ТРАНСПОРТНЫЕ СИСТЕМЫ
2.9.1 – Транспортные и транспортно-технологические системы страны, ее регионов и городов, организация производства на транспорте;
2.9.4. – Управление процессами перевозок;
2.9.6 – Аэронавигация и эксплуатация авиационной техники;
2.9.8 – Интеллектуальные транспортные системы

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Determination of the most dangerous flight modes of aircraft in icing conditions

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Abstract: In this paper, the object of research is the icing of aircraft surfaces during flight in the atmosphere. On many light aircraft, as well as on unmanned aircraft weighing less than 30 kg, there are no on-board de-icing systems. Nevertheless, aviation events occur with these aircraft, which are a consequence of their icing. Therefore, determining the most dangerous flight modes of aircraft in icing conditions is an urgent task. In view of the high cost of conducting flight tests and the impossibility of covering all possible events due to their potential danger, the complexity of creating flight conditions for aircraft in icing conditions on the ground, the mathematical modeling method was used in this study. To solve this problem, the analysis of the airworthiness standards of civil light aircraft, transport category aircraft, rotorcraft of normal and transport category was carried out within the framework of the work, the influence of various parameters on the thickness of ice build-up was investigated using a computational experiment conducted on the software developed by the authors of the article. On the basis of the results of the computational experiment, the dependences of the ice thickness on various icing parameters were obtained, a method was developed for determining the combination of heights and flight speeds of an aircraft, at which ice of the greatest thickness is formed on the surface of aircraft, other things being equal. Possession of this information will allow the aircraft crew and air traffic control specialists to avoid the most dangerous flight modes in terms of icing.

Key words: icing, mathematical model, computational experiment, flight operation.

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Определение наиболее опасных режимов полета летательных аппаратов в условиях обледенения

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Аннотация: В данной работе объектом исследования является обледенение поверхностей воздушных судов при полете в атмосфере. На многих легких летательных аппаратах, а также на беспилотных воздушных судах массой менее 30 кг отсутствуют бортовые противообледенительные системы. Тем не менее с данными летательными аппаратами происходят авиационные события, которые являются следствием их обледенения. Поэтому определение наиболее опасных режимов полета летательных аппаратов в условиях обледенения является актуальной задачей. Ввиду высокой стоимости проведения летных испытаний и невозможности охвата всех возможных событий из-за их потенциальной опасности, сложности создания условий полета воздушных судов в условиях обледенения на земле в настоящем исследовании был использован метод математического моделирования. Для решения поставленной задачи в рамках работы проведен анализ норм летной годности гражданских легких самолетов, самолетов транспортной категории, винтокрылых аппаратов нормальной и транспортной категории, проведено исследование влияния различных параметров на толщину нарастания льда с помощью вычислительного эксперимента, проведенного на разработанном авторами статьи программном обеспечении. На основе результатов вычислительного эксперимента были получены зависимости толщины льда от различных параметров обледенения, была разработана методика определения сочетания высот и скоростей полета воздушного судна, при которых на поверхности летательных аппаратов при прочих равных условиях образуется лед наибольшей толщины. Обладание данной информацией позволит экипажу летательного аппарата и специалистам по управлению воздушным движением избегать наиболее опасных режимов полета с точки зрения обледенения.

Ключевые слова: обледенение воздушных судов, математическая модель, вычислительный эксперимент, летная эксплуатация.

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Introduction

Icing of the aircraft is still one of the most dangerous factors [1–8] throughout the whole history of their operation. Icing of the aircraft surfaces may lead to different adverse consequences. Icing of the aircraft lifting systems leads to the flow lead change and, consequently, to the change of aircraft aerodynamic performance, its steadiness and controllability, flying range and endurance, along with fuel flow increase. Icing of the aircraft gas turbine engines may lead to the gas-dynamic parameter change in all the engine components and damage of the engine structure due to ice fragments entering the flow channel. Icing of aircraft probers and sensors gives the erroneous flight parameters to the crew.

The on-board de-icing systems are developed to prevent the aircraft parts from icing during the flight. The on-board de-icing system consumes either electrical or mechanical energy depending on its type. It is necessary to increase fuel flow for system reliable performance in both cases, which decreases the operational efficiency. That is why they try to refuse from on-board de-icing system use on civil aircraft for aerodynamic characteristics enhancement sake nowadays, for instance, on Tupolev TU-204 [9], which does not contradict the requirements of the aircraft and rotary aircraft[1,2] airworthiness standards in transport category.

There are also the aircraft without the on-board[3] de-icing systems[4], which can inadvertently perform flights in icing circumstances, for instance, light aircraft and rotary aircraft, most of the unmanned aircraft types.

Thus, forecasting of icing providing the given weather forecasting, in other words determination of the flight mode during which icing is most intensive, in order to avoid flight performance on this mode whether it is possible, is the urgent task.

One can use theoretical and empirical approach to gain data on flight parameter influence on icing in forecasted weather conditions.

The high cost of flight testing and coverage of all the probable events being impossible due to their hazard are the drawbacks of the first approach. Thus, the reasonable combination of theoretical and empirical approach appears to be the most efficient. The mathematical modeling is what is meant by theoretical approach. The purpose of the following work is to determine the most dangerous aircraft flight modes using the mathematical modelling methods.

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[1] Federal Aviation Rules, part 25 (2015). Airworthiness standards for airplanes in the transport category. St. Petersburg: SZ RTSAI. 292 p.

[2] Federal Aviation Rules, part 29 (2003). Airworthiness standards for rotorcraft in the transport category. Moscow: Aviaizdat. 130 p.

[3] Federal Aviation Rules, part 23 (2014). Airworthiness standards for civil light aircraft. Moscow: Aviaizdat. 195 p.

[4] Federal Aviation Rules, part 27 (2014). Airworthiness standards for rotor aircraft in the normal category. Moscow: Aviaizdat. 125 p.

Research methods and methodology

Icing of an aircraft is caused by liquid spray of water (a cloud) in the atmosphere and sub-zero air temperature.

The basic meteorological parameters, influencing the icing, are [10–17]:

- temperature;
- air liquid water content (mass of water drop content in air unit volume);
- size of drops;
- size of a cloud (icing zone).

Let us consider heat transfers at surface being iced, without taking the work of on-board de-icing systems and other measures into account.

There is a multitude of icing mathematical models, which are described, for instance, in works [10–12, 15–18]. Myers model, described in work [19], is used in the following paper.

Heat transfers will be estimated with their Q mass density, in other words, heat transfers as surface unit square, having, respectively, W/m^2. There is scheme of heat transfers, being considered in above-mentioned Myers model, in Figure 1.

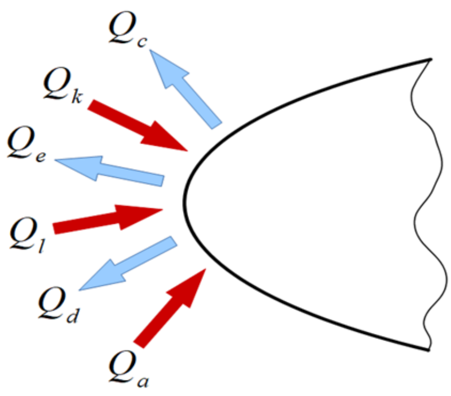

Fig. 1. Heat transfer scheme next to surface in icing conditions

Heat additive to surface is provided due to:

- conversion of drop velocity energy into heat – Q_k;
- coming out of water crystallization latent heat – Q_l;
- air friction heating (due to frictional boundary layer) – Q_a.

Heat transfer from the surface is provided due to:

- heat convective flux from surface into air – Q_c;
- evaporation of water (or ice sublimation, if there is ice on the surface without layer if water on it) – Q_e;
- cooling due to drops of water – Q_d.

Thus, equation of heat capacity can be written this way:

$$Q_k + Q_l + Q_a - Q_c - Q_e - Q_d = 0. \quad (1)$$

Icing on the surface provided drops of water on it with the given temperature remaining unchanged is the only thing being considered monodimensionally according to Myers model in the following work. Myers model allows us to represent icing in time depending on the multitude of parameters (liquid water content, incoming air speed, temperature at surface, etc.). At the same time, it is considered that particles of water set immediately on the surface, creating porously structured layer of ice. Let us call such an ice basically porous. Some time after the ingoing drops of water cannot pass to solid phase at once due to limited ice thermal conduction and remain on ice surface for some time in the form of water which turns gradually into glassy ice.

It is necessary to take into account in the calculation that ice does not accumulate at all in case the following condition is fulfilled:

$$T_f - T_s \leq 0, \quad (2)$$

where T_f, T_s – is the temperature of phasal shift and surface, respectively, [K].

Only the cases of non-fulfilling the following condition (2) are considered below.

Then, as mentioned above, during the first stage porous ice appears, which depth can be distinguished by formula

$$B = \frac{\beta W G}{\rho_i} t, \quad (3)$$

where $\beta = \frac{m_в}{WGc_{\max}}$ – is a wash-out rate;

$m_в$ – mass of water penetrating the unit length (for instance, wing spread) per second, [kg/(s·m)];

W – incoming air speed, [m/s];

G – air liquid water content, [kg/m^3];

c_{max} – maximum vertical body depth (for instance, airfoil depth), [m];

ρ_i – porous ice density, [kg/m^3];

t – exposure time, [s].

Then, it is necessary to doublecheck the following condition:

$$\beta WGL_F + [Q_a + Q_k - (q_c + q_d + q_e)(T_f - T_a)] \leq 0, \tag{4}$$

where L_F – latent crystallization heat, [J/kg];

$Q_a = \frac{r\bar{H}_{aw}W^2}{2c_a}$ – heat transfer rate due to aerodynamic heating, [W/m^2];

r – recovery factor, which reflects distortion of aerodynamic streamline surface heating (r < 1);

$\bar{H}_{aw}$ – heat flux rate between air and water surface, [W/(m^2·K)];

c_a – air thermal mass, [J/(kg·K)];

$Q_k = \frac{\beta GW^3}{2}$ – heat flow mass density due to water drops kinetic energy shift into heat, [W/m^2];

$q_c = \bar{H}_{aw}$ – relative mass density of heat convective flux from surface into air, [W/(m^2·K)];

$q_d = \beta WGc_w$ – relative mass density of heat flux due to cooling by drops of water, [W/(m^2·K)];

c_w – water heat flow mass density, [J/(kg·K)];

$q_e = \chi e_0$ – relative heat flux mass density due to water perspiration [W/(m^2·K)];

χ – perspiration rate, [m/s];

e_0 – rate of perspiration functional relation, [Pa/K];

T_a – temperature, [K].

Only porous ice without water on its surface, which could have turned into glassy ice will appear if condition (4) is met. Depth of ice can be determined, respectively, by formula (3), depending on exposure time.

Whether condition (4) is not met, at some point the water, which will then freeze and turn into glassy ice, will appear on porous ice surface.

Porous ice depth at first water appearance on its surface can be determined by formula

$$B_g = \frac{k_i(T_f - T_s)}{\beta WGL_F + [Q_a + Q_k - (q_c + q_d + q_e)(T_f - T_a)]}, \tag{5}$$

where k_i – ice heat flow mass density, [W/(m·K)].

The following formula can be used for general ice depth (porous and glassy one, appeared on it) calculation, depending on exposure time:

$$B = \frac{1}{\rho_g L_F}\int_0^t \left(\frac{k_i(T_f - T_S)}{B} - k_w\rho_w \frac{Q_a + Q_k - (q_c + q_d + q_e)(T_f - T_a)}{k_w\rho_w + [\beta WG(t - t_g) - \rho_g(B - B_g)](q_c + q_d + q_e)}\right)dt, \tag{6}$$

where ρ_g, ρ_w – glassy ice and water mass density, respectively, [kg/m^3];

$t_g = \frac{\rho_i B_g}{\beta WG}$ – time from the beginning of exposure to first water appearance on porous ice, [s];

k_w – water thermal conductivity, [W/(m·K)].

Fig. 2. Flight altitude dangerous velocities distribution

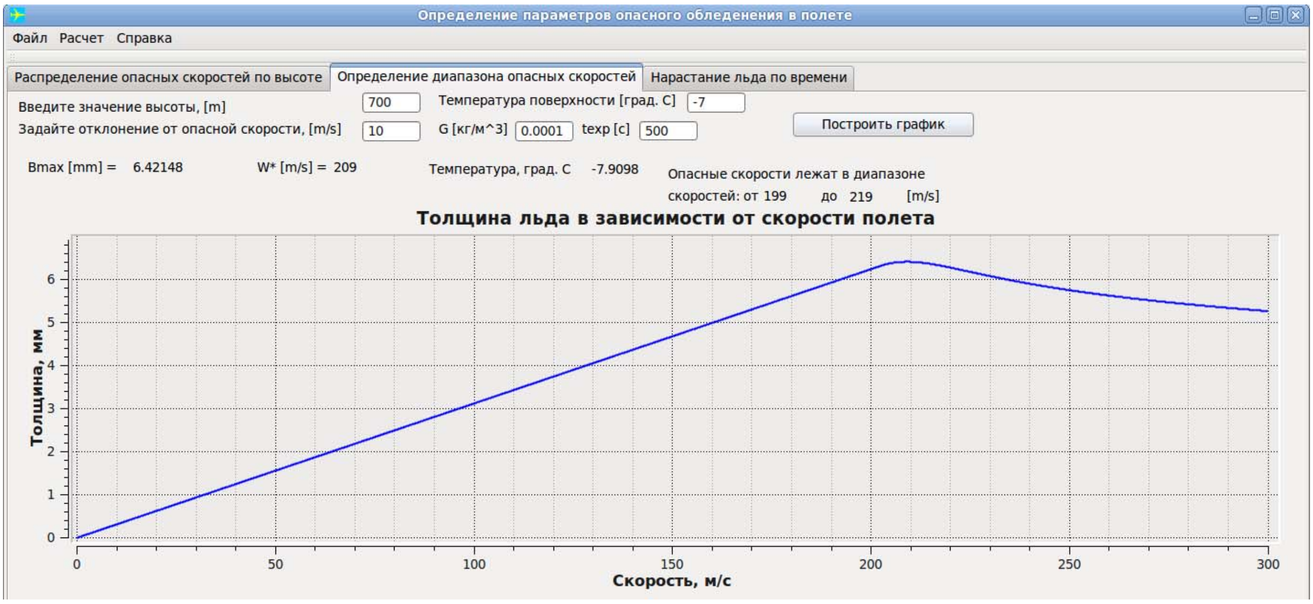

Fig. 3. Determination of the dangerous flight speeds range

Sufficiency of the following mathematical model is confirmed in Myers paper [19].

The respective software ice_1D, which allows to shape icing process depending on given starting conditions, along with distinguishing dangerous velocities and altitudes of flight was created for comfortable calculations by authors of the following work. Let us consider such a velocity, with which ice depth will be the biggest one in other equal conditions, the dangerous one, that is why the biggest ice depth, which appears on the surface in given conditions and time of being in icing zone (exposure time t) is calculated in separate cycles with given step from zero for every speed of flight. Thus, there is a dangerous velocity correspondence with flight altitude (fig. 2) as a result of computational experiment.

Fig. 4. Dependence of ice thickness on exposure time

Ice_1D application also allows to distinguish range of most dangerous flight velocities on the given altitude with the given variable of velocity deviation from dangerous one (fig. 3).

Besides that, the following software allows to get a graphical correspondence of ice depth to exposure time with given starting conditions (fig. 4).

Discussion of research results

The initial data, presented below in Tables 1 and 2, was taken with ice_1D application for numerical modelling. Data for Table 1 was taken from work [19], for Table 2 – from areological diagram, published on internet-resource[5], as on the 1st of January 2020. Sounding was conducted in Moscow, 12:00 Moscow time.

The following investigations were run using ice_1D application:

- dangerous velocities range determination for given altitudes;
- determination of flight altitude influence on ice depth in the other equal conditions;
- determination of surface temperature influence on ice depth correspondence with flight velocity;
- determination of surface temperature influence on dangerous velocities distribution by flight altitudes;
- determination of surface temperature influence on flight dangerous velocity and biggest ice depth;
- determination of cloud liquid water content influence on ice depth and flight dangerous velocities;
- determination of cloud liquid water content influence on dangerous velocities distribution by flight altitudes;
- determination of time being in icing zone on ice depth correspondence with flight velocity in other equal conditions.

Results of numerical modelling are presented in Figures 5–9.

As previously mentioned, flight velocity is one of crucial factors, influencing the ice depth. There is data on repeating of different tempera-

[5] Areological diagrams. flymeteo. org. Available at: www.flymeteo.org (accessed: 03.11.2022). (in Russian).

Table 1

Initial data

№	Value	Labeling	Size	Dimension
1	Air thermal mass	c_a	J/(kg·K)	1014
2	Water thermal mass	c_w	J/(kg·K)	4218
3	Perspiration functional relation rate	e_0	P/K	27.03
4	Heat flux rate between air and water surface	$\overline{H}_{aw}$	W/(m^2·K)	500
5	Ice heat conductivity	k_i	W/(m·K)	2.18
6	Water heat conductivity	k_w	W/(m·K)	0.571
7	Latent heat of ice melting (crystallization)	L_F	J/kg	334400
8	Water captivation rate by investigated surface	β	–	0.55
9	Glassy ice mass density	ρ_g	kg/m^3	917
10	Porous ice mass density	ρ_i	kg/m^3	880
11	Water mass density	ρ_w	kg/m^3	1000
12	Perspiration rate	χ	m/s	11
13	Phase shift temperature	T_f	K	273.15
14	Recovery rate	r	–	0.5

tures while icing [13, 14], basing on which we can conclude, that in range from −6 to −10 °C the probability of icing is higher than in case of other temperatures in some works. Let us take the average temperature for the given range on altitude of 700 m above sea level. Ice depths were calculated on the given flight altitude with velocity change from 0 to 300 m/s. The dangerous flight velocity (209 m/s) with which ice depth will be the maximum one (6.4 mm) can be gained by the following distribution (fig. 3).

It can be seen from dangerous velocities distribution by altitude (fig. 1), that correspondence is non-linear and has an extremum. Nonlinearity is directly connected to temperature distribution by altitude. Presence of extremum (temperature increase higher than 9300 m was noticed in the investigated moment (tab. 2)) can be explained the same way.

Decrease in iced surface shifts extremum of ice depth correspondence to flight velocity right up (fig. 5), at the same time extremum becomes less significant. Let us notice, that the following factor is most significant until the altitude reaches 5000 m. It can be seen in Figure 6, that speed of ice appearance $\frac{\partial B}{\partial t}$ increases with temperature decrease.

There is the influence of surface temperature on dangerous velocity distribution by flight altitudes presented in Figure 7. On flight altitudes from 0 to 4000 m surface temperature mostly influences on dangerous velocity value (the higher surface temperature is, the lower is dangerous velocity value).

There is a correspondence of maximum ice depth and dangerous velocity from surface temperature in Figure 8. It can be seen from the fol-

Table 2

Initial data from aerologic diagram from 01.01.2020 noon

№	Altitude of sounding, m	Temperature, °C
1	0	−5
2	156	−2.1
3	696	−7.9
4	1349	−9.5
5	2825	−17.7
6	5260	−34.7
7	6780	−45.1
8	8660	−54.1
9	9300	−57.9
10	9820	−56.7
11	11200	−56.1
12	12000	−61.1
13	15510	−63.5

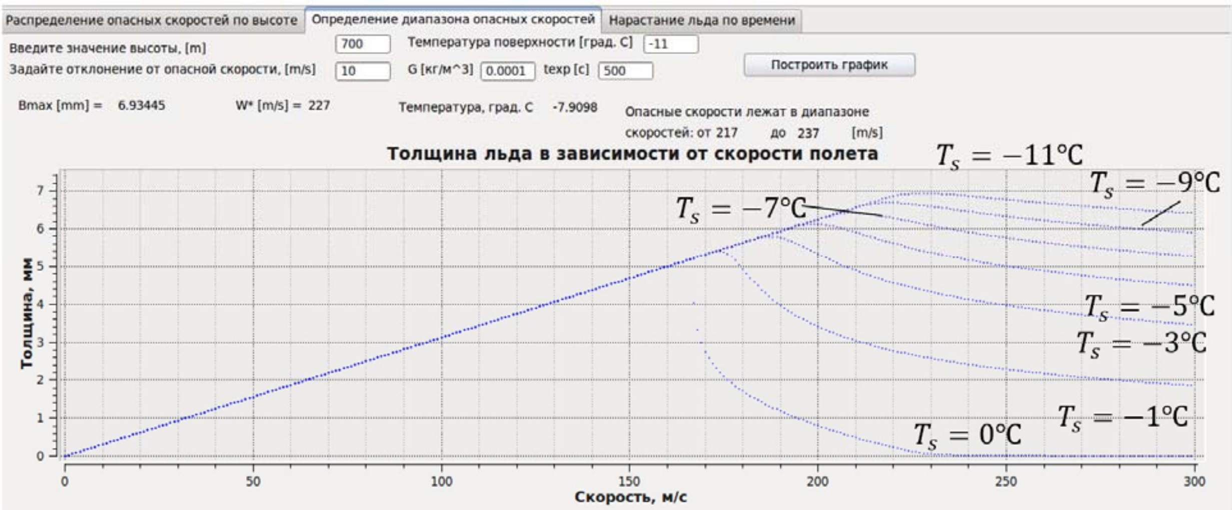

Fig. 5. Surface temperature influence on dependence of ice thickness on high speed at 700 m altitude

lowing graph that the dangerous flight velocity and maximum ice depth decrease whether surface temperature increases. The reason is that the drops freeze faster at lower temperatures while touching the surface, so that ice accumulates more intensively.

There is correspondence of maximum ice depth and dangerous velocity from cloud liquid water content shown in Figure 9. The decrease of dangerous velocity value and maximum ice depth with cloud liquid water content increase can be seen from this correspondence.

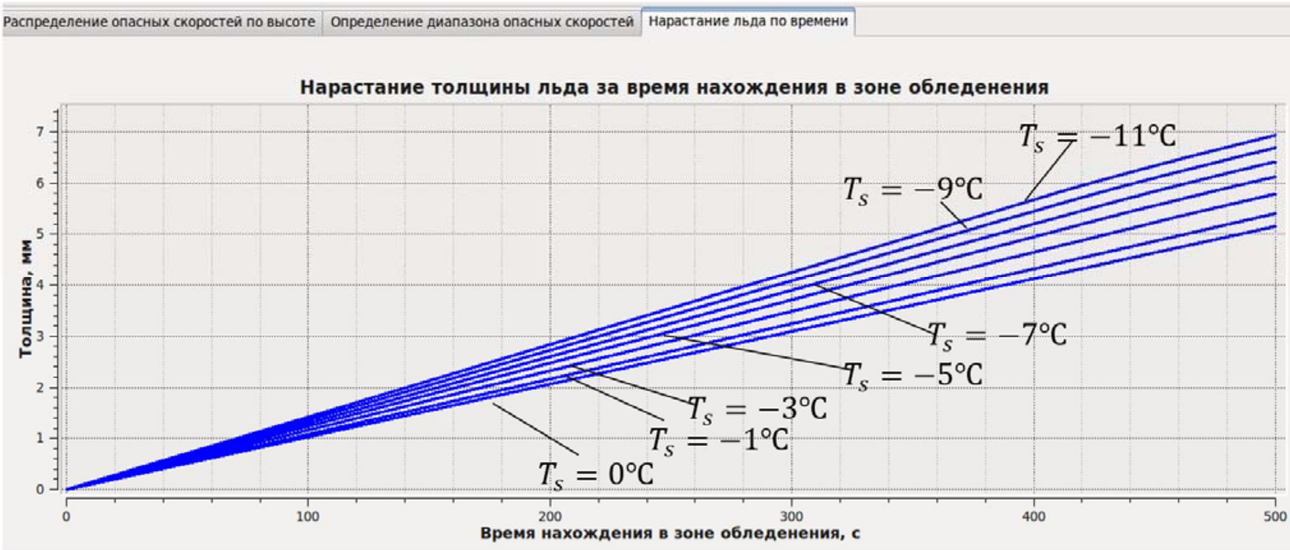

Fig. 6. Surface temperature influence on ice growth rate

Fig. 7. Surface temperature influence on distribution of dangerous speeds by flight altitude

Conclusion

Software, allowing to determine the ice depth on aircraft surfaces, being iced in different conditions was developed basing on the given mathematical model. Graphs of ice depth correspondence with air flow speed were gained in the process of research. There are flight velocities, at which ice depth is the biggest, which was obtained at graph analysis. It was decided to call such velocities the dangerous ones. Furthermore, the research on dangerous velocities determination at different flight altitudes was conducted and their distribution by altitudes within the frame of troposphere was gained. Correspondences of ice depth, flight dangerous velocity and altitude with liquid water content of cloud in which flight is performed, flight duration in icing zone, surface temperature and flight velocity were also gained. It is recommended to generate

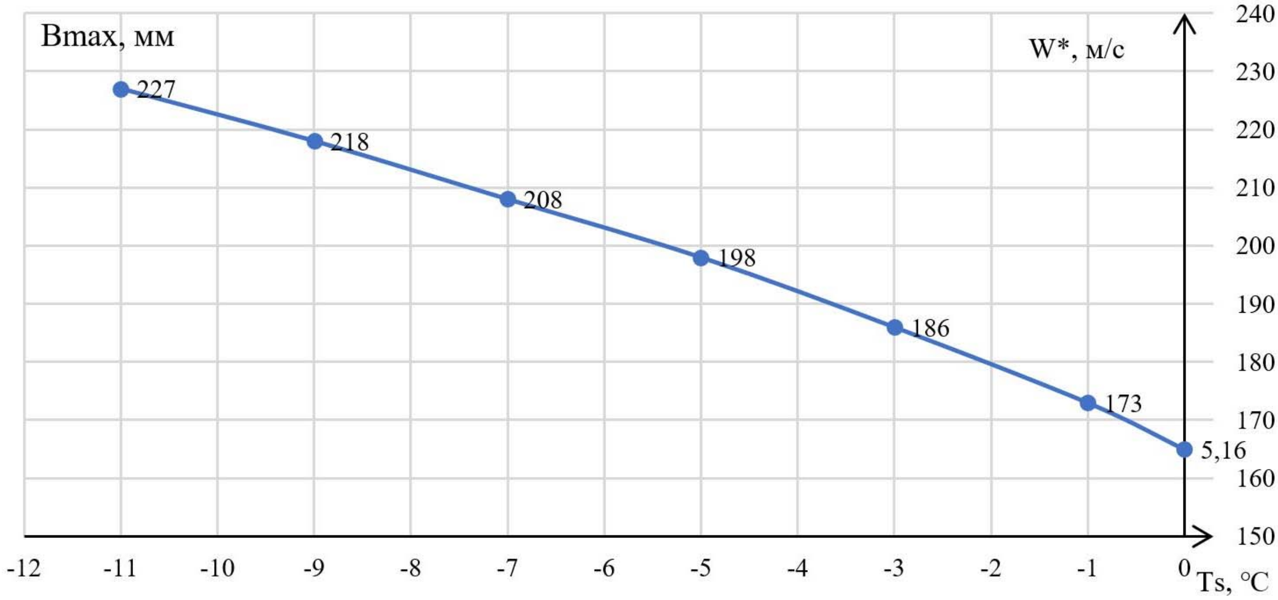

Fig. 8. Dependence of the maximum ice thickness and dangerous speed on the surface temperature

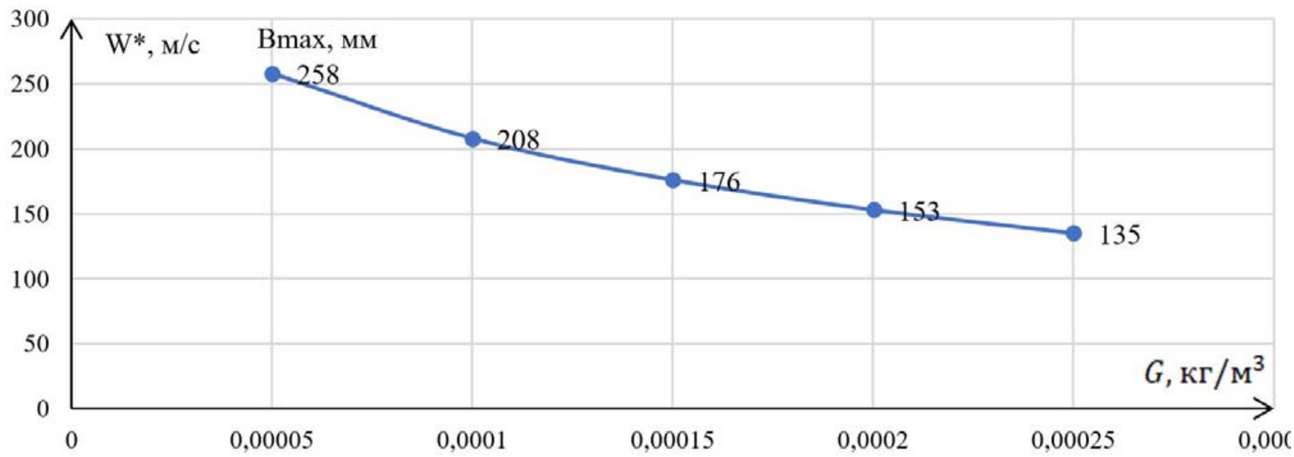

Fig. 9. Dependence of the maximum ice thickness and dangerous speed on cloud water content

the following dependencies prior each flight for dangerous flight velocities determination and their further avoidance.

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