ice formations on aerodynamic surfaces are studied. Further study of the effect of icing will be conducted in the light of the characteristics of flow around bodies of viscous compressible medium in terms of load and liquid phase in case of changes in the geometric parameters of the bodies and reflect this change in the external stream.*

Keywords: *icing conditions, flows near the aerodynamic surface, moisture on the streamlined surface, formation of frost or ice, aerodynamic surfaces.*

АЭРОДИНАМИКАЛЫҚ БЕЙІНДЕ МҰЗДАНУДЫҢ ПАЙДА БОЛУ ШАРТТАРЫ ЖӘНЕ ОЛАРДЫ ЕСЕПТЕУ ӘДІСТЕМЕСІ

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Аңдатпа. *Бұл мақалада аэродинамикалық беттің (Қанаттың) мұздануын зерттеуге сәйкес келетін әдістер мен модельдерге талдау жасалған. Бірлескен әсерге қарсы тұру жүйелері айқындалған. Аэродинамикалық беттерде мұздың пайда болуын есептеу әдістері зерттелді және модельдері қарастырылды. Мұзданудың әсерін зерттеу үшін одан әрі бағыт денелердің геометриялық параметрлері өзгерген жағдайда және осы өзгерісті сыртқы ағынға есепке алып, тасымалдаушы және сұйық фазаны ескере отырып, тұтқыр сығылатын орта арқылы денелердің ағу ерекшеліктері де ескеріле жүргізіледі.*

Түйінді сөздер: *мұздану шарттары, аэродинамикалық беттің жанындағы ағындар, сүйір бетіндегі ылғал, аяздың немесе мұздың пайда болуы, аэродинамикалық беттер, мұздану режимдері, NACA профилі.*

УСЛОВИЯ ВОЗНИКНОВЕНИЯ ОБЛЕДЕНЕНИЙ НА АЭРОДИНАМИЧЕСКИХ ПРОФИЛЯХ И МЕТОДИКИ ИХ РАСЧЕТА

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Аннотация. *В данной статье произведен анализ методов и моделей, подходящих для исследования обледенения аэродинамической поверхности (крыла). Рассмотрены системы по противодействию обледенительному эффекту. Изучены методики и рассмотрены модели расчета образований льда на аэродинамических поверхностях. Дальнейшее направление для изучения эффекта обледенения будет* *проведено при учете особенности обтекания тел вязкой сжимаемой средой с учетом несущей и жидкой фазы, в случае изменения геометрических параметров тел и учета этого изменения на внешний поток.*

Ключевые слова: *условия обледенения, потоки около аэродинамической поверхности, влага на обтекаемой поверхности, образование изморози или льда аэродинамических поверхностей.*

Introduction

To find solutions to complex problems fluid and gas mechanics became possible thanks to a leap in the development

Computer and numerical methods, computational aerodynamics, which is why the possibilities of mathematical modeling have expanded. It became possible to simulate the process of fouling the aerodynamic surface with frost, frost and ice. Icing of the aerodynamic surfaces of machines and aggregates is a very dangerous effect, both for human safety and for the resource of mechanisms.

Icing occurs due to the presence of water droplets that are in a supercooled state, which get on the" cutting " edge of the continuous medium, freezes, gradually changing the shape of the streamlined surface, as a result of which the characteristics of the aerodynamic surface change.

The temperature of the continuous medium, the speed of movement of the masses of the continuous medium relative to the aerodynamic surface, pressure, diameter of supercooled droplets, water content – are parameters that affect icing.

Due to the presence of small particles of both dust and ice on the aerodynamic surface, the effect of crystallization of the supercooled liquid occurs.

At the present stage of development of science, there are already mathematical models of aerodynamic profile icing in which the technique is reduced to the following stages: determining the geometry of the wing, searching for a potential solution for the flow, calculating the boundary layer, determining the trajectories of drops, the equation of the thermal balance of mass conservation and changes in the geometric shape after icing.

Icing has a serious impact on flight safety, causing several dozen deaths a year. Icing also presents detrimental effects on mechanisms, increasing their wear and tear or rendering them completely unusable. The danger of icing increases if there are reservoirs and mountains in the area.

Therefore, the study of this effect in adverse weather conditions is of interest. The process of steam condensation with subsequent ice formation is one of the main stages in the development of an anti-icing system. There are a number of undesirable effects, such as a decrease in the lifting force of the wing, an increase in the load on the elements, and a loss of efficiency. There is a complete change in aerodynamic properties, a decrease in the flow stall angle, an increase in the turbulent wake, and an increase in mass. The ice crust can collapse under the influence of vibrations or aerodynamic forces, causing damage to the machine unit.

The main meteorological parameters during the icing

The formation of ice on aerodynamic surfaces occurs mainly when the surface is flowed by a medium that contains water droplets at negative ambient temperatures. The parameters that determine the rate of ice formation on surfaces are: water content, water droplet size and air temperature. Despite the fact that the water content can be very different in two relatively close regions of the continuous medium, it is customary to operate with the average values obtained at relatively large distances (several km). The water content decreases as the temperature decreases[1].

It should also be taken into account that the formation of ice occurs in places with sharp body geometry at a much higher rate than in flat places. All this is due to the fact that the air velocity in the vicinity of sharp and straight areas is lower, and the pressure is higher, which leads to an increase in temperature. The boundary layer in the vicinity of sharp parts is thinner.

Types of ice and its influence aerodynamic characteristics

The formation of ice under icing conditions, which solidifies firmly on surfaces, is classified as glassy, smooth, loose, mixed[2].

Vitreous-occurs in the event of rain, at temperatures near sub-zero, when drops freeze when they touch a cold surface. The gradual freezing of the drop is a consequence of the release of latent heat of the phase transition, so part of the drop has time to spread over the surface, resulting in layers of solid glassy ice with a high density. Such layered formations as a consequence change the shape of the aerodynamic profile.

Loose ice-is a consequence of the contact of drops with a surface with a temperature significantly below the temperature of zero degrees. The formation is formed from tiny ice particles, a weak structure with pores. Loose ice has a lower mass and density compared to glassy ice formation. It is formed in temperatures from -5 to -15 degrees Celsius.

The formation of a combination of vitreous and loose ice is called mixed ice. Glass is formed from large drops, while small ones form loose ice.

In the case of water vapor, it turns into ice before condensing, settling frost on the surface. The process occurs when the medium flowing around the airfoil changes its temperature upwards. Hoarfrost changes the thickness of the boundary layer causing earlier turbulent flows near the aerodynamic surface.

Based on the above information, we get the assumption that droplets are in the supercooled state temperature equivalent to the ambient continuum, striking the surface aerodynamic when considering the degree of supercooling of droplets and conditions flow profile influence their behavior after contact.

This model is based on when the solidification of droplets occurs in the proportions depending on the frozen fraction of the droplet, namely, the amount of latent heat of the phase transition released, which is absorbed by the environment. During icing, irregularities and roughness are formed, which affect the development of the boundary layer, changing the coefficient of heat exchange with the environment.

Different types of ice cause different types of icing wet, dry, liquid.

Wet-mode characterized by a temperature equivalent to the solidification temperature of water. Solidification occurs in the range of the coefficient from 0 to 1[3].

Water droplets in the supercooled state combine on the surface, turning into rivulets. The film is the case when the liquid is sufficient to cause the pooling of all the streams.

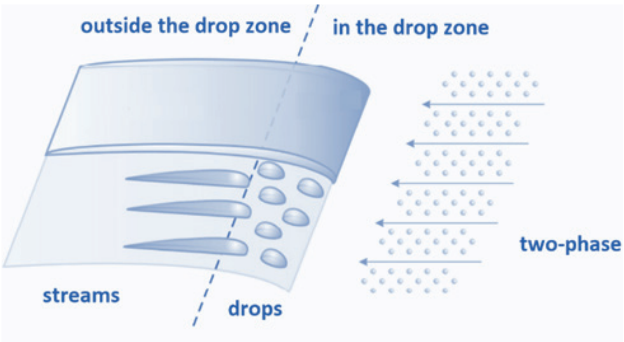

Figure 1 – Surface water condition of streamlined body

In wet icing, the frozen water fraction is zero. The liquid is found in the form of drops, films, or rivulets. Occurs when the surface has a temperature above zero degrees Celsius.

In the case of dry icing, the surface temperature is below zero degrees and the liquid freezes on the surface. The supercooled droplets hit the surface and form ice before spreading out.

Classification of de-icing systems

The choice of system depends on the type and method of application of the aerodynamic profile. Mathematical modeling of ice formation makes it possible to estimate the probability of icing in various conditions[4]. There are the following types that prevent the formation of ice on aerodynamic surfaces:

Thermal-air

They are widely used in machines with gas turbine engine units. Warm air is taken from the GTE compressor and directed to the places most susceptible to ice formation (blades, front part of the wing, fairings, etc.).

Electro-thermal

Vulnerable parts of the airfoil are equipped with special "thermal plates". The system requires high energy costs and is used on relatively small surfaces.

Liquid

It is based on alcohol, glycol. Used for both removal and prevention of ice formation. Limited by the amount of fluid reserve due to the design of the nozzles prone to clogging.

Pneumatic

In the case of an aerodynamic surface, it is a rubber "cushion" that deforms in the event of signs of icing. Ice formation occurs in small portions, then ice is dumped.

Methods for calculating ice formation

Mathematical models describing the formation of ice on aerodynamic surfaces were developed, allowing to assess the impact of formations on aerodynamic characteristics:

In 1951, two modes of icing were established: dry and wet, and the dependence of the intensity of formation on temperature, speed, and water content was demonstrated. The Ludlam border separates the dry and wet modes. Then the formation in the dry mode occurs under the condition of water content below the boundary and the temperature of the aerodynamic profile below the solidification temperature of the water. In wet mode, the profile temperature is equivalent to the water solidification temperature, and excess water is blown off the profile.

In 1952, it was found that a certain amount of water can be "locked" in the ice, thus forming spongy ice.[5]

In 1979, a thermodynamic model of icing on a stationary surface, on which supercooled water droplets fall, was determined. On the basis of the energy equation, a numerical model of ice formation was given, which can be used to judge changes in aerodynamic parameters. The model included the combination of two modes of dry and wet, thermal conductivity and convection of the boundary layer, water flow over the streamlined surface; thermal conductivity and convection inside the boundary layer; latent heat of evaporation, condensation of moisture and sublimation; thermal conductivity of ice and cylinder; aerodynamic heating caused by adiabatic compression of air in the boundary layer and kinetic energy of supercooled droplets falling on the cylinder. The result was compared with experimental data obtained by Stallabrass in 1957 and Macklin in 1961.

In 1980 to the present time, the development and improvement of models has been continuous. Developed 2-dimensional models of ice formation on aerodynamic models in different modes: LEWIS 2D, Wright; ONERA, Gent; TRAJICE2D, Guffond; 2DFOIL-ICE, Dillingh.

Based on one of these models, models of ice formation in 3-dimensional form were developed: FENSAP-ICE 3D, MCGILL University, CANADA[6];

Recent improvements to numerical simulation software products include:

- calculation of the aerodynamic flow based on the shield method in two-dimensional formulation

or on the Navier-Stokes equations in two- and three-dimensional formulations;

- analysis of the trajectories of supercooled droplets, allowing to determine the coefficient of capture of falling moisture on complex geometric shapes, which are usually based on the Lagrange method or on the Euler method;
- calculation of the boundary layer, taking into account the surface roughness caused by the presence of ice crust, when calculating the heat transfer coefficient;
- determination of the thermodynamics of solidification, which allows us to calculate the rate of ice build-up;
- a geometric module that describes the movement of the ice boundary, based on the trajectories of water droplets in dry mode or by the method based on the determination of the normal to the surface, in dry and wet modes [7],
- time sampling, to improve the description of the geometry and increase the accuracy of calculating

local heat and mass transfer coefficients.

The main differences between the programs, not including FENSAP-ICE, are in the calculation of aero-dynamic flow and evolution over time. Programs based on the shield method for calculating the potential flow can not determine the points of separation of the flow, so they give less accurate results compared to programs basedon the Navier - Stokes equations, but they allow you to get a solution much faster[8].

Most models take into account only the flow of water in the form of a film, based on the model developed by Al-Khalil and others. This assumption does not consider that water can be on the surface in various states determined by the action of aerodynamic, gravitational forces, as well as surface tension.

In the program LEWICE takes into account surface tension, which allows you to estimate the amount of water, which remains locked on the surface, based on the Weber number. Such parameters as surface roughness, ice density, residual amount of liquid water, as well as the processes of water droplets escaping outwards and water flowing down along the streamlined surface are currently insufficiently studied and they are taken into account using empirical relations[9].

In particular, Ruff, Shin and Bond were obtained relations for estimating surface roughness, Olsen and Walke for describing the processes of pulling out and spraying droplets, and Jones for determining the density of ice. These ratios were obtained for the icing conditions of the wings and other parts of the fuselage of the aircraft, but they are not very applicable to the blades of aircraft engines in accordance with the operating conditions (speed, altitude, angle of attack) and meteorological conditions (water content and average volume diameter of water droplets), which are very different[10]. Recent studies have also made it possible to better study the roughness of the ice surface and the physics of the liquid phase:

- the paper studies the measure and distribution of roughness on the ice surface, and shows that the empirical ratio is not adequate when the surface is covered with a film of water;
- studies allow us to analytically describe the formation and movement of film and rivulets on the surface;
- the paper shows that surface tension is the main factor affecting the formation of droplets on the wing surface;
- the behavior of the liquid phase on the wing surface is better studied.

These works allow us to use a thermodynamic model in which the liquid phase and roughness are defined using physical parameters, rather than empirical relations.

Conclusion

Methods for studying the formation of icing of aerodynamic surfaces are analyzed, meteorological parameters, types of icing and effects on aerodynamic surfaces are described. Classifications of anti-icing systems are given. The next step in the study of the effect of icing is modeling considering the interactions of the carriers and liquid phases, forms of existence of the liquid on the aerodynamic profile at a certain mode of ice formation, determination of the impact of the change on the aerodynamic parameters, taking into account the effects of geometry changes in the motion of a continuous medium.

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