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A FLIGHT INVESTIGATION OF EXHAUST-HEAT DE-ICING

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SUMMARY

The National Advisory Committee for Aeronautics has conducted exhaust-heat de-icing tests in flight to provide data needed in the application of this method of ice prevention. The capacity to extract heat from the exhaust gas for de-icing purposes, the quantity of heat required, and other factors were examined. The results indicate that a wing-heating system employing a spanwise exhaust tube within the leading edge of the wing removed 30 to 35 percent of the heat from exhaust gas entering the wing. Data are given from which the heat required for ice prevention can be calculated. Sample calculations have been made on a bssis of existing $\frac{\text{engine power}}{\text{wing area}}$ ratios to show that sufficient heating can be obtained for ice protection on modern transport airplanes, provided that uniform distribution of the heat can be secured.

INTRODUCTION

Previous NACA investigations (references 1 and 2) have indicated that the use of exhaust heat offered a practical means of providing ice protection to the airplane wing, but it has been found that additional data were necessary before full-scale application of this means could be undertaken. Tests have been made to determine how much heat can be taken from the exhaust gas and how much heat is required for ice protection. In addition, some observations were made on the temperature-distribution characteristics of model wings, the nature of the mechanics of ice prevention and removal, and methods of control in exhaust heating systems to aid in the interpretation of the data. Calculations were made to determine the applicability of the present result to several modern transport airplanes.

APPARATUS AND TESTS

The tests were conducted in flight on a model wing having an NACA 0012 section, a span of 4 feet, and a chord of 3 feet. The model wing was mounted between the wings on an XBM Navy biplane. The general view of the test apparatus is shown in figure 1. Figure 2(a) shows the model on the airplane, and figure 2(b) illustrates the interior construction of the model wing. The construction was similar to that used in all-metal wings having two spars and stressed skin. End plates were employed in order to preserve, as much as possible, the two-dimensional airflow characteristics. During one of the first flights, the outboard end plate was insulated from the wing to determine whether the heat flow from these plates should be considered, but it was found to be negligible.

In the tests conducted to determined how much heat could be extracted from the exhaust gas, an exhaust tube was placed inside the wing along the interior of the leading edge. (See fig. 2(b).) The mechanics involved in the heat exchange for the model in this form are explained with the aid of figure 3. Heat is transmitted from the exhaust tube to the wing skin by radiation and convection. The transmission by convection is controlled by changing the circulation of air through the model interior. Heat is picked up by the air between points A and B (fig. 3). The air follows a path through the after portion of the wing, as shown in figure 3, and loses a large part of its heat to the wing skin. Any heat remaining in the air is lost at the trailing edge through a discharge slot extending the entire span of the wing.

In the hot-air system, air was heated by an exhaust heater separated from the model, as shown in figure 4. A photograph of the model when heated by hot air is shown in figure 5(a). The heated air flows along the leading edge of the model and thence through the after portion, as it did when the exhaust tube was used. The heat transmission and the de-icing tests were made with the model adapted for the use of hot air because the more precise measurements were obtained with this method of heating.

The exhaust gas from two of the cylinders from the airplane engine was used as a source of heat in all the tests. The rates of flow of the exhaust gas and the air involved in the experiments were measured by the use of orifice meters. Temperature-difference measurements were made with thermocouples, while the ambient-air temperature was read from a strut mercury thermometer. The temperature changes measured in the exhaust gas and the circulated air, combined with the gas and the air-flow measurements, permitted a definition of the heat exchange in the model. The nature of the heat distribution was observed from temperature measurements at numerous points on the model skin. The positions of the skin thermocouples are shown in figures 3 and 4.

The wing was mounted on a support tube running spanwise at the 25-percent chord point and at the trailing-edge midpoint, as is shown in figure 2(a). The angle of attack of the model could be changed in flight by the rotation of the threaded rod extending upward from the lower airplane wing to the trailing edge of the model. All the tests were made at zero angle of attack. The attitude of the model was adjusted by equalizing the pressures of two static orifices at geometrically similar positions on the upper and the lower surfaces.

Visual records were obtained by photographing the ice formations and their removal with a 35 mm motion-picture camera. The camera and the mounting are shown in figure 1. Icing conditions were simulated by the discharge of water from spray nozzles in front of the model. The desired temperatures were obtained by flying at the proper altitude. The spray nozzles in operation are shown in figure 5(b).

Other apparatus for making the measurements, such as millivoltmeter, pressure recorders, heating controls, and thermocouple selector switches, were located in the observer's cockpit.

Test procedure.- All the tests were made at an air speed of 100 miles per hour and, as has been noted, at zero angle of attack. The heat transmission tests were made in "dry" air (no visible moisture) and in misty cloud formations which were thick enough to cause the wing surface to become thoroughly wetted. The tests in the clouds were taken to be representative of actual icing conditions, except that the temperature of the air was above, instead of below, 32° F. Because the tests were made to measure the heat transmission in which the temperature difference was observed, this deviation is believed to be a valid procedure. No attempt was made, therefore, to conduct these flights at any particular air temperature.

De-icing tests were made with air temperatures between 17° and 25° F. The spray nozzles produced a water-drop content in the air stream comparable with that in a very severe icing condition. A distinction was made in the testing procedure between ice prevention and ice removal. Ice-prevention tests were made to measure the heating requirements for the prohibition of any ice on the model wing. The ice-removal tests were made to observe the operation of and to measure the heat required for the removal of ice formed before the heat was turned on. Motion pictures were taken during the ice-prevention and the ice-removal tests.

RESULTS AND DISCUSSION

Characteristics of Exhaust-Tube System

The results of the tests to determine the capacity of the exhaust-tube model to remove heat from the exhaust gas are given in table I. The data indicate that the use of an exhaust tube in the leading edge of the wing provided a system that removed 30 to 35 percent of the heat from the exhaust gas entering the wing.

It was further observed that, by a reduction of the amount of air circulated within the wing, the capacity to extract heat from the exhaust gas was reduced only slightly and that a larger portion of the heat was dissipated from the forward 30-percent portion of the wing. Accordingly, the temperature rise of the leading-edge region was increased and the temperature rise of the after portion was decreased when the circulation of air was discontinued by sealing the baffle. The temperature rise of the after portion of the wing when the air circulation is stopped is largely due to the transfer of heat from the leading edge in a rearward direction through the boundary air. Although a chordwise distribution of heat may be obtained by the air convection over the outside of the wing, the heat given to the boundary-layer air forward can be only partly recovered by the wing surface rearward; therefore, heat is wasted. The most efficient use of the heat is obtained when the distribution results in a uniform temperature rise over the region that is to be protected.

Although the reduction of the quantity of air circulated through the wing may result in a reduction of the efficiency of the heating of the entire wing surface, a consideration of other factors indicates that the concentration of heat at the leading edge may be desirable. Some provision for increasing the quantity of heat that can be directed to the leading edge is desirable when extremely severe icing conditions are encountered. The leading edge should always be kept free from ice, even though accretions may form on the after portion of the wing because, as is shown by reference 3, surface protuberances over the forward 20-percent portion of the wing are of greater harm to the aerodynamic efficiency than are protuberances on the after portion. Recent flight tests on a wing that was equipped with an inflatable de-icer emphasized the conclusions of reference 3. The flight tests made on a full-scale wing with a mean aerodynamic chord of 94 inches showed that simulated ice formations 1/2-inch high in the vicinity of the de-icer attachment strips, which are about 7 percent back from the leading edge, resulted in a profile-drag increase of more than 350 percent and a decrease in $C_{L_{max}}$ of 59 percent.

Attention is called to the fact that the present results do not confirm the conclusions drawn from the preliminary tests of reference 1 as regards the effectiveness of heating only the leading edge. In the tunnel tests, a heating system that maintained the forward 10-percent portion of a model above 200° F under <u>dry-air</u> conditions had sufficient capacity to prevent and to remove ice formations over the entire wing. In the flight tests with the present model, eliminating the circulated air produced skin-temperature rises of about 200° F over the forward 18 percent of the model, but ice formed on the afterbody when the wing was subjected to icing conditions.

Meteorological observations indicate that icing conditions of great severity usually occur over only a limited geographical area and altitude range. A de-icing system, therefore, that can concentrate heat on the leading edge of the wing at the expense of the trailing-edge region is believed to be of particular value in storms of great severity because the leading edge can be kept continuously clear, and the ice which may form near the trailing edge of the wing can be removed after the storm center has been passed.

Heat Transmission Tests

The transmission of heat from the model wing is given in coefficient form in table II. A comparison of the results obtained in the present investigation with those given in reference 2 is made possible by the inclusion in the table of a calculated heat-transfer coefficient based on the wing chord and the air-stream velocity during the present tests. The heat-transfer coefficient α was calculated from the formula

$$\alpha = \frac{Q}{\Delta T(A)}$$

in which Q is the heat transmitted from the model wing, Btu per hour; ΔT, the average temperature rise of the model skin above ambient air, degrees Fahrenheit; and A, the total surface area of the model, square feet. (In this report the total surface area is approximated by using a value equal to twice the product of the wing span and chord.) It is noted that the dry-air coeffieicent obtained in the present tests is about 82 percent of the calculated values from reference 2. The fact that the present tests were made with an NACA 0006 airfoil, whereas the previous work was done on a Clark Y section, may explain the difference. The present measurements are believed to be accurate to within ±5 percent.

The possibility of deriving equations that would make the results of the present model flight tests applicable to full-scale design was suggested by a study of reference 2. From the data provided in this reference, an equation was derived to express the heat-transfer coefficient for any airfoil of a known chord and at any velocity, provided that the coefficient is available for an airfoil that is similar in section, of a known chord, and tested at a known velocity.

The derived equation is:

$$\alpha = \alpha_o \frac{c_o}{c} \left(\frac{V\ c}{V_o\ c_o} \right)^n \qquad (1)$$

in which

α heat transfer coefficient, Btu/hour/square foot/ degree Fahrenheit

c wing chord, feet

V velocity, miles per hour

n exponent determined by angle of attack

and the subscript

o denotes present test conditions

From reference 2, at cruising angles of attack n is approximately 0.8. It seems more reasonable that n could be expressed as a function of the average air velocity over the surface in question rather than as a function of the angle of attack, as in reference 2. Some characteristic of the airfoil, such as the lift coefficient, could then be used to replace the average-velocity term, and the exponent n would have a more general meaning. Because further data are not available, however, the value of 0.8 used is assumed to be correct. If the values from the present tests of 20, 100, and 3 are substituted in equation (1) for α_o, V_o, and c_o, respectively, the following equation is written:

$$\alpha = 0.6 \frac{V^{0.8}}{c^{0.2}} \tag{2}$$

If it can be assumed that a uniform temperature rise has been obtained over the entire airplane wing, the minimum heat required to prevent ice formations, Q_{min}, is given by

$$Q_{min} = \alpha(32 - T) A \tag{3}$$

in which T is the ambient-air temperature, degrees Fahrenheit; A, the total surface area heated, square feet; and Q is given in Btu per hour. The minimum heat Q_{min} may be expressed as a function of airplane chord and speed, and the ambient-air temperature may be expressed by substituting the value of α from quation (2) in equation (3)

$$Q_{min} = 0.6 \frac{V^{0.8}}{c^{0.2}} (32 - T) A \tag{4}$$

If the temperature rise over the wing is not uniform, the required heat according to equation (3) will be in error, the extent of which will depend upon the temperature variation over the wing.

Ice-Prevention and Ice-Removal Tests

The temperature rise, during the ice-prevention tests, over the model wing surface varied rather widely from the leading edge to the atrailing edge; therefore it was expected that the heat expended for ice prevention would be in excess of the calculated heat required.

The results of the ice-prevention and the ice-removal tests are given in table III. Several of the ice-removal tests were repeated for photographic pruposes, during which flights ice formations on the leading edge varying from 1/2 to 1 inch in thickness were removed 10 to 30 seconds after the heat was admitted to the model. The results from two different ice-prevention tests are included in the table. In the first tests, the heat supplied was gradually reduced until ice formations were noted; then the heat was slowly increased until all the ice was removed. In the second tests, the heat was reduced until the ice started for form but did not spread beyond a small region near the trailing edge. The residual ice on the wing during a typical test of this kind is shown in figure 6.

On a basis of the heat-transmission tests, the heat input of 567 Btu per hour per square foot corresponds to an average calculated temperature rise of about 30° F. Because the outside-air temperature was 24° F, a temperature rise of only 8° F was required. Thus, without a uniform temperature rise, the quantity of heat required for ice prevention would be several times as great as would be predicted by the use of equation (3).

Several ice-removal tests were made to observe, with the motion-picture camera, the manner in which the ice was eliminated. In each instance, the ice covering the leading edge was removed in less than 30 seconds and, as shown by the results in table III, in as low as 10 seconds. Figure 7 shows the type of ice formation that was removed, and figure 8 shows the same formation a few seconds after the heated air was admitted to the wing. The blurred regions on the photograph are pieces of ice being blown away from the wing. Ice formations on the after portion of the wing were readily removed when heated air was circulated throughout the interior of the wing. When the model that was heated by the exhaust tube was tested without internal-air circulation, the removal of ice from regions near the trailing edge (icing conditions being discontinued) was slow, and a greater total quantity of heat was employed than during other successful ice-removal tests.

Application of Test Results

The design of ice-prevention equipment that uses exhaust heat is principally a problem of heat distribution. The important considerations in the problem are: (1) the range of ambient-air temperature over which protection is desired; (2) the ratio of exhaust thermal energy to the surface area to be protected; and (3) the extent to which a uniform temperature rise can be obtained over the heated region.

For any particular geographical location, the temperature range common to icing conditions is a factor that can be defined only by statistics. The information of the temperatures at which icing conditions have occurred on the North American continent is limited. On a basis of reports on air-line operations within the United States, however, severe icing occurs with the greatest frequency at temperatures above 15° F. Reports received indicate that in Canada severe icing conditions occasionally occur at still lower temperatures. Inasmuch as the most common icing condition occurs just slightly under freezing temperature and at the higher temperatures the largest amount of water is encountered, it will be assumed, for purposes of this analysis, that the temperature rise over the protected area must be not less than 17° F. This rise would be sufficient to give ice protection at air temperatures of 15° F or above, provided that the temperature distribution over the wing surface is uniform.

An analysis has been made on the basis of the characteristics of 12 modern transport airplanes to determine what temperature rise might reasonably be expected if 30 percent of the available exhaust heat is applied to wing heating. Although several assumptions and qualifications must be made in such a study, it is believed that this analysis is a good indication of the applicability of the exhaust heating system. Two assumptions have been made: (1), that the available exhaust heat is equal to the engine power at maximum speed; and (2), that this heat will be uniformly applied to the entire wing surface. Actually, the exhaust-gas energy wasted by the modern engine is in excess of the useful power and, therefore, if the heat is used economically, the first assumption will be valid. The second assumption also appears to be conservative because portions of the wing covered by the fuselage or engine nacelles may not require protection from ice formations. It may be shown by reference 3 that a large part of the lifting surface in the trailing-edge region could be covered with ice and would not produce a great loss in aerodynamic efficiency of the airplane, although a protection for the flaps and the ailerons should be provided.

On the basis of these assumptions and the results of the present investigation, the temperature rise resulting from the use of an exhaust tube inside the leading edge of the wing has been calculated. An approximation of the applied heat per square foot, q, is given by the equation

$$q = \frac{P}{2S} (E), \quad \text{Btu/hour/square foot} \qquad (5)$$

in which

P engine power at V_{max}, Btu per hour

S wing area, square feet

E exchange efficiency of heating system, 30 percent

The transmission coefficient has been calculated from equation (2) for the 12 transport airplanes previously mentioned on a basis of the average wing chord and maximum velocity V_{max}. From a knowledge of the heat applied q and the heat-transfer coefficient α, an average temperature rise ΔT for the lifting surfaces has been calculated by the use of the equation

$$\Delta T = \frac{q}{\alpha}$$

The results of these calculations are shown plotted in figure 9, which indicates that a satisfactory temperature rise can be obtained. The plotted points that show the greatest wing-surface temperature rise refer to the most recent airplane designs, which indicates that the present design trend is toward a greater potential heating capacity for the wing surface.

When the excess temperature rise in figure 9 is considered, that is, the horizontal displacement of the plotted points from the line that is designated 17° F, it should be remembered that the location of the points is based upon the uniform distribution of the temperature. In any practical case, some departure from this condition will be noted and a smaller temperature rise than indicated will be obtained.

Experience in the design and the operation of wing-heating systems for de-icing should bring improvements in the uniformity of heat distribution and greater efficiency in removal of heat from the exhaust gas. In view of the favorable results of NACA investigations on the application of heat in de-icing and also in consideration of the reports that have been received describing the successful application of exhaust-heat de-icing on numerous four-engine transport airplanes in Germany, it is believed that full-scale application of this method should be undertaken at an early date in the United States. A full-scale application of exhaust-heat de-icing is planned by the NACA in cooperation with the Army Air Corps, from which it is hoped will be obtained additional data on the application and the operation of this heating method.

CONCLUSIONS

1. A wing with an exhaust-gas tube running spanwise inside of the leading edge provided a system capable of removing 30 to 35 percent of the heat from the exhaust gas entering the wing.

2. Heat-transmission tests in misty cloud formations indicated that the heat required for ice prevention may be calculated from an equation involving the airplane speed and chord, and the ambient-air temperature.

Langley Memorial Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., September 24, 1940.

REFERENCES

1. Rodert, Lewis A.: A Preliminary Study of the Prevention of Ice on Aircraft by the Use of Engine-Exhaust Heat. T.N. No. 712, NACA, 1939.

2. Theodorsen, Theodore, and Clay, William C.: Ice Prevention on Aircraft by Means of Engine Exhaust Heat and a Technical Study of Heat Transmission from a Clark Y Airfoil. Rep. No. 403, NACA, 1931.

3. Jacobs, Eastman N.: Airfoil Section Characteristics as Affected by Protuberances. Rep. No. 446, NACA, 1932.

TABLE I.- Heat Exchange Data from Exhaust-Tube-Model Tests

Air circulated through model (lb/sec)	Heat content of exhaust gas entering model wing above ambient air (Btu/hr)	Heat removed from exhaust gas by model (Btu/hr)	Heat transmitted through skin of model (Btu/hr)	Percentage of heat entering wing removed by model system	Percentage of removed heat transmitted through model skin	Efficiency of exhaust tube model (percent)
0.19	259,000	100,500	89,000	39	89	34
.16	251,000	86,000	74,500	34	87	30
0	284,000	96,000	96,000	34	100	34

TABLE II.- Heat Transmission Data from Hot-Air-Model Tests

Weight of air circulated (lb/sec)	Heat added to circulated air (Btu/hr)	Heat transmitted from model skin, Q (Btu/hr)	Efficiency of model heat exchange (percent)	Average temperature rise of model skin above ambient air ΔT ($^{\circ}F$)	Heat transmission coefficient, α (Btu/hr/sq ft/$^{\circ}F$)	Calculated heat transmission coefficient from reference 2 (Btu/hr/sq ft/$^{\circ}F$)	Surface condition of wing
0.18	44,500	30,500	69	78.3	16.2	19.7	Dry
.19	45,000	29,900	66	65.3	19.1	-	Wet

TABLE III.- Ice-Prevention and Ice-Removal Data (Hot-Air Model Wing)

Air circulated (lb/sec)	Heat dissipated through model skin (Btu/hr/sq ft)	Outside air temperature °F	Type of tests	Remarks
0.08	917	23	Prevention	Ice prevented over entire wing
.046	567	24	Prevention	Ice formed along the trailing edge (see fig. 6)
.176	1300	24	Removal	Ice removed over the leading edge in 10 seconds.

Figure 1.- General view of XBM airplane, showing wing heated by hot air, and motion-picture camera mounted above and in front of model.

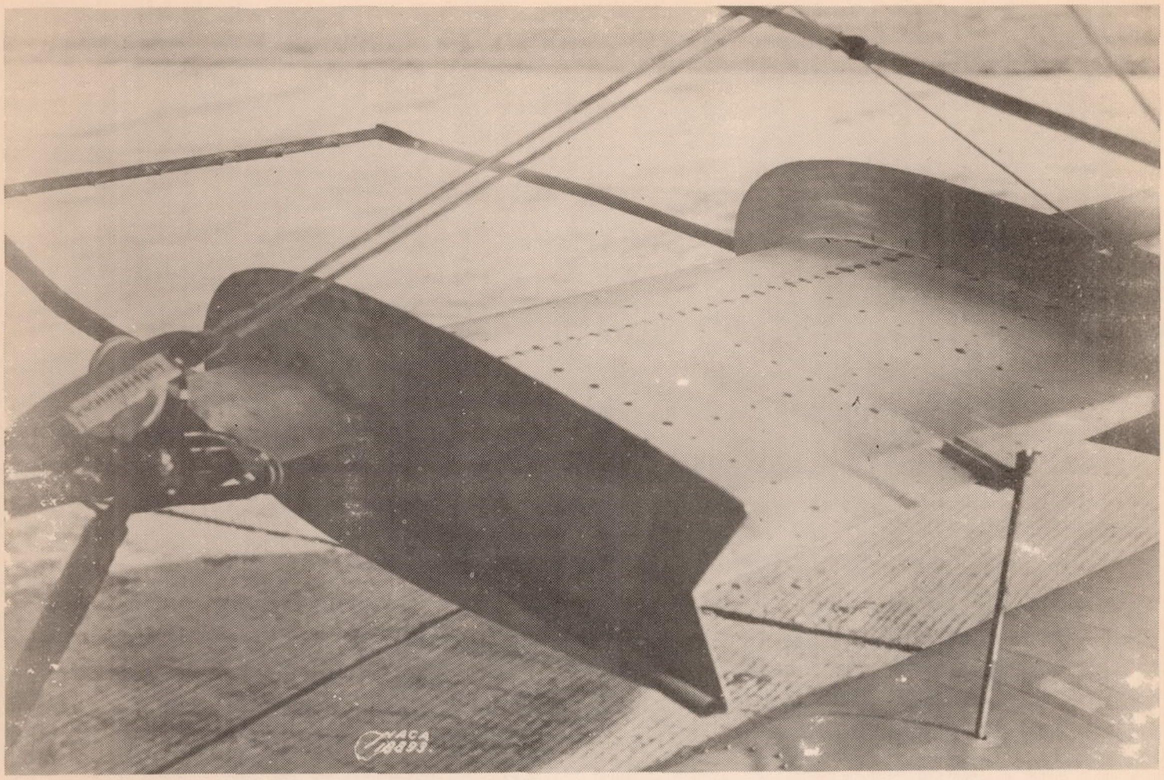

Figure 2a.- Model wing heated by exhaust tube and mounted on XBM airplane for flight tests.

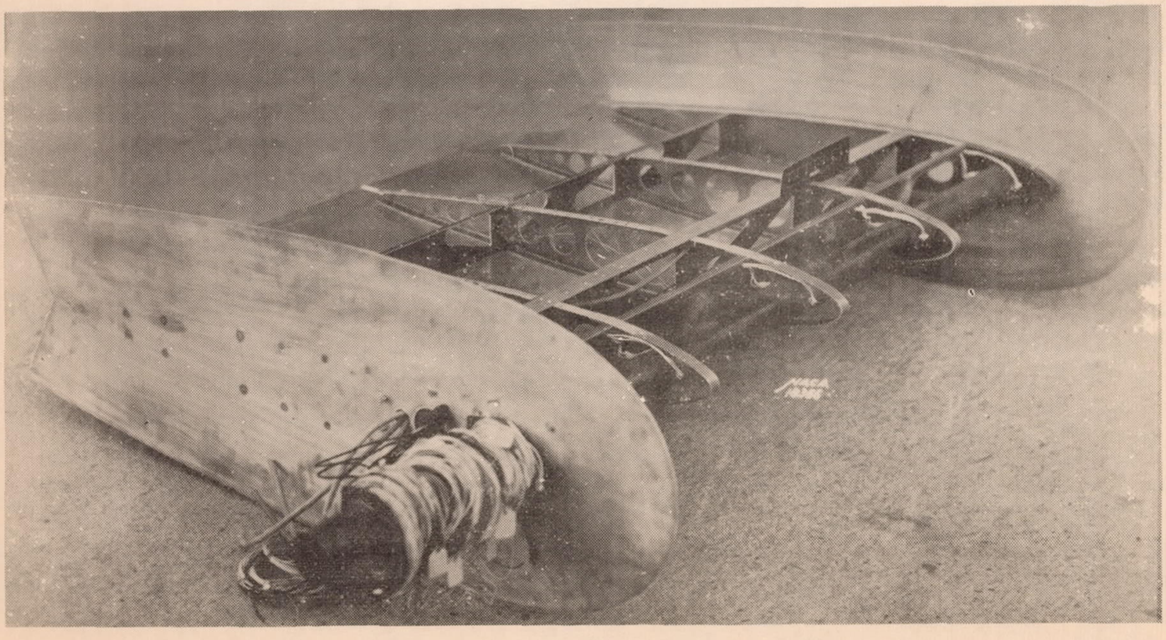

Figure 2b.- Model wing in construction showing exhaust tube along interior of leading edge.

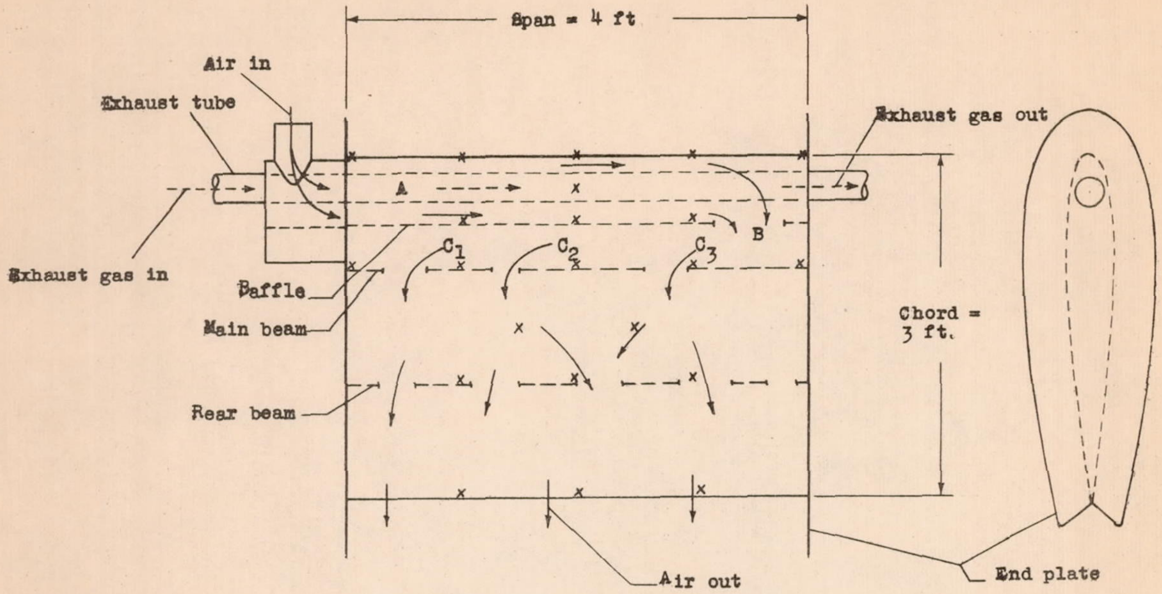

Figure 3.- Set-up of wing heated by exhaust tube, showing path of exhaust gas and air through the model and the location of skin-temperature thermocouples, x.

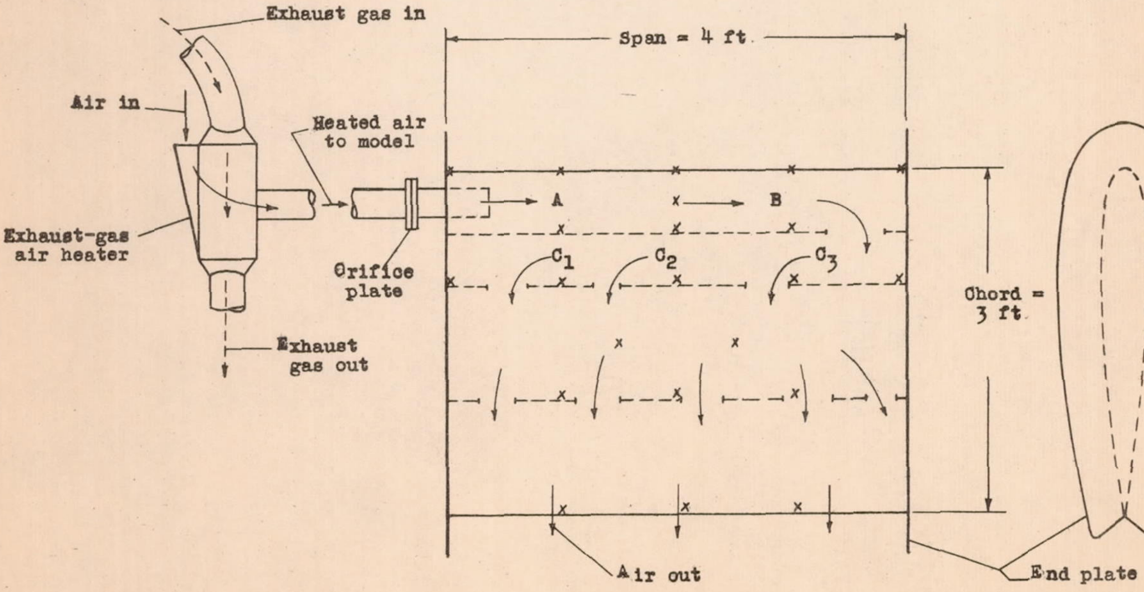

Figure 4.- Set-up of wing heated by hot air, showing path of heated air through the model and the location of skin-temperature thermocouples.

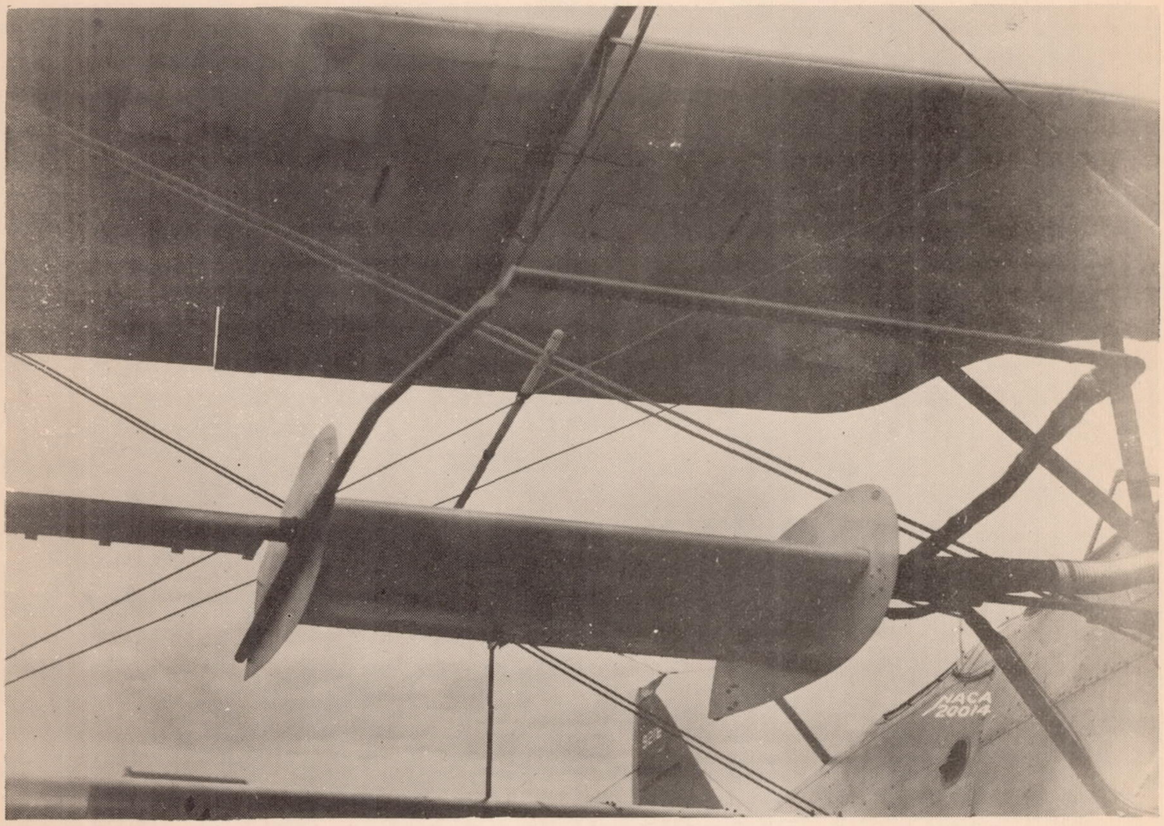

Figure 5a - Wing, heated by hot air, mounted on XBM airplane for flight tests.

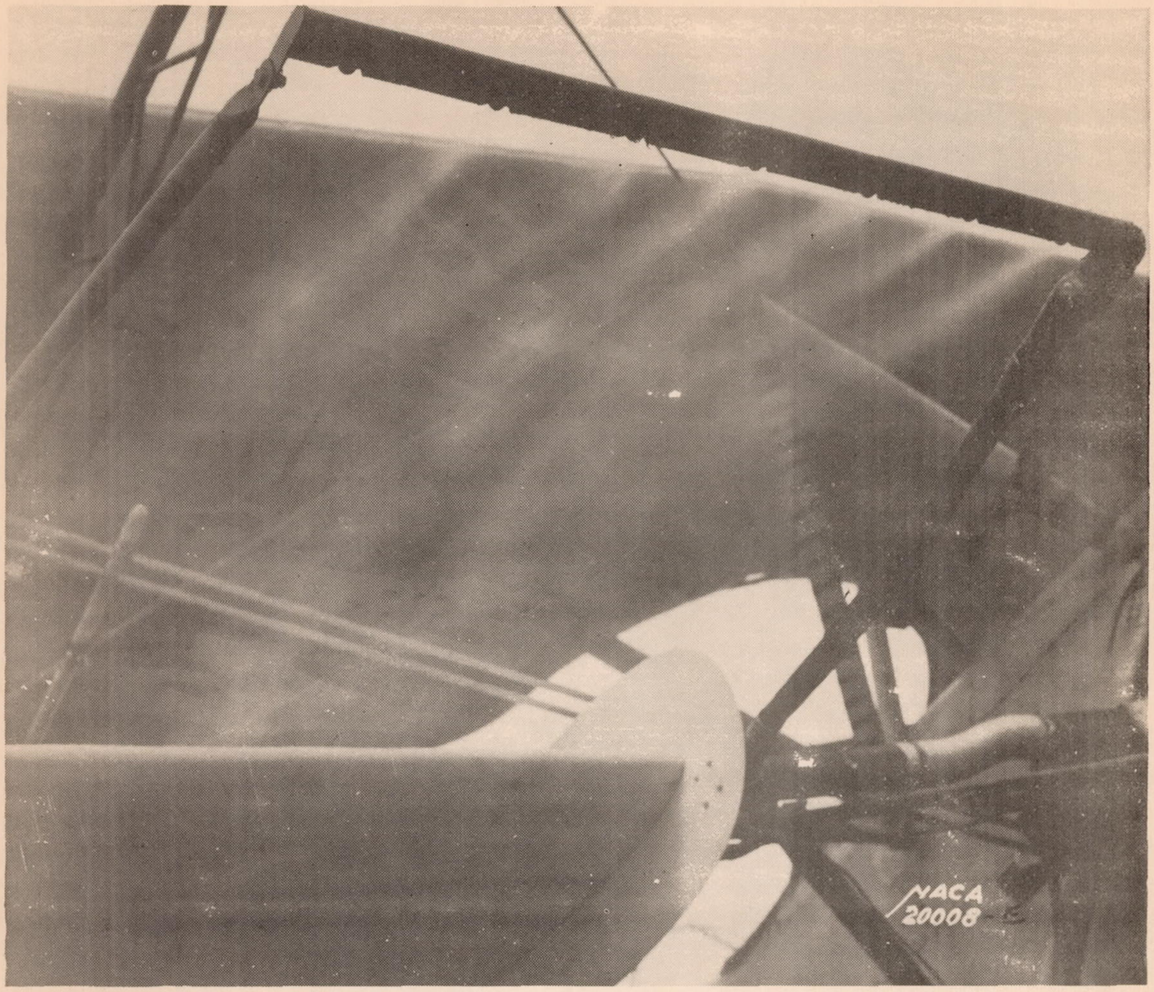

Figure 5(b).- Spray nozzles in operation.

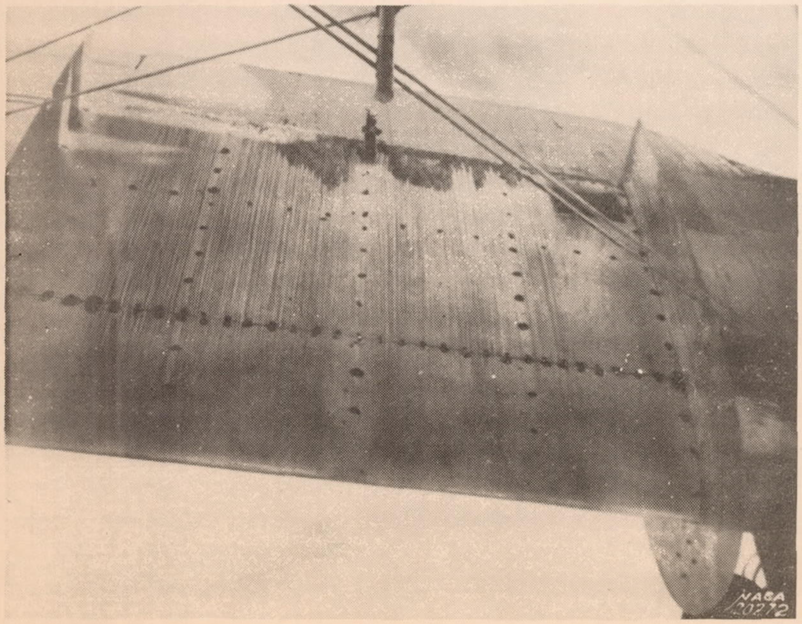

Figure 6.- Model wing with ice along trailing edge. The quantity of heat required for prevention of ice over rest of model was reduced to the minimum.

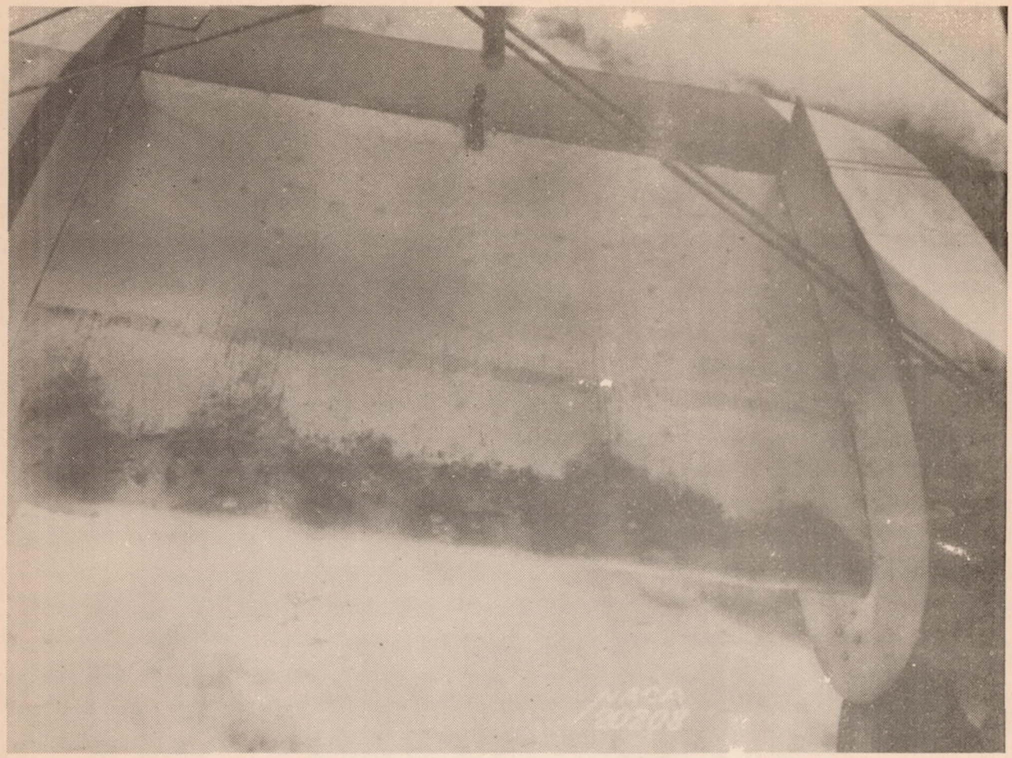

Figure 7.- Nature of ice formation on model wing prior to application of heat.

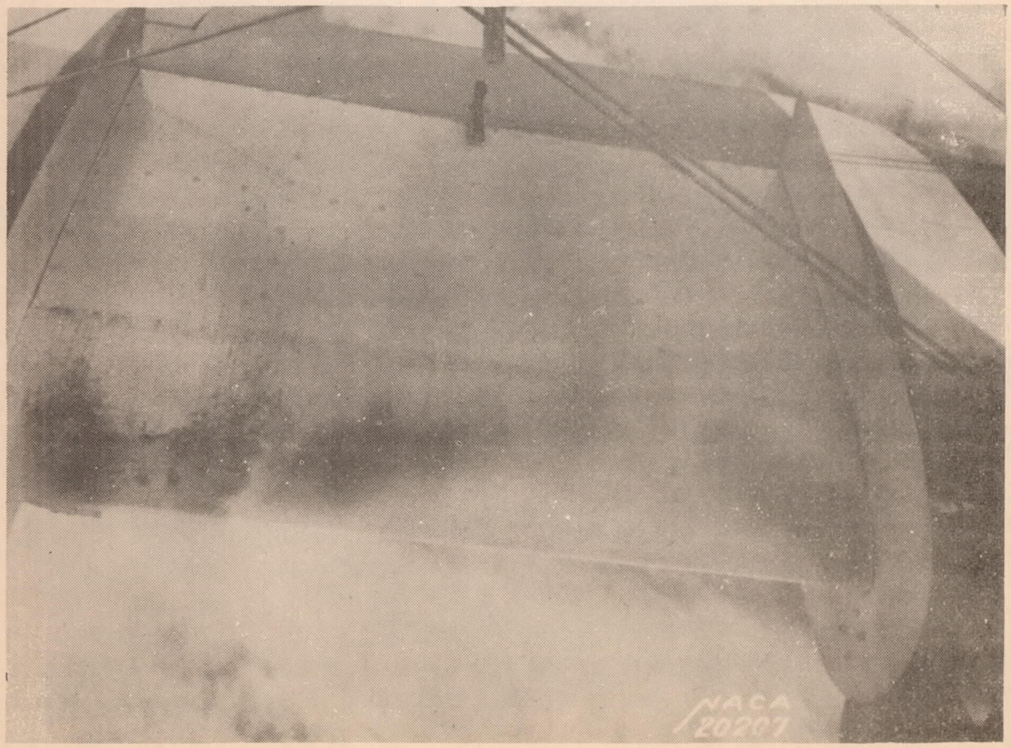

Figure 8.- Large pieces of ice being blown away less than 10 seconds after hot air was admitted to the wing

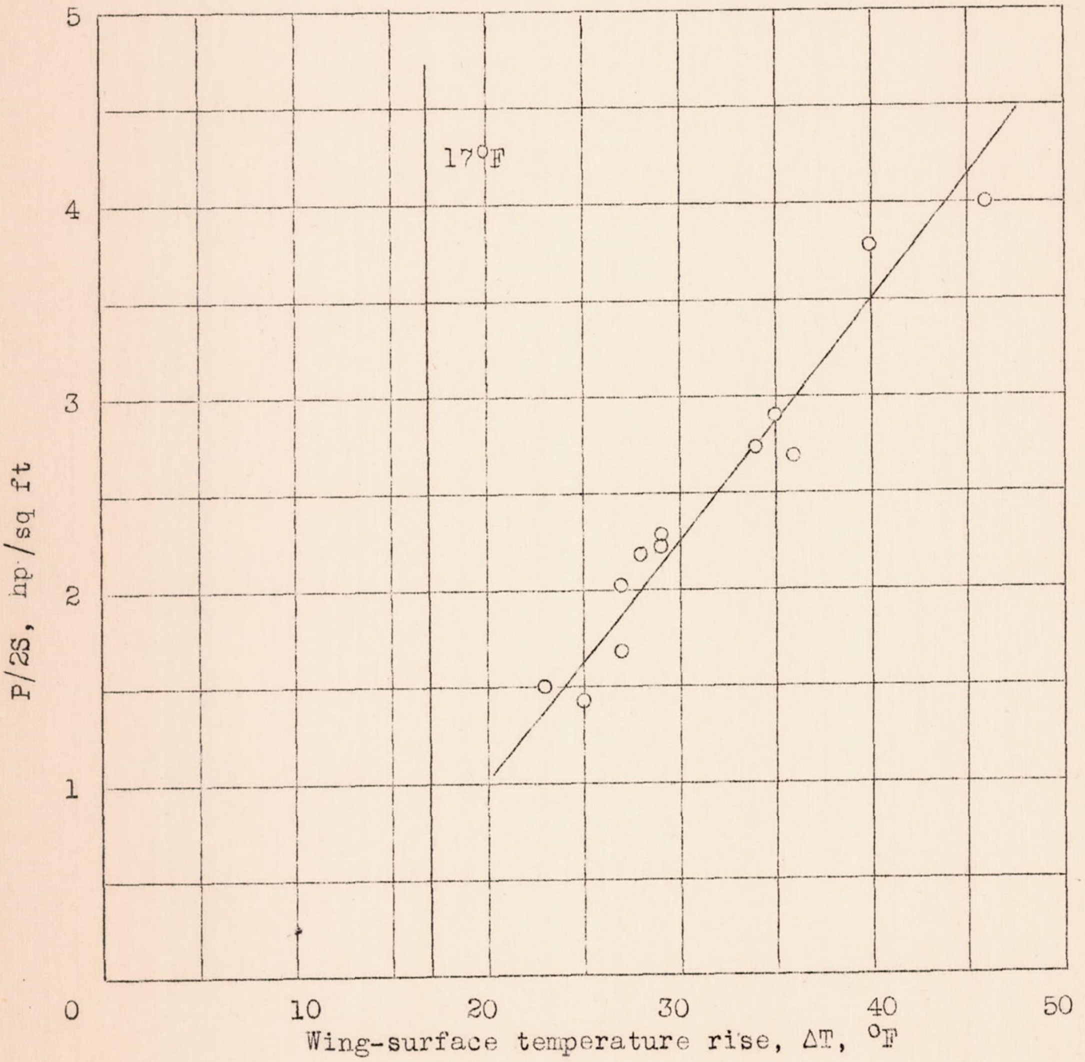

Figure 9.- The calculated temperature rise for 12 modern transport airplanes. (17°F is temperature rise required for ice prevention at 15°F)