# INVESTIGATION OF ICING EFFECTS ON AERODYNAMIC CHARACTERISTICS OF AIRCRAFT AT TSAGI

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## Abstract

*Investigation of icing effects on aerodynamic characteristics of aircraft is an important task because of the problems of providing flight safety. The main consequences of icing are the aircraft performance degradation and lower efficiency of controls.*

*The methodologies and facilities used at TsAGI for conducting researches into icing effects on aerodynamic characteristics of aircraft as well as test results concerning the models of different types of aircraft with straight (including operating power plant simulation) and swept wings are presented.*

## 1 Introduction

Experimental researches with artificial ice shapes are the part of the process of aircraft certification for flight into known icing conditions. This process finishes off with flight tests with artificial ice shapes (ice simulators) and in natural icing conditions (Fig. 1 and 2). Pilots should be ready to the aircraft performance and control degradation due to icing. Moreover, for flights with artificial ice shapes, it is important to know the aircraft performance even in unacceptable for real operation situations such as a take-off with ice accretions including the large ones.

The active researches into the icing effects on aerodynamic characteristics of aircraft have begun at TsAGI since the 1960s. The methodologies for conducting experimental studies using artificial ice shapes on various parts of aircraft models have been developed over the past time.

Fig. 1. In-flight icing of an aircraft wing

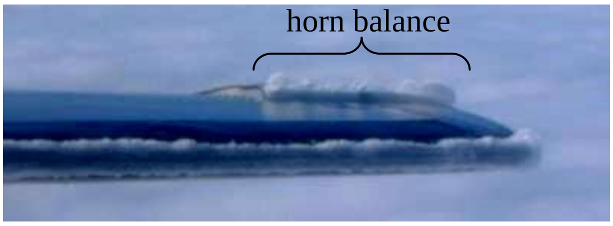


Fig. 2. In-flight icing of a horizontal tail and a horn balance of an elevator

On the basis of the studies of the icing effects, TsAGI makes recommendations for the necessity to install ice-protection systems (IPS) and for their design. Moreover, such studies may be conducted as a part of aviation accident investigations.

## 2 Classification of civil aircraft for investigation of icing effects

The analysis of TsAGI's experimental studies into the icing effects on aerodynamic characteristics made it possible to classify civil aircraft according to the recommended optimal installation of IPS (Fig. 3). IPS installation requires additional power consumption and maintenance costs. That is why the studies are conducted on IPS optimization and possible leaving some airframe components without ice protection. For example, such studies allowed for the Tu-204 aircraft to be certified for flight into known icing conditions without IPS.

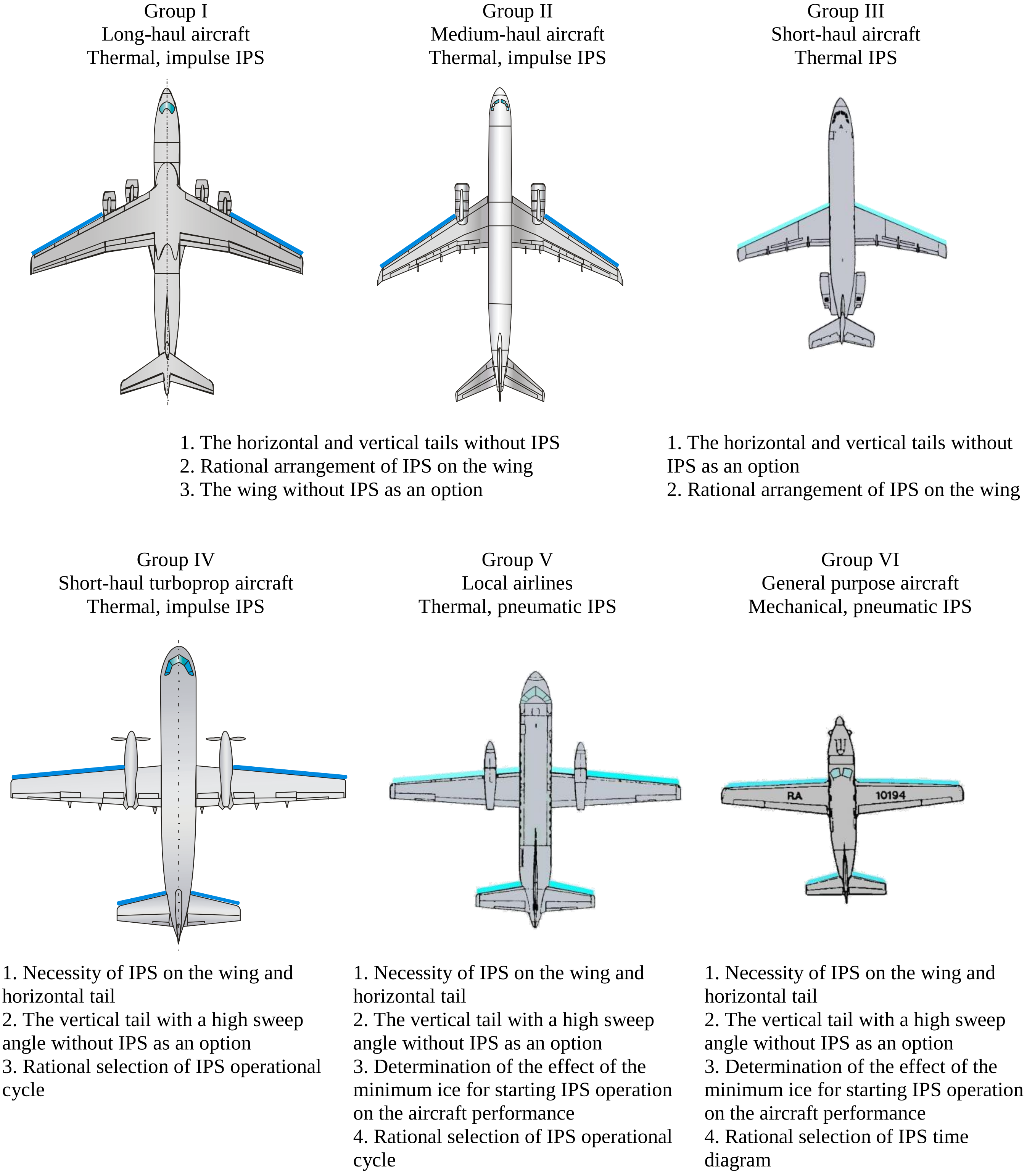


Fig. 3. Recommendations for IPS installation on civil aircraft

The following factors may be in favor of not installing IPS:

- large thicknesses and chords of lifting surfaces of heavy aircraft making them less prone to icing compared to light aircraft;
- high climb and descent rates decreasing the time of an aircraft flying through the altitude range of H=0–6 km where the icing probability is 90%;
- high cruise altitudes substantially above those where icing conditions are encountered;
- greater engine power margins of heavy aircraft;
- adjustable horizontal stabilizers, their oversizing;
- power-control for all control surfaces;
- highly swept lifting surfaces.

According to these factors, aircraft are divided into six groups:

I. Long-range trunk-route and heavy cargo aircraft with swept wings.
II. Medium-range trunk-route aircraft with swept wings.
III. Short-range trunk-route aircraft with swept wings.
IV. Short-range trunk-route turboprop aircraft with straight wings.
V. Straight-winged turboprop aircraft for local airlines and light-weight transports with pneumatic IPS on lifting surfaces.
VI. General aviation aircraft with pneumatic IPS on lifting surfaces.

The rational installation of IPS in accordance with the aircraft groups requires more accurate estimation of icing effects.

## 3 The application of the full-scale T-101 wind tunnel for investigation of icing effects

The influence of ice forms, sizes, and roughness on aerodynamic characteristics is most reliably estimated in tests of large-scale aircraft models because the scale effect plays important role in such investigations. That is why, for investigation of icing effects, the full-scale T-101 wind tunnel was traditionally used at TsAGI. This wind tunnel is suitable for conducting not only tests of large-scale aircraft models with scales from 1:2 to 1:3 but also of their full-scale parts. The large-scale aircraft models with wing spans of 15 and 16 m in the T-101 wind tunnel are shown in Fig. 4.



Fig. 4. The large-scale aircraft models in the full-scale TsAGI T-101 wind tunnel

The examples of experimental data on the effects of artificial ice shapes on aerodynamic characteristics acquired in the T-101 wind tunnel in tests of large-scale aircraft models with straight and swept wings for Reynolds numbers of $Re=4–5\cdot10^6$ are given in Figs. 5 and 6.

The artificial ice shapes on the wing cause a significant loss of maximum lift and a decrease in the angle of attack at stall. By contrast, the artificial ice shapes on the horizontal tail (HT) have little effect on the lift. However, these ice shapes on the horizontal tail significantly affect the longitudinal characteristics of the straight-winged aircraft especially with deflected high-lift devices at negative and low angles of attack (Fig. 5) and can cause an abrupt nose drop.

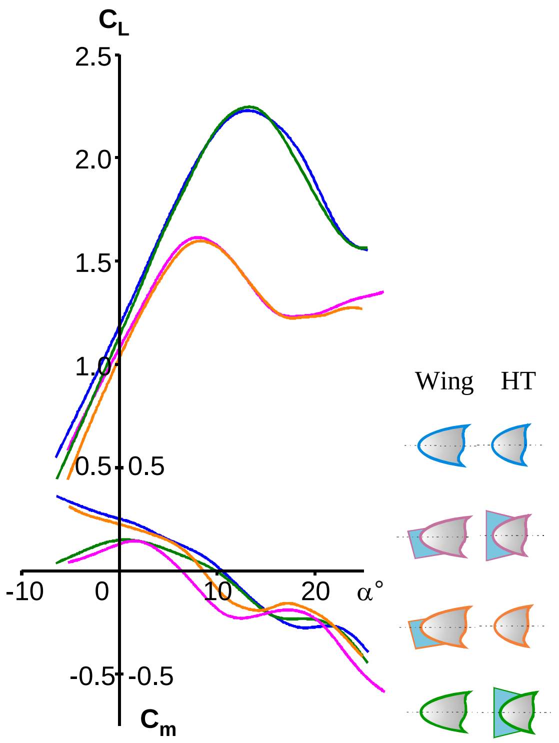


Fig. 5. Aerodynamic characteristics of a straight-winged aircraft model with a flap deflected to an angle of $\delta_f$=40°

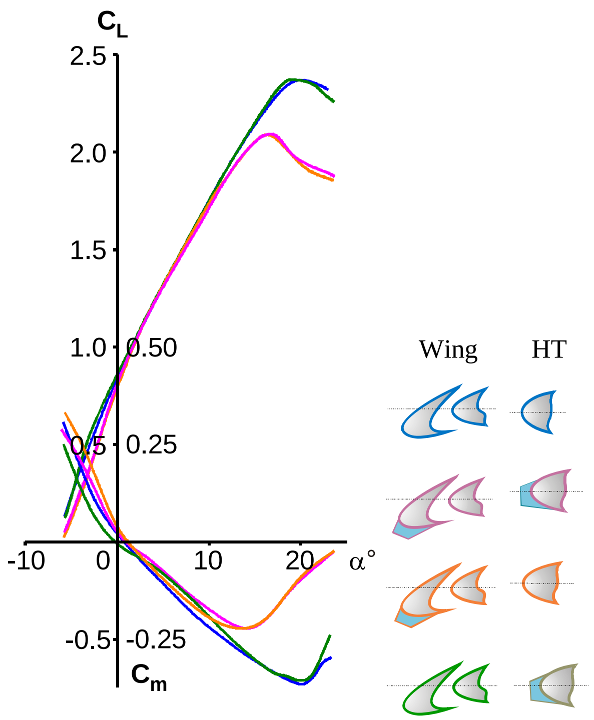


Fig. 6. Aerodynamic characteristics of a swept-winged aircraft model with a flap deflected to an angle of $\delta_f$=44°

Various aircraft models with artificial ice shapes were tested in the T-101 wind tunnel. The Figs. 7 and 8 show generalized data on the lift losses for the straight-winged and swept-winged aircraft models in landing configurations at Re=3–5·$10^6$.

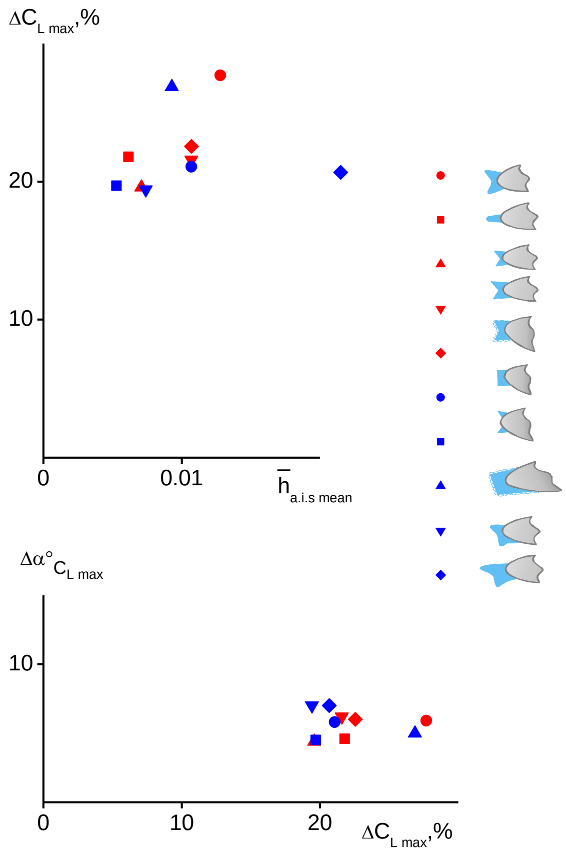


Fig. 7. The maximum lift and stall angle of attack decrease due to artificial ice shapes for the straight-winged aircraft models in landing configurations

According to TsAGI's experience, the general tendency is observed for the larger influence of artificial ice shapes on the maximum lift $\Delta C_{Lmax}$ and stall angle of attack $\Delta\alpha_{C_{Lmax}}$ decrease for straight-winged aircraft compared to swept-winged aircraft in the typical range of mean heights of artificial ice shapes of $h_{a.i.s\ mean}\approx0.005\text{-}0.02$.

The investigations of artificial-ice-shape effects for the aircraft models with simulated engine operation were also conducted at TsAGI. Especially important results were obtained for a straight-winged aircraft model with simulated turboprop engine operation.

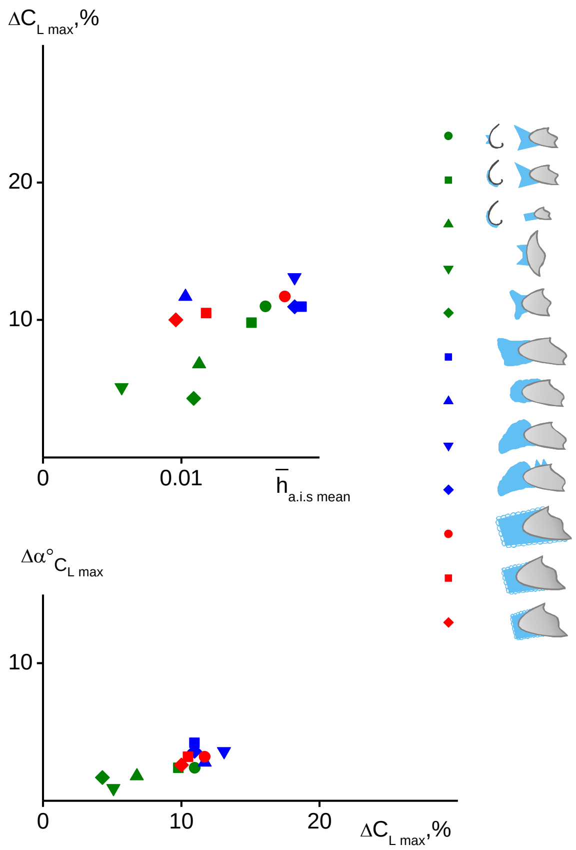


Fig. 8. The maximum lift and stall angle of attack decrease due to artificial ice shapes for the swept-winged aircraft models in landing configurations

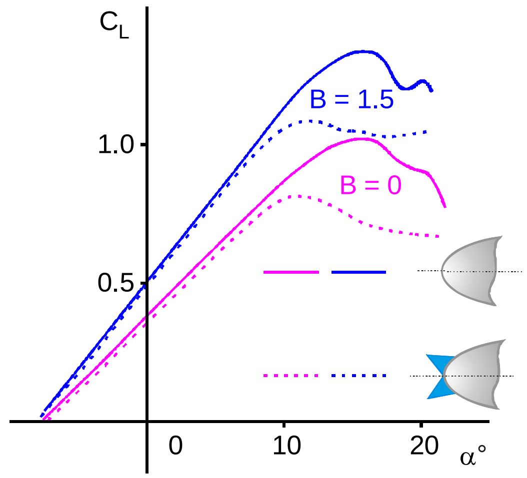


Fig. 9. The lift change due to the simulated engine operation for the straight-winged aircraft model with the artificial ice shapes on the wing

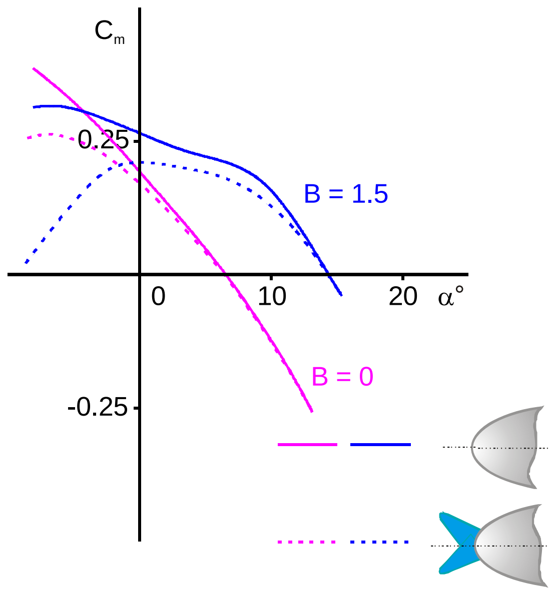


Fig. 10. The pitching down tendency induced by the operating simulated engine at negative angles of attack due to the artificial ice shapes on the horizontal tail of the straight-winged aircraft model in the landing configuration, $\delta_f$=38°

The artificial ice shapes on the wing mainly affect the aircraft lift both with the operating (propeller disc loading coefficient B=1.5) and not operating (B=0) engine (Fig. 9). However, when the flap deflection angle increases and reaches the landing one the downwash on the horizontal tail increases too leading to decreasing the absolute value of the $C_m^\alpha$ derivative at negative and low positive angles of attack. With the simulated engine operation (B=1.5), the $C_m^\alpha$ derivative changes its sign due to artificial ice shapes on the horizontal tail. This results in the aircraft pitching down, which may lead to an accident (Fig. 10).

The installation of thermal IPS on the leading edges of the wings may result in the formation of runback ice behind IPS. The investigation shows that this kind of ice can be very dangerous, especially when slats are deflected and runback ice hinders normal development of the flow past the slot. For example, Fig. 11 makes it possible to estimate the maximum lift loss for the semispan wing model depending on the geometrical parameters of the artificial ice shapes, primarily on their relative height $\bar{h}_{a.i.s}$.

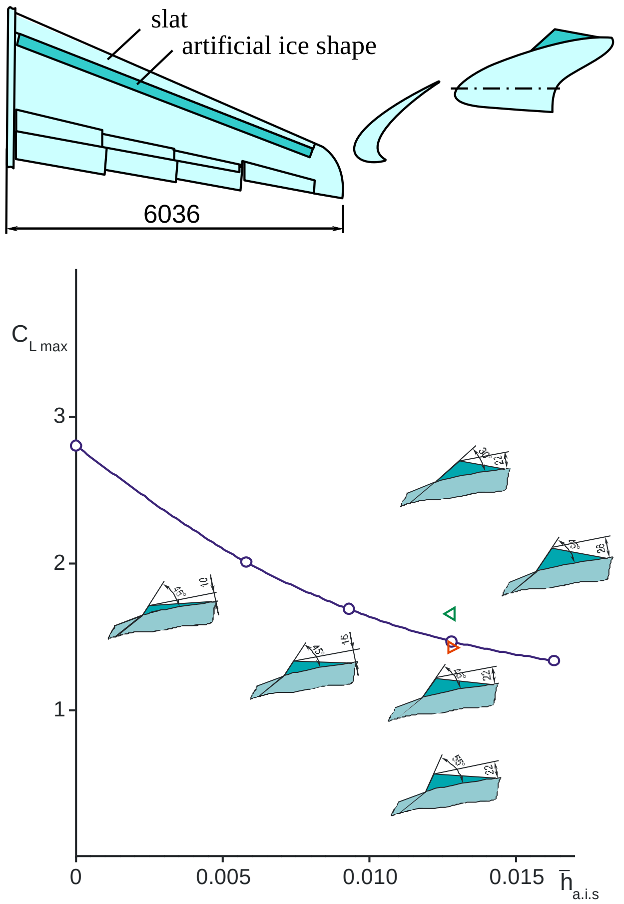


Fig. 11. The maximum lift depending on the height of artificial ice shapes simulating runback ice on the semispan wing model in landing configuration, $\delta_s$=19°, $\delta_f$=40/35°

The scales of the models tested in the T-101 wind tunnel allow for the investigation of the ground icing effects when the thickness of ice or frost covering lifting surfaces is small. According to the clean aircraft concept, the operational regulations prohibit a take-off when any ice, snow, or frost deposits are adhering to the critical surfaces of an aircraft. Nevertheless, such precedents took place. The unique investigation of a real Yak-40 aircraft wing with ground ice simulators was conducted in the T-101 wind tunnel in order to determine the causes of a crash at take-off (Fig. 12).

The abrasive cloth strips of various thicknesses h were used to simulate ground icing (Fig. 13). Since the ground icing has the most influence near the leading edge of the wing, the abrasive cloth was glued to the nose part of the wing approximately from 19% of local chords on the upper surface to 4 – 10% on the lower one.


Fig. 12. The semispan wing of the Yak-40 aircraft with the ground ice simulators in the T-101 wind tunnel

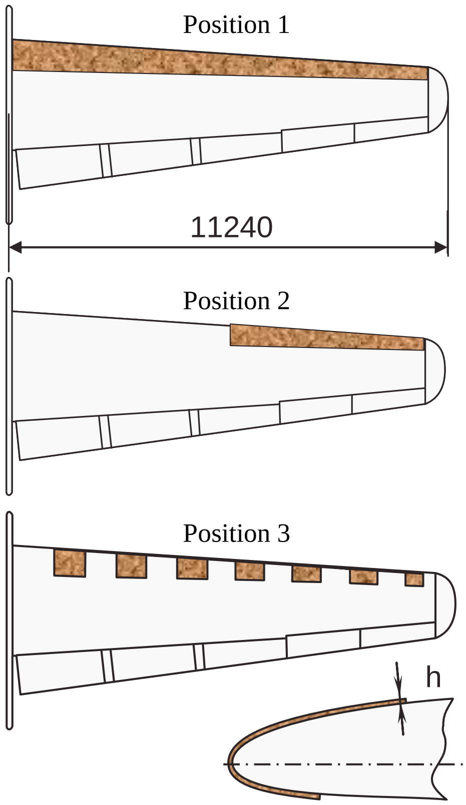


Fig. 13. The ground ice simulators on the semispan wing of the Yak-40 aircraft

Figs. 14 and 15 show the influence of thickness and spanwise position of the ground ice simulators on the lift coefficient for the flap deflection angles of $\delta_f$=11° and 20°. It can be seen that even the ice simulators of small relative thickness (0.00028–0.00064 of the wing MAC) and positioned only on the part of the wing span cause significant losses of the maximum lift of the wing.

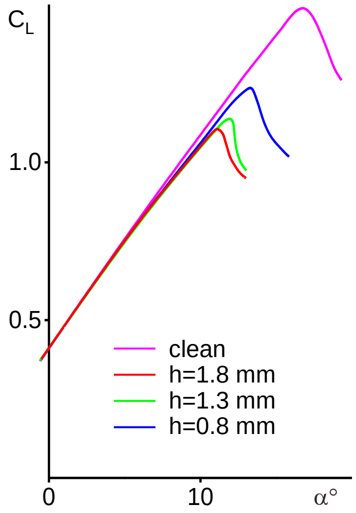


Fig. 14. The lift losses of the semispan wing of the Yak-40 aircraft for the various thicknesses of the ground ice simulators in the position 1, $\delta_f$=11°

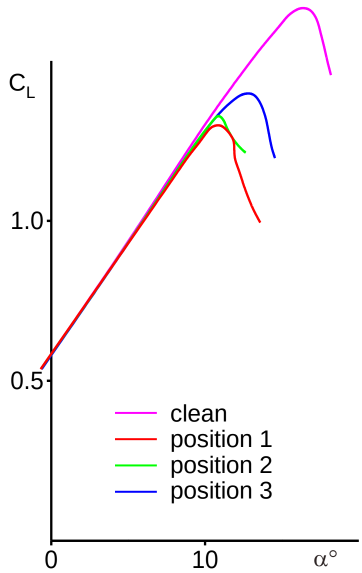


Fig. 15. The lift losses of the semispan wing of the Yak-40 aircraft for the various positions of the ground ice simulators of the thickness h=1.8 mm, $\delta_f$=20°

## 4 Practice of investigation of icing effects at different TsAGI wind tunnels

For the models of small aircraft or if the cross sizes of artificial ice shapes are relatively large, it is possible to conduct the researches of smaller models in smaller wind tunnels for reducing the cost of experiments (the T-102, T-103 wind tunnels) and also for investigation of larger velocity ranges (the T-106, T-128 wind tunnels).

Particular attention, as regards flights in icing conditions, should be given to general aviation aircraft and small passenger and cargo aircraft with pneumatic IPS on lifting surfaces (groups V and VI in Fig. 3). Due to their small absolute sizes, these aircraft are more sensitive to icing than larger aircraft.

For testing the models of general aviation aircraft and their parts (wings and tail units) with artificial ice shapes, the T-103 wind tunnel was used. For example, Fig. 16 shows some results of investigation of the residual ice influence on the lift of a general-aviation-aircraft semispan wing model. Due to a small size of the aircraft the model has a fairly large scale of 1:2.7. The ice simulators in the form of abrasive cloth strips were attached near the wing leading edge. The position of the ice simulators on the upper and lower surfaces varied. According to the experimental data, changing the distance from the wing leading edge to the simulator on the lower surface within the range of $\bar{x}_{lower}$≈0.02-0.06 of local chords has little effect on the lift. On the other hand, the ice simulator on the upper surface significantly decreases the lift. At a flap deflection angle of $\delta_f$=20°, for example, the maximum lift drops by 36% for $\bar{x}_{upper}$≈0.021 with ice simulators having the thickness of only $\bar{h}$=0.0017 in fractions of MAC (Fig. 16).

For testing aircraft models at TsAGI, the T-106 and T-128 wind tunnels are extensively used. They are suitable for conducting researches at large Mach numbers, including complex transonic flows, and also conducting tests under raised pressure for increasing Reynolds numbers. As a rule, the aircraft model test programmes include tests with artificial ice shapes. The importance of proper Reynolds numbers follows from Fig. 17, which shows the comparison of lift curves $C_L(\alpha)$ obtained in the tests of the aircraft model with and without artificial ice shapes at normal pressure

($Re=0.9\cdot10^6$) and pressure raised to P=5 atm ($Re=4.6\cdot10^6$). It can be seen that the lift curve $C_L(\alpha)$ for the clean model at larger Re goes noticeably further to reach the stall than for the model with the artificial ice shape.

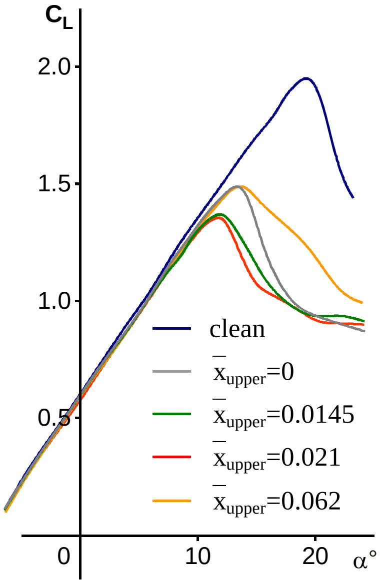


Fig. 16. The lift losses of the semispan wing model of the general aviation aircraft for various positions of the residual ice simulators on the upper surface, the ice simulator thickness is of h=0.8 mm (0.0017 MAC), $\delta_f=20°$

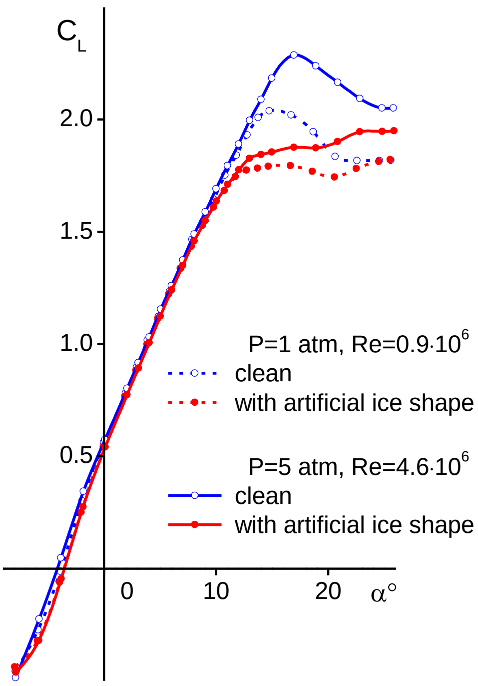


Fig. 17. The influence of Reynolds number on $C_L(\alpha)$ curves for the aircraft model in the T-106 wind tunnel

The tests of relatively small models with artificial ice shapes may impose stricter requirements for the precision of artificial-ice-shape manufacturing. That is why, in recent times, the 3D-printing technologies based on 3D models of artificial ice shapes have found applications (Fig. 18).

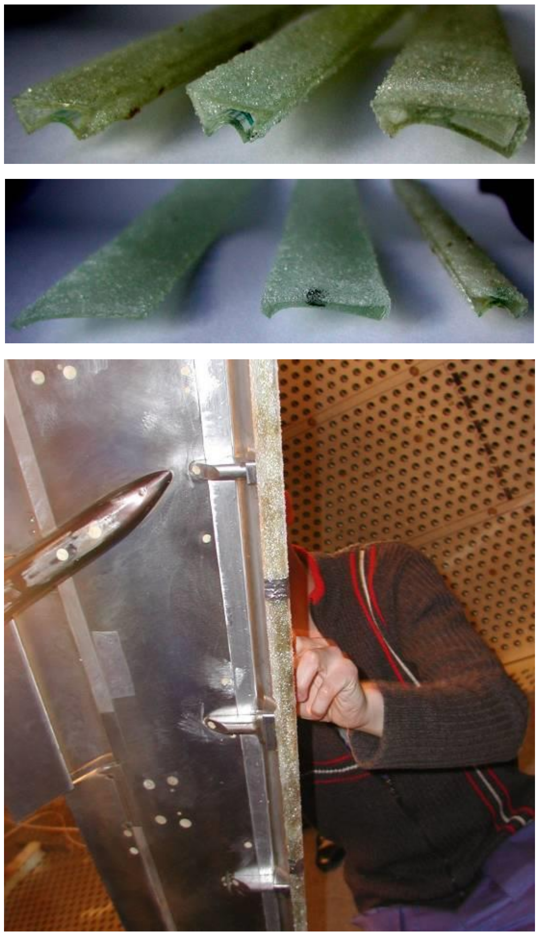

Fig. 18. The artificial ice shapes manufactured using the 3D-printing technologies on the slat of an aircraft model in the T-128 wind tunnel

## 5 Comparison with flight tests

The test results acquired for a series of large-scale models in the TsAGI T-101 wind tunnel satisfactory agree with the flight data for aircraft with artificial ice shapes (Fig. 19).

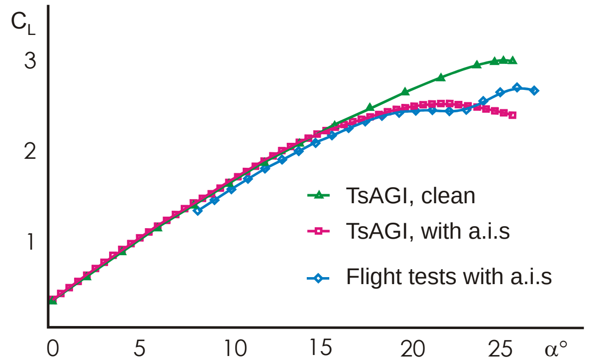


Fig. 19. The comparison between the flight data and tests in the T-101 wind tunnel for an aircraft with artificial ice shapes

## 6 General analyses of the researches

The bulk of data acquired at TsAGI during many years of the researches into the icing effects on aerodynamic characteristics of different aircraft types is currently systematized and digitized. Based on these data, the reference book "Influence of various artificial ice shapes on aerodynamic characteristics of large-scale aircraft models and their components", the manuals for increasing flight safety (volume 1 for general aviation aircraft, volume 2 for swept-winged aircraft, volume 3 for turboprop aircraft), and also the computer data base (Fig. 20) are created and kept being revised.

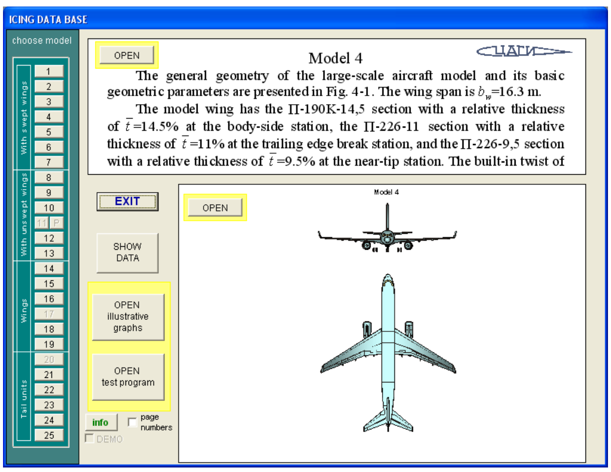


Fig. 20. The computer data base on the influence of artificial ice shapes on the aerodynamic characteristics of aircraft models

## 7 Conclusion

TsAGI has the unique experimental facilities and practical experience for conducting researches of aircraft models with artificial ice shapes in order to estimate the icing effects on aerodynamic characteristics. It allows for faster aircraft certification, reduces risks and costs of flight tests, and improves regularity of flight schedules.

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