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TECHNICAL MEMORANDUMS

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

No. 888

ICE FORMATION ON WINGS

By L. Ritz

Hauptversammlung der Lilienthal-Gesellschaft für Luftfahrtforschung, Berlin, October 12-15, 1938

Washington
February 1939

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By L. Ritz

The important findings which Dr. Findeisen presented in his very interesting paper give some extremely useful information on the manifold possibilities of atmospheric conditions under which ice formation on the airplane can occur. In agreement with what has been found in practice, it follows that the icing layers of the atmosphere cannot always be avoided by navigating around them and hence there is still to be found an answer to the problem of the effect of ice formation on the airplane.

I shall not go into the qualitative considerations that already have received extensive treatment, considerations which show that the ice formation leads to certain functional disturbances of the individual airplane parts as, for example, the wing, propeller, windshield, control members, antenna, instruments, etc., where in individual cases the deposit of ice may result in serious consequences and be especially dangerous if, as is generally to be expected, several functional disturbances arise simultaneously. I should like to give here a quantitative discussion of only one of the most important cases of ice formation, namely, icing of the wing.

I shall make use of the results obtained in the Göttingen ice tunnel in which the atmospheric conditions are simulated and the process of ice formation photographed (figs. 1 to 4).

The effect of ice formaton, such as that shown in figure 2 on an airplane in flight, is threefold:

1) Added weight to the airplane.

2) A change in the lift and drag forces.

3) A change in the stability characteristics.

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*"Vereisung." Reprint of paper presented at meeting of Lilienthal-Gesellschaft für Luftfahrtforschung, October 12-15, 1938, Berlin.

Considering, for example, a twin-engine airplane of the type HS 124, ice deposit of 2- to 4-centimenter thickness means an added weight of about 190 kilograms. This additional load is only of slight significance in comparison with a gross weight of 7.5 tons. What is of importance, however, is the change in all of the aerodynamic characteristics as a result of the profile changes brought about by the ice layer.

Figure 5 shows two polars, one of which corresponds to the normal wing, the other to the same wing with ice deposit. The considerable reduction obtained in the horizontal speed is generally of secondary importance. Of greater importance is the considerable lowering in the ceiling height. Simultaneously, the airplane may become neutral or unstable as a result of a number of factors as, for example, the weight of the ice accretion at the wing nose, the change in the air forces on the wing and their points of application, the manner of the ice distribution over the wing span, the change in the downwash angle, and, finally, the icing of the tail itself. By the large number of ways in which these effects may be combined is to be explained the nose-heaviness or tail-heaviness and the impairment in the stability characteristics that may result through ice formation. Particularly vexing is the ice formation on a constructional element which originally serves to improve the stability characteristics, such as the slot, for example, in figure 6, which is put out of operation through the ice formation, as shown in figure 7. It is also possible for the elevator to freeze solid and no longer be available for balancing the lowered stability characteristics, as shown by the same film strip.

It is clear from the above that an intensive study appears to be necessary in order to judge the effect of wing icing. This problem is considerably further complicated by the fact that the ice formation is not at all unique but occurs in a variety of forms whose origin depends essentially on the meteorological conditions, the speed of flight, and the profile shapes, the effects of which may be quite different. The photographs show the manner of formation of three different ice deposits, which we shall denote as clear ice (fig. 8), rime (fig. 9), and hoar frost (fig. 10). The various effects of the different profile distortions on the aerodynamic characteristics are shown by the flow photographs. (The film strip compares the flows about a smooth profile, one with clear ice deposit (fig. 11) and one with rime deposit (fig. 12). It ap-

pears that the flow about the smooth profile separates last and the one with rime first.) These flows correspond to the three polars (fig. 13), which bring out clearly the effects of each type of ice deposit.

CAUSES OF ICE FORMATION

It may at first appear peculiar that all three types of ice deposit are obtained at equal wind velocity and air temperature. The question thrus arises, what is the essential condition for ice formation. Before answering this question, we shall first consider several well-known attempts at explanation.

In the literature on the subject there is often pointed out the danger to which an airplane is exposed if, on coming out of a cooler air mass, it flies into a warmer, saturated one, since, due to the undercooling, ice formation is to be expected. That this danger is actually not very great may be shown by a simple heat computation. For example, a Ju 52 which has assumed a temperature of -15° C. and suddenly enters an air mass of -5° C. would, on account of the undercooling, be covered by a uniform sheet of ice of about 2/100-millimeter thickness until complete temperature balance is reestablished. Only the liberated sublimation heat has here been taken into account. The simultaneously occuring heat conduction from the air even further reduces the ice thickness. Also in the presence of droplets, in spite of the low crystallization heat of water, an ice layer of less than only 2/10 millimeter would be deposited until the undercooling of the airplane has been removed. Actually, however, ice is formed principally at the wing nose of a thickness that may often attain several centimeters. The undercooling of an airplane cannot be given, therefore, as a principal cause of the ice formation.

Of similarly small significiance is the electrostatic charge of the precipitation and cloud particles. Solid cloud particles likewise do not lead to any icing if they are not mixed with liquid particles. There is thus obtained as the fundamental condition for ice formation the presence of floating liquid cloud droplets or falling rain in the fluid state.

We shall now briefly consider whether the fluid particles measured in the atmosphere are actually in sufficient

quantity to explain the observed thicknesses and rates of ice formation. There is here to be taken account of the fact that not all the water droplets in the space passed through by the airplane actually impinge on the wing. In particular, the smaller droplets, due to their smaller inertia, will be better able to follow the streamlines and therefore partially flow around the wing. Figure 14 shows the relations which obtain. Although the results are applicable to the cylinder, they nevertheless apply approximately to airplane wings. The abscissa is the velocity in kilometers per hour and the ordinate the ratio of quantity of water intercepted to that existing in the flight space, expressed in percent. The droplet diameter in centimeters is taken as parameter. The computation was carried out for two cylinders of 1- and 0.5-meter diameter, respectively. It may be seen from the curves that for all flight velocities rain is almost completely intercepted, drizzle up to about 60 percent, while fog is intercepted up to only about 50 percent at most. It may be seen further that a thinner wing catches relatively more droplets than a thicker one. This theoretical result was confirmed by test. Figure 15 shows four NACA 2412 profiles of 25, 50, 100, and 200 centimeter chord, respectively, on which ice was allowed to form under the same conditions. It is seen that the deposit on the smaller sections is relatively thickest and, moreover, has a shape different from the deposits on the larger sections, a fact which will be explained below.

Figure 16, showing the ice deposits reduced to the same wing chord, brings out this phenomenon still more clearly. For a flight velocity of 100 meters per second, a wing thickness of 0.5 meter and a mean water content of the air computation gives a rate of ice accretion of 12 millimeters per minute. The assumption is here made, however, that all the water impinging on the surface freezes and is not partially blown off. It is thus seen that each rate of ice formation may be explained solely on the basis of proportion of droplets intercepted.

The time required for completely solidifying the droplets is a factor of importance in determining the type and shape of the ice deposit. This depends on how rapidly the heat liberated during the crystallization is conducted away. Crystallization is started by the impinging of the undercooled droplet on the surface. Since the latent heat of freezing is 80 calories while the specific heat of the water is only 1 calorie, only a small amount of ice formation is necessary for warming up the remaining water con-

siderably. The temperature gradient thus set up leads to a transfer of heat from the surface of the water to the air. This is generally not sufficient, however, to carry off completely the liberated heat of fusion.

The rapid solidifying of the droplets must therefore be explained by still another effective process that occurs; namely, the process of evaporation. For a more accurate estimation of the two factors let us consider a water surface of temperature t_w. Corresponding to this surface temperature is the saturation vapor pressure p_w. The moist air in contact with the water surface is assumed to be of temperature t_o and the water vapor contained in the air to have the partial pressure p_o. Under these conditions, two processes will occur. As a result of the temperature difference, there will be a heat exchange and as a result of the vapor pressure difference, there will be a mass exchange, the corresponding equations being:

$$Q_2 = G\ r$$

$$Q_1 = \alpha\ F\ z(t_w - t_o)$$

$$G = \frac{\beta\ F\ z}{R\ T_m}(p_w - p_o)$$

where $\alpha \frac{\text{kcal}}{m^2\ h\ {}^oC}$ is the heat-conductivity coefficient

F, the surface area (m^2)

z, time (h)

t, temperature ($^oC.$)

Q, quantity of heat (kcal)

β, evaporation rate (m/h)

R, gas constant ($m/^oC.$)

T_m, mean absolute temperature ($^oabs.$)

r, heat of evaporation of 1 kg of water $\left(\frac{\text{kcal}}{\text{kg}}\right)$

G, quantity of water evaporated (kg)

$$Q = Q_1 + Q_2$$

Due to the temperature drop, a quantity of heat Q_1 calories passes from the surface to the air

$$Q_1 = \alpha\ F\ z(t_w - t_o)$$

Due to the pressure drop, an exchange of mass G occurs:

$$G = \frac{\beta\ F\ z}{R\ T_m}(p_w - p_o)$$

As a result of the exchange in mass, there is a further heat exchange

$$Q_2 = G\ r$$

where r is the heat of evaporation of 1 kilogram of water and is about 600 calories. The total heat quantity conducted away is thus

$$Q = Q_1 + Q_2$$

It may be shown now that in the temperature range about 0° C. $Q_1 : Q_2 = 3:2$, approximately. As follows from the above formulas, the value of Q_1 depends essentially on the heat conduction coefficient and the temperature difference, the value of Q_2 essentially on $p_w - p_o$, that is, the vapor-pressure difference between the water surface and the air in contact with it and further on the evaporation coefficient.

In order to obtain an idea as to the magnitude of the evaporation, we recall that the evaporation coefficient is approximately proportional to the heat convection coefficient and like the latter increases with increasing speed. The more detailed relations are shown in figure 17 of the English measurements (reference 1) where the heat convection coefficient is plotted against the distance along the wing section. We see that this coefficient and hence also the evaporation rate is large in the neighborhood of the stagnation point. A second maximum occurs on the upper surface. The dependence on the speed is similarly shown on figure 17.

The impinging of the water droplets is likewise great-

est in the neighborhood of the stagnation point (leading edge). The equilibrium in the atmosphere between the droplets and the air with respect to the vapor pressure is disturbed by the impinging of the droplets on the wing since, as already mentioned, a portion of the water freezes and the heat of crystallization thus liberated warms up the rest of the water so that the vapor pressure on the water surface rises. The vapor pressure and temperature drops thus arising then lead to the heat conduction given by the above equations.

According to the above, therefore, a droplet freezes immediately at the place it impinges if the heat liberated in the crystallization is conducted away so rapidly that the droplet does not reach the 0° limit.

This condition can be satisfied in a number of ways as a result of the large heat convection at the wing nose. In this case a sharp ice nose is formed. If, on the contrary, the impinging quantity of water and consequently the crystallization heat to be conducted away is so large, or the differences in temperature and vapor pressure so small that the zero degree limit is reached on the wing nose, there is sufficient time for the droplet to melt. In this case there is formed a more or less broad ice nose, which finally, as a result of the increased heat convection may grow at its two edges into a double nose.

We thus see that the various types of ice formations observed even for the same air temperature, air speed, and relative humidity may be explained by the heat transfer relations described above. From this follows another conclusion that should be borne in mind in airplane design, namely, that all rather sharp edges and projections, as for example, struts, bracing wires, rivet heads, etc., are, on account of the favorable heat-transfer relations, particularly subject to ice formation. Similarly, the notably rapid growth of the ice needles is explained.

I should like to show several more examples of ice formation photographed. The pictures were similarly taken in the ice tunnel of the aerodynamic testing laboratory. Figure 18 shows ice formation on struts and bracing wires, figure 19 on an antenna, figure 20 on an oil cooler, figure 21 on a static tube, and figure 22 on a nozzle. The disturbance of the regular flow in each case may be seen by comparison with figures 23 and 24. There is further shown for the first time a picture of ice formation on a propeller.

In addition to the lowering of the engine power, there may may be danger to the airplane and its occupants under certain conditions.

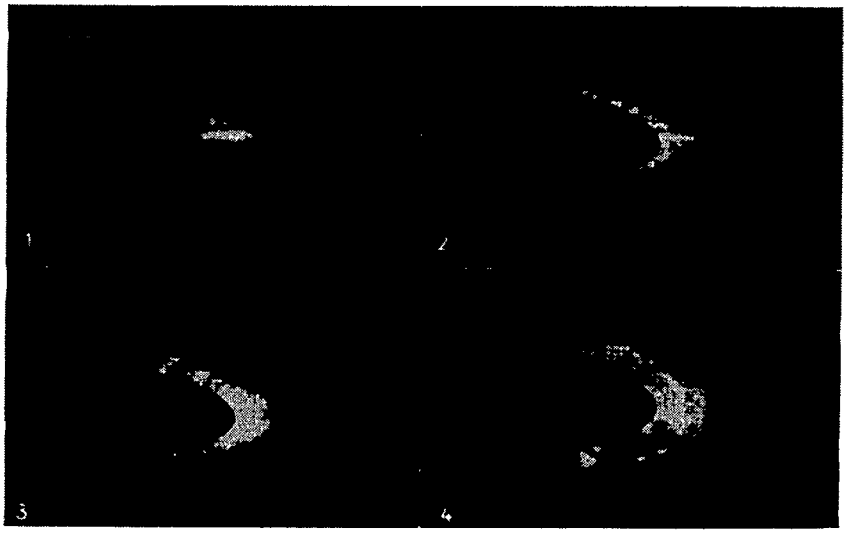
CONCLUSIONS

I had the honor of giving a brief outline here of our tests at Göttingen in connection with the ice formation problem. The more important problem of practical de-icing methods is similarly being given consideration. This latter problem can in our opinion receive a satisfactory solution only after the process of ice formation has been physically explained. Simultaneously with the information acquired, there is a rise in our demands for protection against ice formation. We thus require of a de-icer that it should prevent the ice formation at the very start and accomplish this result with the least expenditure in power and weight. The results already obtained with a de-icer developed in the course of our work, thanks to the enthusiastic support and cooperation, particularly of the Junkers company and the German Lufthansa, justify our hope that German aviation will be shortly in possession of a de-icer that satisfies even these extreme requirements. Nevertheless, the various development possibilities and particularly the adaptability to the most varied operating conditions and requirements are still far from being exhausted and give impetus to our further work on this problem.

Translation by S. Reiss,
National Advisory Committee
for Aeronautics.

REFERENCE

1. Bryant, L. W., Ower, E., Halliday, A. S., and Falkner, V. M.: On the Convection of Heat from the Surface of an Aerofoil in a Wind Current. R. & M. No. 1163, British A.R.C., 1928.



Figures 1-4.- Stages in the growth of ice formation. (GLAZE)

Figure 6.- Slot (extended).

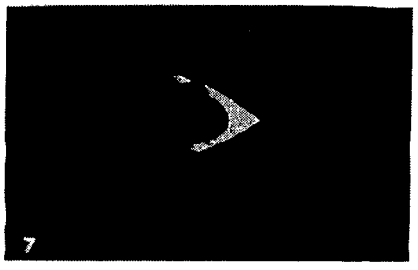


Figure 7.- Slot (made immovable by ice formation).

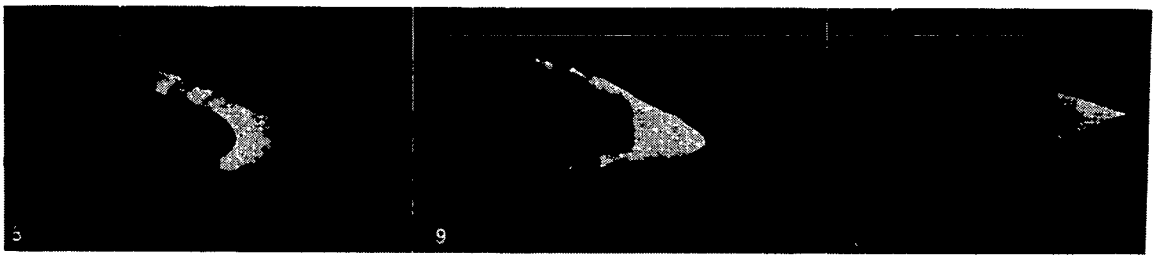


Figure 8.- Clear ice. GLAZE

Figure 9.- Hoar frost.

Figure 10.- Rime.

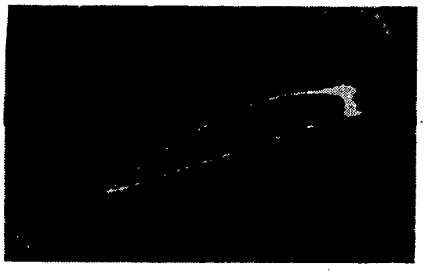


Figure 11.- Profile with clear ice in water tunnel.

Figure 12.- Profile with rime in water tunnel.

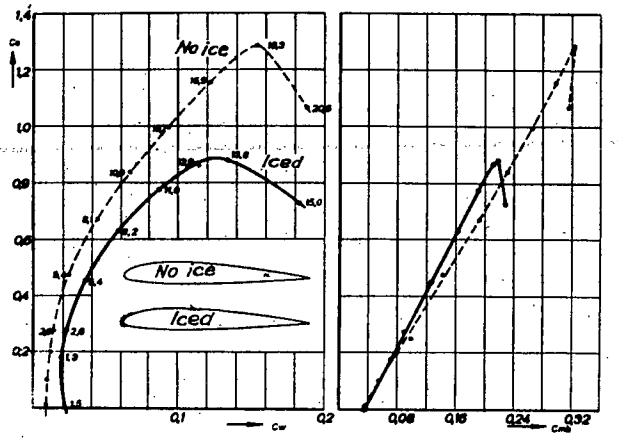


Figure 5.- Polars of a rectangular wing.

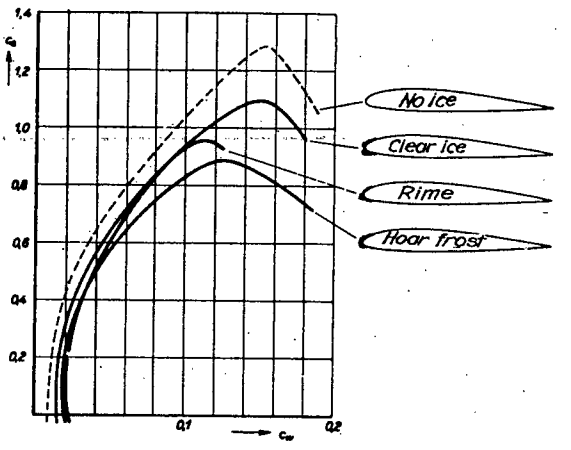


Figure 13.- Polars for three forms of icing.

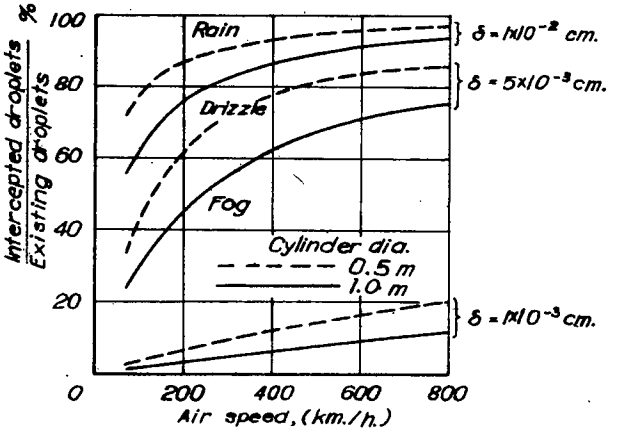


Figure 14.- Droplets intercepted by cylinder.

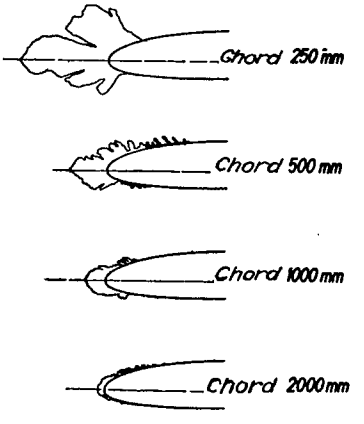


Figure 16.- Icing of NACA profile 2412 for various chords.

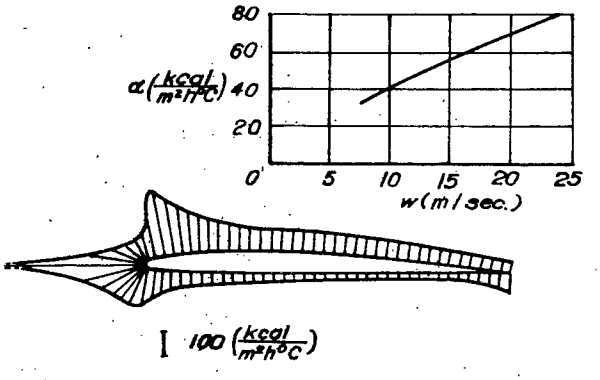


Figure 17.- Heat transfer at wing.

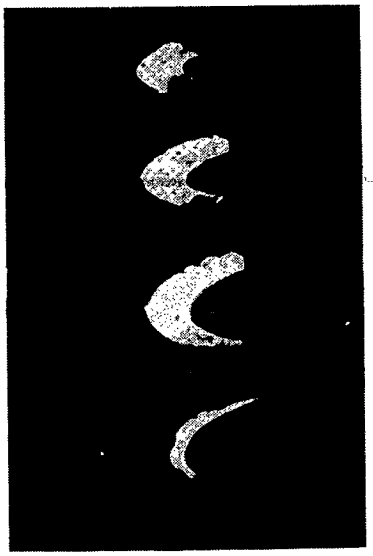


Figure 15.- Icing of profile noses of various chords.

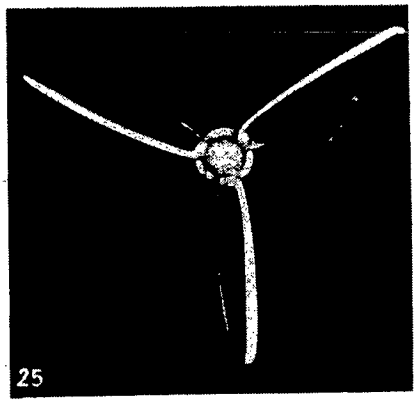


Figure 25.- Ice formation on propeller.

Figure 18.- Struts and bracing wire.

Figure 19.- Antenna.

Figure 20.- Oil cooler.

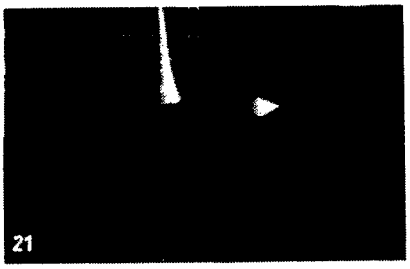


Figure 21.- Static tube.

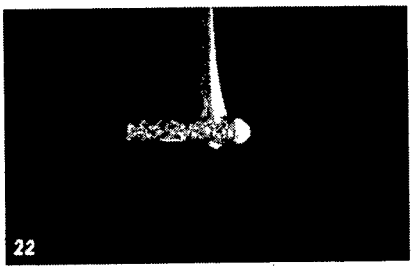


Figure 22.- Nozzle.

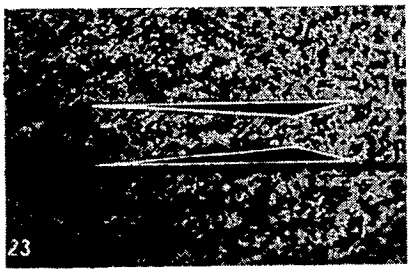


Figure 23.- Venturi in water tunnel (no ice formation).

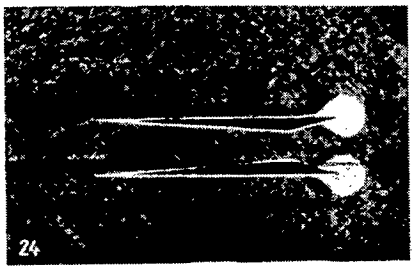


Figure 24.- Venturi in water tunnel (with ice formation).

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