NACA-TN-4220

NACA TN 4220

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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A FLIGHT EVALUATION AND ANALYSIS OF THE EFFECT OF ICING CONDITIONS ON THE ZPG-2 AIRSHIP

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Washington
April 1958

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SUMMARY

A series of test flights was conducted by the U. S. Navy over a 3-year period to evaluate the effects of icing on the operation of the ZPG-2 airship. In supercooled clouds, ice formed only on the forward edges of small protuberances and wires and presented no serious hazard to operation. Ice accretions of the glaze type which occurred in conditions described as freezing drizzle adversely affected various components to a somewhat greater extent. The results indicated a need for protection of certain components such as antennas, propellers, and certain parts of the control system.

The tests showed that icing of the large surface of the envelope occurred only in freezing rain or drizzle. Because of the infrequent occurrence of these conditions, the potential maximum severity could not be estimated from the test results. The increases in heaviness caused by icing in freezing rain and drizzle were substantial, but well within the operational capabilities of the airship.

In order to estimate the potential operational significance of icing in freezing rain, theoretical calculations were used to estimate: (1) the rate of icing as a function of temperature and rainfall intensity, (2) the climatological probability of occurrence of various combinations of these variables, and (3) the significance of the warming influence of the ocean in alleviating freezing-rain conditions. The results of these calculations suggest that, although very heavy icing rates are possible in combinations of low temperature and high rainfall rate, the occurrence of such conditions is very infrequent in coastal areas and virtually impossible 200 or 300 miles offshore.

INTRODUCTION

The nonrigid airship ("blimp") has been adapted to carry aircraft detection equipment for use in the air defense system. The aircraft-early-warning mission requires that picket aircraft endure all types of

A preliminary study of the airship icing problem indicated that accumulations of ice or snow on the large surface areas along the top of the envelope and fins could produce the serious problem of weight greater than the lifting capacity of the airship. This problem would exist only in the more unusual conditions of freezing drizzle or rain where the drop sizes are of sufficient size to strike the envelope surface. Droplets in the smaller size range of supercooled clouds (<100 microns) would not impinge on the envelope in sufficient amounts to be of concern. The low airspeed and gradual curvature of the large airship envelope allow the small light-weight droplets to be easily deflected by the airstream around the envelope. Atmospheric conditions encountered during the flight tests did not provide sufficient information to evaluate this primary problem of ice loads from freezing rain adequately. It was considered advisable, therefore, to calculate rates of ice formation on the airship envelope based on theoretically derived droplet trajectories and heat-transfer relations combined with rainfall rates and temperatures typical of freezing-rain conditions. The operational significance of this problem during offshore missions was also considered desirable. The second part of this report presents the results of these calculations, including an analysis of the probability of freezing rain for offshore areas.

DESCRIPTION OF TEST AIRSHIP AND INSTRUMENTATION

The ZPG-2 airship used in the tests (fig. 1) has a fabric envelope filled with approximately 975,000 cubic feet of helium. The over-all length is 342 feet and the maximum diameter is 75 feet. Two 18-foot propellers are mounted on outriggers projecting from each side of the car. Power is transmitted through shafting from the engines mounted inside the car. The stabilizers and control surfaces (ruddevators) are mounted at 45° angles and are supported by brace wires attached to the envelope surface. Exposed control cables run from the car to the ruddevators. The airship is normally operated in a heavy condition (i.e., heavier than the air displaced by the envelope) and thus requires some dynamic lift for flight.

The test instrumentation consisted of equipment to measure and observe ice accretions on various airship components and to evaluate the effects of the ice on the operation of the airship. Rate-of-accretion meters indicated the magnitude of ice formations on the forward edges of small exposed components. These meters recorded the rate at which ice formed on the leading edge of a thin rotating disk and were used in flight to detect the presence of icing and the duration of the icing conditions (see ref. 2 for a description of these meters). Ice deposited per unit area on the top surfaces of the envelope in freezing rain or drizzle was measured at three locations (nose, center, and tail sections) by use of a device developed specifically for this purpose by the Clevite

The increasing ice accumulation with time as measured by the icing-rate meters is shown in figure 2 for a chronology of events reported during the flight. Icing was encountered during climb shortly after takeoff from South Weymouth. The greatest icing rate appeared to be at the 3000-foot level where the temperature was -1.5° C and the visibility very limited. After 25 minutes of continuously increasing ice accumulation at this altitude, a slight vibration of the car was noted. About 5 minutes later this vibration became excessive and caused the instrument panel to shimmy up to the limits of its shock mounts. The frequency of the car vibration was estimated as about 5 cycles per second. During this period ice thrown from the propellers was heard striking the sides of the car which suggested that propeller unbalance may have been present. These pieces of ice also caused a rip in the fabric fairing between the car and envelope. The vibration diminished during the following 10 to 15 minutes, then increased again and became very pronounced about 5 minutes later. A descent was made shortly thereafter out of the icing level into above freezing temperatures. The airship had been exposed to continuous icing for about 70 minutes. The clear ice formed under these conditions is illustrated in figure 3, which shows ice formations on the yawmeter mounted below the pilot's window.

During the descent sheets of ice began sliding off the envelope from the bow area and falling back into the propellers and windshield. Ice was also noted falling from other areas along the sides of the envelope during the approach to the runway. The surface-ice accretion meters were inoperative during this flight, and therefore the envelope ice load was not measured. A total ice load of about 4000 pounds was estimated by considering airspeed, deck angle, and power settings. This included the accumulated ice on fin brace wires and protuberances as well as on the envelope surface.

Near the end of the icing period the fin brace wires were observed oscillating at an estimated 6-inch amplitude. Ice accretions up to $1\frac{1}{2}$ inches in diameter had formed on the 3/16-inch-diameter wires. Some flapping motion of the fins was also detected. The control cables had also collected some ice, but their operation was not impaired. An inspection upon landing revealed some 30 punctures in the fabric surfaces of the two lower fins. These 1- to 6-inch punctures were attributed to pieces of ice thrown from the oscillating brace wires or to chunks of ice falling from the leading edge of the upper fins or both.

Other operational problems resulting from the icing included the freezing shut of an air damper controlling air to the center ballonet and ice on the windshield which completely obscured forward visibility. Operation of the damper by either electrical or manual controls was not possible. The windshield defogging system was ineffective in preventing or removing the ice coating.

During the next $1\frac{1}{2}$ hours the airship proceeded to the Cape Cod area where icing again was encountered. All ice accretions from the previous encounter had melted. Vibration again was felt when about 1/4 inch of ice had accumulated. Excessive antenna whipping was also present. When maximum accretion was reached (about 1/2 in. in 30 min), there was excessive vibration of the car for about 5 minutes. This was accompanied by propeller ice throwoff. A climb at this point to 3200 feet produced melting at 1° C, which indicated that an inversion was also present in this icing area. As the melting continued, ice in thin sheets fell from the sides of the envelope and struck the propeller, the outriggers, and the windshield.

The third icing condition was entered upon return to the South Weymouth area at 3000 feet. This condition was similar to the first encounter of the flight in that only 1/4 inch of ice accumulated over a 40-minute period. Antenna whipping again appeared excessive. Airspeed was reduced to help prevent the wires from snapping. Inspection of the airship after landing disclosed ice accretions 1/2 to 3/4 inch thick on the fin brace wires and control cables, but no ice had remained on the envelope surface.

During a takeoff on the day following this flight, a control problem arose which was considered related to the icing encountered on the previous day. In an attempt to climb the airship veered sharply to the right. Flight was maintained, however, and a landing was effected with the controls still fouled. Inspection showed that movement of the lower left ruddevator was prevented by the control cable, which had jumped a pulley and lodged between the pulley and its guard. The failure was assumed to have developed during the rollout phase of the landing from the previous flight. A buildup of ice on the affected cable and pulley would cause no trouble for normal flight, because the control movements are usually small. However, the large cable travel required on landing could cause the enlarged cable to ride up and out of the iced-over pulley groove. A similar control-system difficulty was encountered during flight number 6 also. When the automatic pilot was disengaged prior to letdown, movement of the controls was dangerously restricted. They could be moved manually only in small increments. Complete control was regained after descent into above freezing temperatures.

Flights in Rime Ice

The rime icing conditions were found in typical supercooled clouds with temperatures ranging from -2° to -10° C and liquid-water contents from 0.1 to 0.5 gram per cubic meter. The ice formations were different from those produced in freezing drizzle in that the rime accretions were confined to the forward edges of small objects only and, unlike glaze-ice formations, had less tendency to spread. A comparison of the two types of ice formation is shown in the flight photographs of figure 3.

cold air over a warm sea surface. Icing occurred in four separate periods with an estimated cumulative time in icing of about 5 hours. Ice accretions (about $1\frac{1}{4}$ in.) were the largest recorded for rime icing encounters. The pilot noted that the ice on small protuberances would build up to a certain thickness and break off. Thus, it would seem that this condition approached the maximum effect of prolonged periods of rime icing. The total ice load was estimated not to have exceeded 2000 pounds. Some snow in the tail section contributed to the increased heaviness.

In general, the over-all operation of the airship was not seriously impaired by the rime icing conditions that were encountered. The limited icing protection installed on the second airship appeared adequate for those components which were adversely affected by the rime accretions.

Flights in Snow

Several flights were conducted in moderate to heavy snow with little or no in-flight effects on the airship. Snow loads accumulated while an airship is on the mast have long been recognized as a serious problem. In flight, however, most of the snow catch blows off at the higher airspeeds, except possibly very wet snow. The results of a 2-hour flight in light to moderate snow at -2° to -6° C are shown in figure 5(a). A small catch estimated to be about 1000 pounds can be seen distributed along the top of the envelope and in the catenary seam along the side. On other flights snow was observed only on the top, between and aft of the fin area, as shown in figure 5(b).

During the test flights snow loads created operational problems on two occasions. While the airship was on the mast prior to takeoff for flight number 9, a heavy snow load collected on the top. Although some snow blew off during takeoff, the airship remained very tail-heavy and required all ballonet air forward plus the elevator down to effect a 13° angle of attack at 2000 feet. The airship was operating at maximum gross weight and low power settings to minimize fuel consumption because of the endurance requirements of the mission. About 20 minutes of icing was encountered soon after takeoff, which produced a small accumulation (0.1 in.). The combined effect of all these conditions created a stall situation which required descent to a lower altitude. This provided increased ballonet air capacity, which was used to reduce the high angle of attack. With less down elevator also reducing the drag, level flight could be maintained without an increase in power.

Heavy snow produced another problem during a special maneuver conducted while on a barrier station. An attempt to pick up sea-water ballast was abandoned when altitude could not be maintained at the very low critical freezing rate is greater than the impingement rate, all the impinging water freezes, and the icing rate equals the impingement rate. Where the impingement rate exceeds the critical freezing rate, the icing rate is greater than the critical freezing rate by the amount of ice formation required to release sufficient latent heat to raise the temperature of the excess water to 32° F.

For example, in figure 6(a) at a location of 60 feet from the nose the impingement rate (33 (lb/hr)/ft) is less than the critical freezing rate (44 (lb/hr)/ft), and the icing rate is equal to the impingement rate (33 (lb/hr)/ft). At a location 20 feet from the nose, on the other hand, the impingement rate (117 (lb/hr)/ft) is greater than the critical freezing rate (67 (lb/hr)/ft). The excess water (50 (lb/hr)/ft) undergoes a temperature rise from 27° to 32° F, which absorbs heat at a rate of 50x5 or 250 (Btu/hr)/ft, and thus freezes additional ice in the amount of 250/144 or 1.7 (lb/hr)/ft. The local icing rate is therefore 67 + 1.7 or 68.7 (lb/hr)/ft.

The total icing rate for the entire envelope is found by integrating the local icing rate over the total length. In the coordinates of figure 6(a), this integration is accomplished by determining the area under both the impingement-rate and critical-freezing-rate curves, using whichever curve is lower at any location. To this area is added $(32 - t_{kw})/144$ times the area lying below the impingement curve and above the critical-freezing-rate curve.

Figure 6(b) shows how the relation between impingement and critical freezing rate changes as the rainfall rate increases at constant temperature and airspeed. At rainfall rates up to 0.04 inch per hour, for the conditions shown in figure 6(b)(28° F, 30 knots), the area of excess impingement and runoff comprises only a small portion of the envelope at the nose. Thus, the icing rate increases almost linearly with the rainfall rate. At a rainfall rate of about 0.047 inch per hour runoff sets in along the rear half of the envelope about 250 feet from the nose, and at a rainfall of 0.05 inch per hour most of the rear half is running wet. Beyond this point the icing rate increases more slowly with increasing rainfall. Finally, beyond 0.075 inch per hour the entire envelope is subject to runoff, and further increases in rainfall cause only a small increase in icing. Curves such as those shown in figure 6 provide a means of estimating the total icing rate as a function of rainfall rate for a given airspeed and temperature, as shown in figure 7.

aircraft-early-warning airship operation over land at low altitudes during return to or departure from the base. An estimated frequency distribution of rainfall rate applicable to freezing rain is shown in figure 11. The method of selecting data and the theory underlying their use to represent freezing rain are given in appendix D.

Combining the temperature distribution of figure 10, the rainfall distribution of figure 11, and the relation between icing rate and temperature and rainfall rate shown in figure 7 yields the frequency distributions of icing rate shown in figure 12 for airspeeds of 30 and 50 knots. Thus, if an airship is flying at 30 knots in freezing rain, the chances are 1 in 10 that the icing rate exceeds 6300 pounds per hour and 1 in 100 that it exceeds 14,000 pounds per hour. The temperature and rainfall distributions would not be expected to vary widely in the limited geographical area of the northeastern United States because the occurrence of freezing rain fixes the air-mass temperatures within rather narrow limits. Thus, figure 12, which gives the probability of various icing rates when freezing rain is known to be occurring, may be regarded as applicable generally to land areas near the east coast of the United States in winter. The geographical effects within this area are included in the frequency of occurrence of freezing rain (fig. 9).

Estimated conditions off northeastern coast of United States. - As implied in figure 9, the probability of encountering freezing rain is much less over the ocean off the coast of the northeastern United States than it is over adjacent land areas. Since direct observations of freezing-rain frequencies at sea are not available, it is desirable to estimate the effect of flow over the relatively warm sea surface in modifying the air-mass temperature structure in freezing-rain situations.

An analysis of heat transfer occurring when a layer of cold air topped by an inversion flows over a warm water surface is presented in appendix C. The distance of travel over the ocean (surface temperature, 6° C) required to raise the surface-air temperature to 2° C was calculated as a function of the initial surface-air temperature and the height of the first freezing level. A surface-air temperature of 2° C was chosen as representing a condition under which an airship could safely descend to below the freezing level (about 700 ft) and shed accumulated ice. The relative frequency of various combinations of surface-air temperature and height of the first freezing level measured during freezing rain were combined with the calculated values of distance to 2° C to obtain the frequency distribution shown in figure 13. This curve shows the percentage of cases of freezing rain (observed on land) that would be warmed sufficiently to have a surface-air temperature of 2° C or higher as a function of distance transported over water at 6° C. Thus, one-half of the freezing-rain cases at the coast would be effectively eliminated at 64 nautical miles offshore, 90 percent at 145 miles, and 99 percent at 260 miles.

(1) It is possible to encounter very heavy rates of icing under conditions of high rainfall rate and low temperature.

(2) Statistics on rainfall rate and temperature in freezing rain indicate that combinations giving rise to hazardous icing rates may be expected in from 1 to 5 percent of freezing-rain occurrences over land areas in the northeastern United States. Since freezing rain occurs in this area in only about three to five storms per year, the probability of severe icing is very small.

(3) Because of the warming effect of the sea surface, the probability of encountering hazardous icing in freezing rain decreases rapidly with distance offshore, becoming negligible at 200 to 300 miles.

(4) The effect of freezing rain in aircraft-early-warning operations is likely to be confined to arrivals and departures, when the airship is over land or a short distance offshore. Hazardous icing during these phases of operation can probably be avoided with the aid of weather forecasts, since the synoptic conditions required for freezing rain can be forecast satisfactorily for short periods.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, December 17, 1957