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Research Article

THE ISSUE OF ICING IN AVIATION. STUDY WITH THE USE OF NUMERICAL SIMULATION

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ABSTRACT
Although it has been over 100 years since Wright brothers' first flight, icing has not been entirely investigated yet. The article is divided into 4 parts. The first one introduces the receiver of meteorological aspect of icing. Second part is devoted to physics aspect of ice accretion. The third and fourth parts describe icing with mathematical models and present a numerical simulation. We have completed our presentation with the results of numerical simulation.

Key words: icing, numerical simulation, ice accretion, meteorological aspect of icing, physics of icing.

INTRODUCTION

Icing is a process of creating an ice layer on a surface (e.g. of an aircraft). It can result in a change of aerodynamic characteristics of aerodyne or, worse, in a damage of the engine. The most exposed parts to icing are: leading edges of wings and stabilizers, engine inlets, leading edges of propeller blades and rotors. Other parts include: outer antenna, windshield or struts [8, 9].

It is generally accepted that aircrafts which move faster than 1000 km/h (540 kts) are practically resistant to icing due to frictional heat.

Considering causes of icing the following aspect are discussed: direct sedimentation of ice crystals or snow, freezing of supercooled water droplets when they hit the aircraft surface and water vapor sublimation on the aircraft surface [7].

Classification of icing, which is the most obvious and important for aviation study, is due to the shape of ice, therefore we can encounter [3]:

- Ice with a shape of a profile. It appears when the temperature is below -20 °C and the cloud is not very watery. When droplets hit the airplane, they freeze immediately and they do not change the shape of the airfoil (Figure 1). With small droplets ice accretion appears in the vicinity of the leading edge. With bigger ones the range of icing will grow. It's the most dangerous kind of ice accretion.
- Ice with a shape of a block. This type of icing forms in the temperature about -5 °C or lower when the cloud is very watery and an aircraft is moving at low speed. The droplets hitting the leading edge do not freeze, therefore, they are blown further where they do freeze (Fig. 2). It is less dangerous type of icing because vibration on flying airplane shatter the ice which in consequence falls off.
- Hoarfrost. It is possible to encounter it when the cloud has a small rate of aquosity or through sublimation of water vapor when the sky is cloudless. When an aircraft descends rapidly descending from high altitude (the surface of the airplane is colder than outside air temperature), the situation is perfect for creation of hoarfrost.

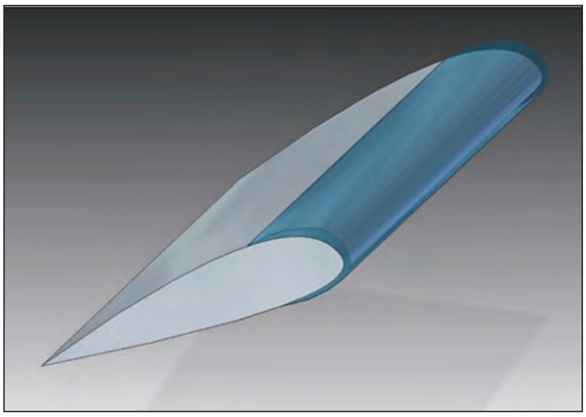

Fig. 1. Ice with a shape of the profile

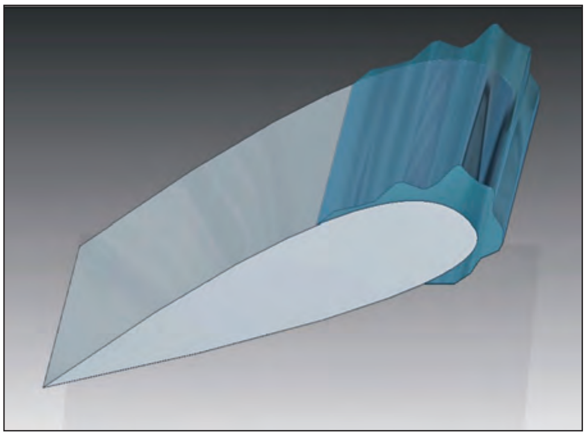

Fig. 2. Ice with a shape of a block

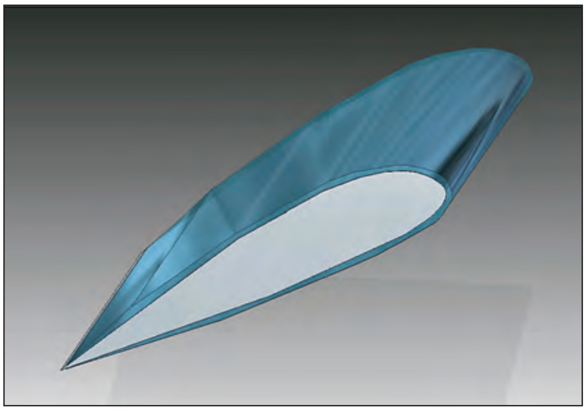

Fig. 3. Hoarfrost

The thickness of ice layer is normally slight and it does not change aerodynamic properties significantly, however, it remains dangerous due to the reduction of visibility from the cockpit (Fig. 3).

The speed of ice accretion provides other classification [4]:

- Trace – intensity of ice accretion is slightly bigger than rate of loss due to sublimation.
- Light – speed of ice accretion does not exceed 0.5 mm/min. It is assumed that this type of icing poses danger to flights in icing environment exceeding 1 hour.
- Moderate – the velocity is between 0.5 – 1 mm/min. With that rate of accretion it affects also flight of short duration.
- Severe – with intensity between 1 – 2 mm/min de-icing systems are not efficient enough.

It is relevant that preceding division is approximate, therefore, moderate conditions of icing for one aircraft could be severe for another.

According to ice structure we can name [2, 4]:

- Clear ice (glaze ice) – it occurs in the temperature of -20 °C – 0 °C, in watery clouds, from droplets which freeze at the moment when they hit the surface. It is quite dense and hard, therefore, it is very difficult to remove.
- Rime ice – the temperature for this type of icing is below -10 °C, in clouds formed by ice crystals or supercooled droplets with a diameter of 0.5 mm. Rime ice's most common characteristics are crystal structure, roughness of surface and lower density than clear ice due to content of air bubbles.
- Mixed ice – it is a combination of two above types of icing. It occurs in cumulus clouds (especially Cb clouds), where it is easy to find strong mixing of small and large water drops in the temperature of about -10,0 °C. It is also possible to encounter in Ns clouds.
- Hoarfrost – it is homogeneous layer on the aircraft's surface. Besides increase in drag, it causes reduction in visibility.

Icing is so hazardous because of consequences which it has in aviation. Among numerous effects the following should be emphasized [10, 13]:

- Ice accretion on leading edges of an aircraft disturbs the aerodynamic shape of wing. It results in reduction in lift, increase in drag, weight, stall speed or fuel consumption, which is the worst from the point of view of ergonomics.
- In conditions of severe icing the rate of ice accretion may amount to 1.25 cm/min. That would result in the loss of stability due to irregular distribution of weight. Furthermore, ice on the propeller may cause engine vibration. The moment it falls off it might damage the skin of the aircraft.
- As a result of icing it is possible to clog pressure sources (alike static and total inputs). Obviously, this would have an impact on instruments' readings (airspeed indicator, altimeter and vertical speed indicator).

- Deposition of ice causes (as mentioned) limitation in visibility from cockpit or precludes retraction of the undercarriage.

PHYSICS OF THE PHENOMENA

Considering icing from the physical perspective is an extremely complicated task due to multiplicity of processes which occur in the ice zone. Furthermore, there are phenomena with juxtapose the qualities of great power [5, 11, 12]. However, 3 basic conditions for ice creation can be named:

- water presence in the atmosphere;
- transport of water to the profile i.e. aircraft movement, fluid movement around the airfoil or diffusion;
- dissipation of heat leading to water freezing.

Basic processes seem to be obvious, but fragmentary issues are far more complex. Fragmentary issues include:

- Deflection of air stream induced by airfoil movement towards surrounding air;
- Water uptake by profile;
- Undercooling of water droplets in liquid state. Small water droplets remain in liquid state even in -40 °C.
- Kinetic heating of air. It occurs in a zone where the biggest air accumulation exists i.e. at the leading edge. It is remarkable that this process opposes icing but still leading edges are most susceptible to ice accretion.
- Kinetic heating produced by droplets. Water drops hitting the surface transfer their kinetic energy.
- Convective exchange of heat. It occurs between aircraft surface and the flowing air stream.
- Water evaporation or ice sublimation located on the surface of profile. This phenomenon contributes to heat dissipation.
- Heat emission related to crystallization (freezing of water which hits the surface).
- Heat emission related to friction. It is especially important considering high speed flow.

The above mentioned phenomena are not the only ones which have impact on icing but they are considered to be most essential ones.

Another aspect which complicates the comprehension of icing is the necessity consider many fields of classic physics such as atmospheric physics, meteorology, thermodynamics, aerodynamics and flight mechanics. With simplification of the process itself, it is possible to consider the phenomena based on fundamental laws and physical dependencies:

- The first law of thermodynamics. The change in internal energy of the system is equal to the amount of heat exchanged with the surroundings and the amount of work performed on or by the system. To simplify the problem – the temperature is a measure of the internal energy of a system. Considering icing using the first law of thermodynamics, it is possible to explain kinetic heating of air. In the stagnation point the kinetic energy of air particles is converted into the internal energy which increases the temperature.
- Temperature. As mentioned above, it may be defined as a measure of the internal energy of a system. The temperature lower than water freezing temperature is an indispensable condition for icing occurrence.
- Normal physics conditions. Normal temperature is equal to ice melting temperature under normal pressure. It provides a reference point to physical conditions in which icing occurs.
- Specific heat. According to the definition it is a measure of the amount of energy per unit of mass required to increase the temperature by one degree Celsius. Analyzing icing, it is important to remember that water has high specific heat.
- Isentropic gas transformation. In case of that transformation it is practicable to establish precisely the relation between variations in density, pressure and temperature of the considered system. For example, 100% increase of pressure causes 60% increase of density and 21% increase in absolute temperature. Considering 5% decrease in the temperature of melting that would mean 13.5 K drop. It is substantial for icing process .
- The relation between the velocity of gas stream and variation in the temperature and pressure. Taking the first law of thermodynamics into account and the decrease in gas speed, the increase in the temperature is observed and other way round. Pondering the isentropic gas transformation, one may designate changes of particular parameters.
- Continuity equation. If liquid or gas flows through a tunnel with a variable cross-section, mass flow remains constant. Considering the

flow around the airfoil, such as upper surface, one encounters the biggest growth of speed. Thus, the increase in speed is observed, there is also a decrease in internal energy and, hence, decrease in temperature.

Other factors should also be taken into consideration: water phase transitions (which has even higher specific heat than water - crystallization of one water drop supplies enough heat to warm a few other drops), humidity (cold air can hold smaller amount of water vapor than warmer), saturation pressure (under the ice layer it is bigger than the one you may find above the water layer). On the basis of the above facts, one may conclude that unsaturated air for water might be oversaturated for ice. This explains why ice occurs on airfoil without water presence in the atmosphere in a liquid from. Another factor which should not be omitted is water droplet uptake (which grows with an increasing drop diameter and flow speed while it decreases with the increase in distance from the leading edge). Heat exchange is a very important process . It is a basic way to interchange heat between the profile and surroundings. Moving fluid collects and carries energy from the body of higher temperature to the one with lower energy. For the aircraft flying in supercooled atmosphere the amount of lost heat by convection increases with the increase of speed and the decrease of dimensions. This explains why ice grows at first on antennas as well as small and protruding elements. In order to define icing, scientist had introduced icing coefficient β. It is a ratio of water amount that forms ice layer to all the water captured by the surface.

MATHEMATICAL ICING MODELS

There are the following mathematical icing models [2]:

- **Bilanin model.** a mathematical model of ice growing in time according to cloud aquosity, temperature and icing coefficient.
- **Dietenberger model.** It is a mathematical model which describes changes of lift coefficient C_z, drag coefficient C_x and critical angle of attack α_{cr} in correlation to the type and intensity (p) of contamination also maximum camber of its surface structure (k). Dietenberger model can be applied with under the following assumptions: ice layer appears at the whole leading edge (p = 1), wing chord equals MAC (mean aerodynamic chord), $k=\delta_l=\delta_{l\ max}(t)$, a and b coefficients are selected depending on the considered profile and contamination type.
- **Messinger model for icing.** In this consideration, the fundamental is the law of conservation of energy for equilibrium of temperature in isolated, unheated surface exposed to icing. The model has several limitations including: icy surface in Messinger model is smaller than the real one; the base is isolated; the model does not imply heat dissipation by the system; therefore, the only method of balancing the energy is to create hidden heat. In practice ice growth would be encountered [1].

NUMERICAL SIMULATION

For our simulation ICEM program was used for creating structural mesh and FLUENT as analysis system from ANSYS package [6]. The type of the simulation was 2D. The airfoil of ATR72 was used with average chord of 2.255 m [14]. The following parameters were set: air velocity v = 50 m/s, density $\rho = 1.225\ kg/m^3$, angle of attack $\alpha = 0°$. The computational domain dimensions were as follow: length – 22 m, height – 20 m, semi circle with radius of 10 m from the leading edge side. Mesh type for both cases was quad and the number of cells was around 30 000. Structural mesh with boundary layer for clean airfoil is displayed in figure 4.

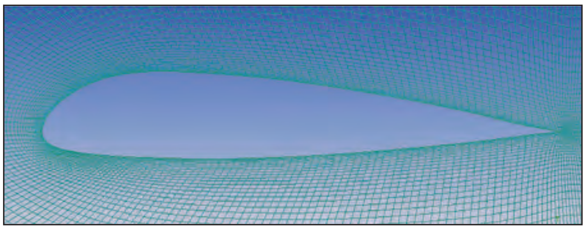

Fig. 4. Structural mesh for clean airfoil

Results which we obtained are presented below:

Airfoil	Drag	Lift
Clean	100%	100%
With ice accretion	212.729%	92%
Difference	+ 112.729%	-8%

Significant degradation of aerodynamics characteristic of the airfoil was observed. Drag increased significantly by 112.729% and lift decreased noticeably by 8%. The distribution of

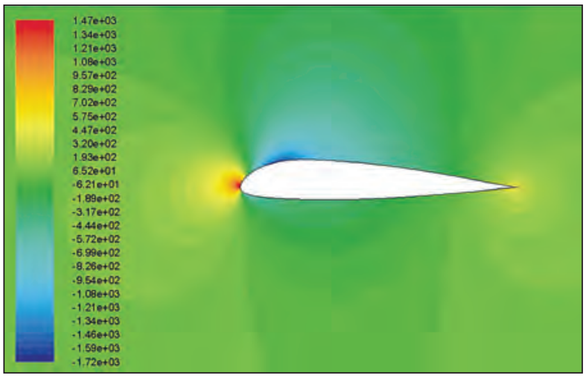

Fig. 5. Pressure distribution over clean airfoil

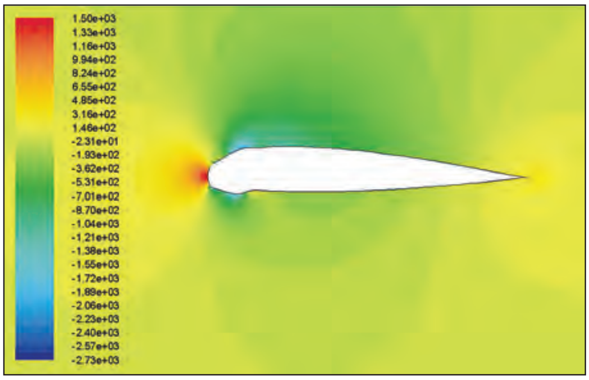

Fig. 6. Pressure distribution over airfoil with ice

pressure around both profiles is displayed in figures 5 and 6. Comparing both illustrations one can clearly see that the area of low pressure over clean airfoil is larger than the one over the airfoil with ice. What is more, the area of high pressure in stagnation point is significantly greater for airfoil with ice. Both of this observations explain the degradation of performances.

CONCLUSION

The study confirmed that icing is a very complicated phenomenon. Over the years since the beginning of aviation icing proved to be extremely dangerous. Even though the aeronautical industry is one of the most developmental branches; the 100% efficient method of counter-acting ice influence has not been discovered yet. For this reason, every pilot should respect the unpredictability and strength of nature and, therefore, when it is possible avoid the known icing conditions.

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