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Tailplane Icing and Aircraft Performance Degradation

Ice accretions on horizontal tail surfaces can decrease stall margins, impair control, increase drag and decrease lift.

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Although the sensitivity of airplanes to inflight icing has been recognized for many years and can be minimized by ice protection systems, the advent of the medium-altitude turboprop commuter transport aircraft has resulted in renewed attention to the icing problem. This review of icing has been prompted by several recent accidents that apparently were caused by an oversensitivity to ice buildup on the horizontal stabilizer of these aircraft.

Icing Phenomenon Reviewed

Icing cloud characteristics

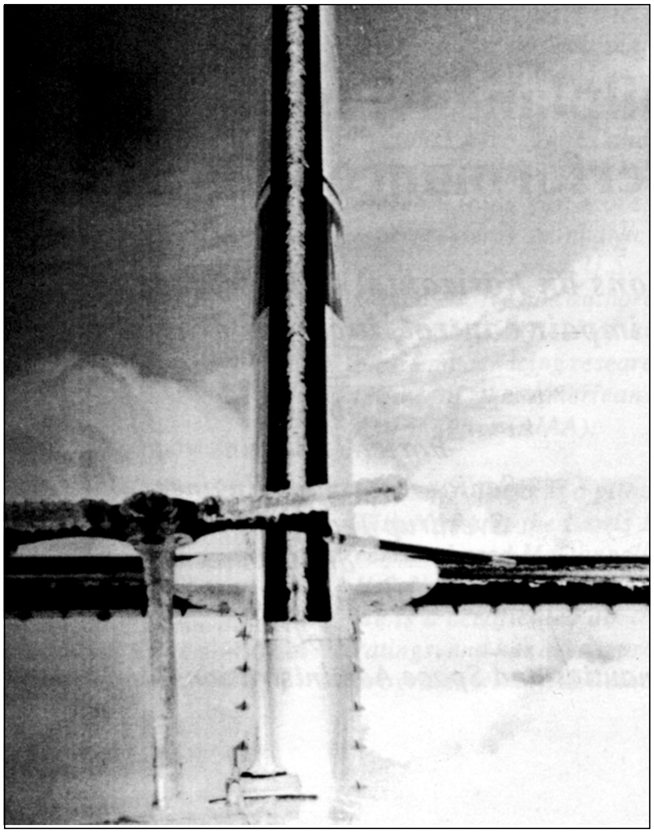
Aircraft icing can occur: if the aircraft surface temperature (which rises with increasing airspeed) is below freezing; some water in a cloud is liquid; and, the sizes of the cloud droplets are large enough to strike an aircraft surface rather than follow the streamlined airflow around them. Also, the clouds must be extensive enough along the flight path to form a discernible amount of ice.

Ice forms when supercooled liquid water droplets turn to ice upon or after striking a moving surface. Two ice accretion factors have the most adverse influence on aircraft performance: the shape of the ice formation on the surface; and, the amount or thickness of the ice.

Shape of ice accretions

Aerodynamic performance degradation is primarily influenced by the shape of the ice that forms and the amount of ice that accumulates. The amount of liquid water in the cloud and the duration of the exposure to icing primarily determine the quantity of ice collected. Cloud droplet size is generally a secondary consideration. Temperature can determine the amount of accretion; if it is close to freezing, some of the intercepted water droplets blow off before they can freeze.

Ice accretion shape is a result of the rate of freezing on the surface. Low temperatures and droplet impingement rates (water concentration X velocity), along with small droplets, promote rapid freezing on the surface. Such conditions produce a rather smooth ice surface and pointed accretion shape called rime ice. However, temperatures near freezing, higher rates of accretion and larger droplet sizes result in delays in freezing when the droplets strike the surface. These conditions create irregular ice formations with flat or concave surfaces sometimes having protuberances ("double-horn" ice formation) facing the airstream either side of the airflow center or stagnation line. This type of ice formation is usually described as glaze ice.



Ice can form on tailplanes and antennas faster than on wings.

Ice shapes are of extreme importance because the contour, roughness and location of the ice formation on the various aircraft components can significantly deteriorate aerodynamic performance. Glaze ice shapes, runback ice (formed when water droplets flow in liquid form to freeze on a colder region of the airfoil) and ice caused by freezing rain (large droplets that do not follow the airflow but form ice on all surfaces they strike) can produce significant aerodynamic penalties by decreasing lift and stall angle and increasing drag and stall speed. This is caused by the ice destroying the aerodynamics necessary for peak airfoil performance.

Ice thickness factors

In addition to the distance flown in icing clouds, the amount of ice collected depends upon the concentration of liquid water in the clouds and a factor called the collection efficiency (the higher the efficiency the greater the amount of ice collected). Values of collection efficiency depend upon airspeed, size of the cloud droplets and size and shape of the moving surface.

In general, the collection efficiency is greatest for high airspeeds, large droplets and small objects (windshield wiper posts, outside temperature probes, airfoils). For aircraft wings, the collection efficiency can vary from near zero for very small droplets to nearly 100 percent for large droplets in freezing rain. Because of their smaller leading edge radius and chord length, tail surfaces have higher collection efficiencies than wings and can collect two to three times greater ice thickness.

Parameters determining icing intensity

Two significant parameters of icing intensity for a given aircraft component are: the amount of liquid water and distribution of droplet sizes in the clouds, which for a given airspeed determine the rate of ice accretion; and, the total amount of ice accumulated in a given encounter, which depends upon the amount of liquid water and the distance flown during the icing encounter. The rate of ice build-up and the amount collected may depend on whether the aircraft is in a layer type (stratiform) cloud or a cumulus type cloud with large vertical development. Ice can generally build up twice as fast in cumulus clouds because of their high water content; but the extent of the icing exposure in cumulus clouds is not nearly as long as that of stratus clouds, and the total amount accumulated could be small.

Data acquired in past research studies[7] have indicated the very limited vertical extent of icing clouds (90 percent within less than 3,000 feet vertically) so that during climb and descent, icing will continue for only a short time, depending upon airspeed and rate of climb. A survey[2] has disclosed that, at constant altitude, 90 percent of the icing encounters are less than 50 miles in horizontal extent and none measured longer than 180 miles.

The greatest amount of liquid water, and therefore the highest rate of ice accretion, occurs generally near the tops of clouds. This condition is to be expected from the physics of cloud formation, i.e. the cooling of ascending air and resulting increase in condensation with height above the cloud base.

Probability of encountering icing when in clouds

If an aircraft is flying in clouds and the outside air temperature (OAT) is sufficiently below freezing to form ice on it, will the airplane pick up ice? Not necessarily. On the average, this aircraft has only approximately a 40 percent chance of icing, and that occurs near freezing temperatures[3]. As the temperature gets further from the freezing point (colder) there is less chance of picking up ice. If the temperature is below -20^{o} C, the chance for accumulating ice is 14 percent. Why does he temperature effect the existence of icing? Most clouds below freezing are starting to glaciate (change over to ice crystals), and the colder the temperature the more rapidly this process occurs. Also, the droplets may be too small to strike the wing in any significant amount.

If one were free to choose a flight level under 20,000 feet and vary it as required between points A and B to avoid icing, the frequency and intensity of icing would be cut to a minimum, except for encounters during climb and descent. In these cases, the amount of ice formed would be a function of the thickness of the icing cloud layer and the rate of climb through it. Only about one in 10 single icing cloud layers exceed a thickness of 3,000 feet. None of the icing cloud thicknesses (single or multiple layers) that were measured totaled more than 6,000 feet in thickness. These data were acquired from instrumented fighter-interceptor aircraft operating from air bases in the northern United States.

In severe icing conditions, evasive action would be required.

U.S. Federal Aviation Regulations (FAR) on icing

Extremes of icing have been defined in ice protection design standards adopted by the U.S. Federal Aviation Administration (FAA) in FAR Part 25, Appendix C for the certification of ice protection systems for transport aircraft[4]. Tests of these systems must be conducted to demonstrate that the airplane is capable of operating safely in the conditions defined by the cloud parameters that produce maximum icing.

Maximum icing conditions are treated separately for cumulus clouds and for stratiform clouds. Icing cloud parameters are called "maximum intermittent" for cumulus clouds and "maximum continuous" for stratiform clouds. Separate parameters were required because of the differences in vertical and horizontal extents of the two cloud types. Cumulus clouds are limited in horizontal extent but extend through a wide range of altitudes; stratiform clouds can extend long horizontal distances but are limited in vertical thickness.

Icing cloud meteorological parameters for FAR Part 25 were based on historical data obtained more than 40 years ago by the U.S. National Advisory Committee for Aeronautics (NACA). Their use in establishing ice protection design standards has proved successful for many different types of aircraft. These design standards were determined on the basis of an ice protection system providing nearly complete protection in 99 percent of the icing encounters, and that some degradation of aircraft performance would be allowed[5]. A statistical study determined that in the 99 percent of the icing encounters, the probability of exceeding the maximum values of all three icing parameters simultaneously (liquid water, temperature and droplet size) would be equivalent to one in 1,000 icing encounters[6].

In severe icing conditions, evasive action would be required. In previous recommendations for inflight reporting of icing intensity, the definition of heavy or severe icing was stated as that situation where the rate of ice accumulation is such that the ice protection system fails to reduce or control the hazard and immediate diversion of the flight becomes necessary. Not knowing the quantitative value of an existing icing condition, the point to emphasize is that a pilot cannot become complacent by assuming that the aircraft's certified ice protection system will provide complete protection under all conditions. For example, it is not possible for designers to provide complete protection against ice accretions caused by freezing rain.

One might suggest that the certification values are too conservative and that designs based on them provide over-protection. Yet, with the volume of air traffic that exists worldwide, encountering extreme values of icing becomes a possibility. Extreme values do exist and have been measured, and can be extrapolated by statistical analysis beyond the measured values. However, the extreme values are limited in horizontal extent and are a function of air temperature, decreasing with colder temperatures. Maximum instantaneous values occur in very short distances (one-half mile) usually in cumuliform clouds; this situation could be critical for certain aircraft components.

Ice Crystals, Freezing Rain or Drizzle Are Determining Factors

Ice is not accreted if a cloud is composed only of ice crystals. If some liquid water is present (mixed clouds), ice does form, but the condition does not last long. In the presence of ice crystals, liquid drops evaporate because of the difference in saturation vapor pressure between ice crystals and liquid droplets. Usually, little, if any, icing is found in areas of snow.

However, when flying below the snow level, aircraft icing can occur if a temperature inversion exists to melt the snow and the resulting rain falls to a below-freezing level — the conditions for freezing rain. These conditions are characterized by very large drops and low values of liquid water. Despite the low concentration of liquid water, a considerable amount of ice can accumulate because of the high collection efficiency of the large drops. In freezing rain, ice can form on many different surfaces of the aircraft.

Freezing drizzle can occur under different conditions than freezing rain. Drops smaller than freezing rain are produced by the joining process of coalescence and collisions of small droplets; an above-freezing level is not necessary. Both freezing rain and drizzle can exist down to ground level below a cloud deck and thereby cause ice to form on aircraft surfaces during landing, takeoff and ground operations if the aircraft surface temperature is below freezing.

Stall Can Be Caused by Ice On Tail Surfaces

Tailplane stall is certainly not a new phenomenon. However, it has recently been thrust into the spotlight by a series of accidents involving turboprop aircraft. Several FAA airworthiness directives (ADs) have been issued that affect several different turboprop aircraft. The common element leading to these ADs appears to be a sensitivity to ice build-up on the horizontal stabilizer that results in control problems which can include an uncontrollable pitch-down during flap extension. The specifics of ice formation on the tailplane and the penalties associated with it may not be fully understood by many aircraft crew members exposed to the icing environment.

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A joint U.S. National Aeronautics and Space Administration (NASA)/FAA International Tailplane Icing Workshop to address this problem was held November 4-5, 1991, at the NASA Lewis Research Center in Cleveland, Ohio, U.S. Approximately 100 representatives from manufacturers, key special interest groups and airworthiness authorities of Canada, China, France, Germany, Italy, Japan, the Netherlands, Sweden, the United Kingdom, and the United States attended. The problem of horizontal tailplane stall caused by ice accretions also has been studied by the Swedish-Soviet Working Group in the Field of Flight Safety[7].

The workshop provided the most complete information to date on the tailplane icing problem. Among numerous recommendations resulting from it were the need for a survey of the current fleet to determine whether unsafe conditions exist on various aircraft and the need for ice detection capability on the horizontal tail. The FAA is planning to conduct such a survey with upcoming ice-detection studies.

The tailplane almost always has a sharper leading edge than the wing, and therefore becomes a more efficient collector of ice as speed and droplet size increase. It is possible to have very little or no accumulation on the wing and yet have a significant accretion on the tailplane.

In addition to the fact that the horizontal stabilizer is a more efficient collector, the aerodynamic effect of a given thickness of ice on the tail will generally be more adverse than the same thickness of ice on the wing because of the ratio of thickness to chord length and leading edge radius.

Tailplane stall due to ice contamination is seldom a problem in cruise flight. However, when trailing edge flaps are extended, some new considerations enter the picture. On conventional aircraft, the horizontal tail provides longitudinal stability by creating downward lift (in most cases) to balance the wing and fuselage pitching moments. With flaps extended, the wing center of lift moves aft, downwash is increased and the horizontal tail, as a result, must provide greater downward lift. In some aircraft, depending on forward center of gravity (CG), the tail may be near its maximum lift coefficient and a small amount of contamination could cause it to stall.

As the aircraft slows after flap extension, the requirement for downward lift by the horizontal tail increases to increase the angle of attack of the wing and produce a given amount of lift at a slower speed. With flaps full down and the aircraft at approach speeds, the angle of attack of the horizontal stabilizer is very high. It is high also because of the downwash over the tail created by the extended flaps. This will increase the angle of attack of the stabilizer even more.

This situation is where tailplane ice can cause trouble. A small amount of ice contamination on the leading edge of the horizontal stabilizer can interfere with the airflow on the underside of the stabilizer because it may be working near its maximum angle of attack.

Landing Approach After or During an Icing Encounter May Cause Problems

Current aviation wisdom advises the pilots of boot-equipped aircraft to wait until one-quarter inch to one-half inch of ice has collected on the wing before activating the deicing system. On some horizontal stabilizers one-half inch of a ice shape may cause unacceptable aerodynamic penalties. In addition, since the horizontal stabilizer is normally a more efficient collector of ice, it is very possible that it has collected much more than the half inch of ice a wing may have collected. Remember, it is possible to have very little or no accumulation of ice on the wings and yet have significant accumulation on the tail.

It also seems to be an accepted practice to increase the landing airspeed some amount if the wings are contaminated. It also may be that the pilot has opted not to deice because there is only a minor accumulation of ice on the wing. Trouble may now come from two sides. There may be much more ice on the horizontal stabilizer than on the wing, and the increased speed will create a much greater wing downwash and therefore higher angle of attack for the stabilizer. This may lead to separation of the flow on the lower surface of the stabilizer, a sudden change in elevator hinge moment and forward stick force that may overpower the pilot. In aircraft without boosted controls, the pilot may notice lightening stick forces, although the above sequence has happened suddenly and without a recognizable warning when flaps are extended. The answer is to reduce flap angle immediately, if altitude and airspeed permit.

In most instances, this problem manifests itself when the final segment of flaps is extended (creating the greatest amount of downwash) at very low altitude during the landing phase. The odds of recovery from uncontrollable nose pitch-down at low altitude are poor. Adding airspeed in this case may actually reduce the margin of safety. The remedy is to land at a reduced flap angle or get rid of all of the ice.

Generally, the tailplane stall problem that has been presented here seems to be associated with aircraft which have the following characteristics. They:

- Do not have powered control surfaces, and rely on aerodynamic balance to keep stick forces low;
- Have high efficiency flaps that produce relatively high downwash which results in high angle of attack on the tailplane;
- Have non-trimmable stabilizers;
- Have efficient stabilizers with short chord length and small leading edge radii; and,
- Mostly have inflatable boots for ice protection.

The characteristics listed above fit most of the turboprop aircraft used in the regional airline fleet today. The six ADs regarding the effects of tailplane ice on turboprop commuter aircraft plus several recent accidents have prompted a closer look at the problem.

One of the highlights of the NASA/FAA workshop was the recognition of the need for more education and training for pilots. This workshop recognized that much training, both initial and recurrent, has been provided for recognition and proper actions related to windshear; however, crew training for operations in icing conditions have been emphasized less. Some of the current recommended procedures suggested during crew training (e.g., increased airspeed) may actually exacerbate an already adverse situation at the horizontal tail.

Other Adverse Affects of Ice on Aircraft Performance Examined

Ice accretions can degrade the performance of aircraft by:

- Causing loss of control, particularly during a critical maneuver such as landing (e.g. tailplane stall as discussed above);
- Increasing total drag substantially;
- Reducing lift and climb capability;
- Losing the capability to maintain altitude with one engine out on a twin-engine aircraft; and,
- Causing the loss of artificial stall warning.

Increase in total drag

Research measurements taken on an aircraft with a glaze ice accretion disclosed a substantial increase of more than 60 percent in total drag compared to an un-iced condition. These data were from a typical twin engine commuter type aircraft operating at a normal lift coefficient[8].

Loss of lift

Accompanying the above increase in drag was a 17 percent loss of lift.

Loss of engine-out capability

Analysis of the power required vs power available curves for the above situation with the aircraft at 6,000 feet, where the measurements were made, indicated that without de-icing, the aircraft would descend if one of the two engines failed. On many routes, a 6,000-foot minimum en route altitude (MEA) could spell disaster.

Loss of artificial stall warning

Activation of an artificial stall warning device, such as a stick shaker, is based on a preset angle-of-attack several knots above stall speed. This setting allows warning prior to stall onset characteristics where buffeting or shaking of the aircraft occurs. Thus, for an un-iced aircraft, the pilot has adequate warning of impending stall. However, an iced aircraft may exhibit stall onset characteristics before stick shaker activation because of the affect of ice formations on reducing the stall angle-of-attack. In this case, the pilot does not have the benefit of an artificial warning of stall.

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