The Adverse Aerodynamic Effects of Inflight Icing on Airplane Operation

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Despite efforts to improve airplane safety, inflight icing accidents continue to occur involving airplanes certified for flight in icing conditions. With knowledge of the aerodynamic effects of ice accretion on aerofoil surfaces, and the limitations inherent in ice protection systems, a better understanding of icing accidents can be made. This knowledge and understanding is essential for improving airplane design practices and certification standards for approval of flight in icing conditions.

For airplanes of conventional design, the main aerofoils are the wing, horizontal stabilizer and vertical stabilizer. For maximum efficiency, aerofoil cross sections are characterized by a relatively blunt leading edge and a sharp trailing edge. As the aerofoil travel through the air, the air stream is deflected above and below the wing with a point on the leading edge, known as the stagnation point, where the air directly impacts the leading edge (see Figure 1).

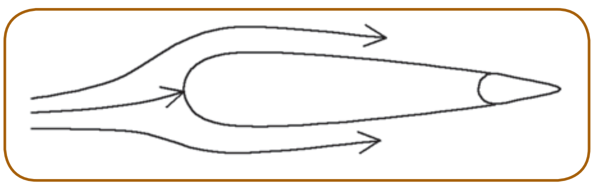

Figure 1: Air impacting stagnation point

In icing conditions, the air contains water droplets, which, although at a temperature at or below freezing, are still liquid. These supercooled droplets have more mass than air particles and are not as easily redirected as the aerofoil flies through an icing cloud. The droplets impact the surface, not only at the stagnation point, but both above and below the stagnation point. When the water drops strike the surface, part of the drop freezes into ice and adheres to the surface. The initial buildup of ice is around the stagnation point, but as more ice builds up, the aerofoil section effectively changes, thus changing the flow around it and affecting subsequent ice buildup (see Figure 2).

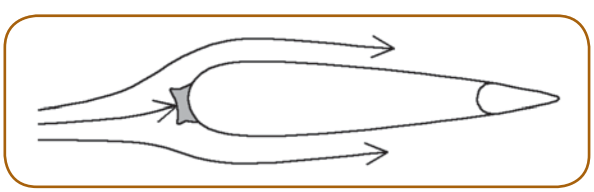

Figure 2: Ice droplets impacting and freezing around stagnation point

There are many factors that affect the size and shape of the ice accretion, including:

a) *The icing atmosphere*. For certification purposes, the icing atmosphere has been characterized in terms of envelopes of altitude, temperature, liquid water content, droplet size, and cloud horizontal extent. It is important to note that, although these envelopes encompass most icing conditions likely to be encountered, it is possible to encounter icing conditions that exceed the certification envelope.

b) *The aerofoil section and size*. Different aerofoil section shapes and physical size affect the ice accretion. Due to the temperature depression effects of accelerating airflow around the leading edge of an aerofoil, local temperatures can be lower than the ambient temperature. Hence, it is possible to get ice accretion at ambient temperatures above 0°C. This is one of the reasons that icing conditions are defined in the aircraft flight manual (AFM) of some airplanes, as existing when the static air temperature is at or below +5°C, and visible moisture is present.

c) *The flight condition*. Of particular importance are the angle of attack (AOA), the airspeed, and the time spent in the icing condition. The AOA of an airplane wing is a function of the airplane weight, load factor, thrust or power, airspeed and slat/flap configuration. The AOA of the horizontal stabilizer, which is negative, is a function of the wing AOA, but is also significantly affected by the wing slat/flap position due to the effects of airflow downwash at the tail (see Figure 3).

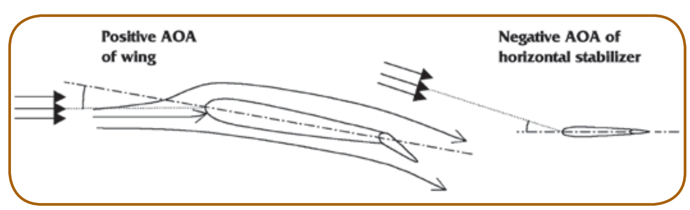

Figure 3: AOA at wing and horizontal stabilizer

From the above, it is evident that in any operational flight involving icing conditions, most of the above parameters are continuously varying. Hence, the size and shape of ice accretion on aerofoil surfaces during flight operations cannot be readily predicted. However, by making certain simplifying assumptions, and through the use of computational fluid dynamics based icing codes and/or through the use of icing wind tunnels, conservative estimates of expected ice accretions can be made.

The fundamental aerodynamic characteristics of an aerofoil are the lift, the drag and the pitching moment. Since conventional control surfaces (e.g. elevators, ailerons, rudder) are located on the trailing edge of aerofoils, the surface hinge moment characteristics (i.e. the moment or torque required to deflect the control surface from its neutral position) are also important.

Different aerofoil sections and planforms result in different aerodynamic characteristics. However, the effect of ice accretion is always adverse. In particular, maximum lift is decreased, the AOA for maximum lift is decreased, and drag is increased.

The lift and drag characteristics of an aerofoil can be quantified using non-dimensional coefficients that are dependent on the AOA. The lift coefficient is the ratio between the lifting force and the dynamic pressure of the air multiplied by the wing area. Figure 4 shows the classical relationship between the lift coefficient and the AOA for an aerofoil section without ice accretion. Aerodynamic stall is indicated by the decrease of the lift coefficient with increasing AOA. The lift coefficient of the wing is the major contributor to the lift coefficient of the airplane.

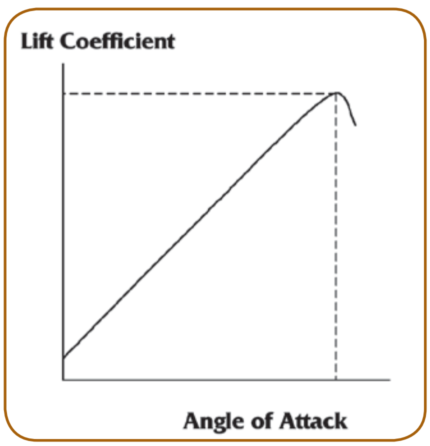

Figure 4: Lift coefficient versus AOA showing stall

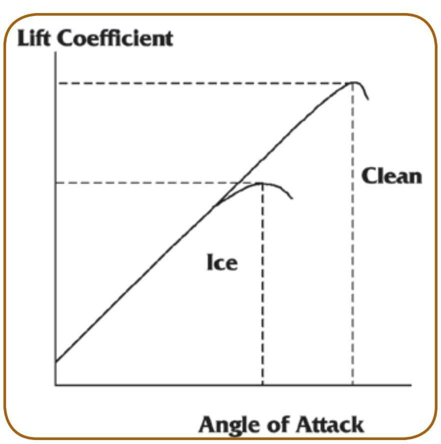

Figure 5: Effect of ice on maximum lift coefficient and AOA for stall

Figure 5 shows the effect of ice contamination on the leading edge. Not only is the maximum lift coefficient decreased, but the AOA for stall is also decreased. The loss in lift coefficient and stall AOA is dependent on the depth, shape and texture of the ice accretion in relation to the aerofoil section.

Figure 6 illustrates the effect of increasing the depth of contamination on the loss of maximum lift coefficient. Although this is only an illustration, the important aspect to note is that the decrease in maximum lift with ice contamination depth is not linear. Most of the adverse effects occur with relatively little depth. In fact, the decrease in aerodynamic performance can be very significant for small, rough textured ice accretions. Figure 7 illustrates the effect of an increasing ice depth on increase of the drag coefficient. This is much more linear in nature, with the increase in drag being proportional to the depth.

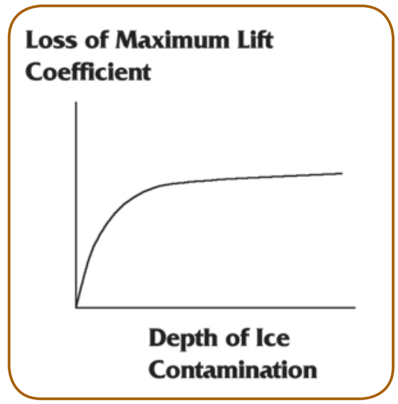

Figure 6: Effect of increasing ice accretion on loss of maximum lift coefficient

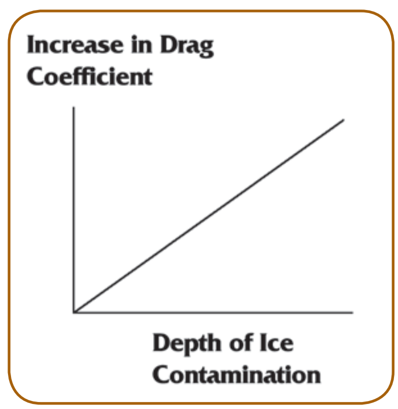

Figure 7: Effect of increasing ice accretion on increase in drag coefficient

Considering the airplane as a whole, the adverse aerodynamic effects of ice accretion on its aerofoil surfaces can be summarized as follows:

a) Due to ice accretion on the wing leading edge, the maximum lift coefficient is decreased and the AOA for stall is decreased. The consequence of a loss in maximum lift coefficient is an increase in stall speed.

Because stall AOA is decreased, stall warning and stall protection systems that activate at fixed preset values applicable to the clean wing, will not function correctly with ice accretion.

b) Due to ice accretion on the horizontal stabilizer leading edge, the maximum downward balancing force is reduced and the AOA for stall is reduced. The consequence is the potential for a stall of the horizontal stabilizer, commonly known as tailplane stall.

c) Due to ice accretion on wing, horizontal and vertical stabilizer leading edges, the drag of the airplane is increased. The drag is also increased due to ice accretion on other forward-facing surfaces, such as the radome, engine pylons, landing gear struts, etc. The consequence is a loss of climb capability, loss of the ability to maintain level speed, or loss of the ability to make a controlled descent and landing.

d) Due to ice accretion on the leading edges of wing and stabilizer aerofoils that support trailing edge control surfaces, control hinge moment discontinuities at these surfaces can occur. For fully-powered flight controls, the pilot's control force is dependent on the artificial feel system characteristics. For unpowered controls, the pilot's control force is proportional to the hinge moment of the surface. Hinge moment anomalies at the surface can result in pulsing of the pilot's control, and in the extreme, a reversal in the direction of the pilot's force can occur. That is, the control will automatically deflect to an extreme position, and pilot effort will be required to return the control to a neutral position, which is known as control overbalance.

e) Ice accretion on the aerofoil surfaces and other surfaces adds weight to the airplane, thus increasing the stall speed and the drag for a specified airspeed.

f) Ice accretion on propeller blades will increase the drag and may decrease the lift of the blades. Increased power will be required to maintain propeller speed. Eventually, thrust will be decreased because of reaching power limits and/or loss of lift on the blades.

As noted previously, the size and shape of ice accretion on an aerofoil leading edge are dependent on a large number of factors, including the aerofoil cross section. However, with all other conditions remaining the same, a smaller wing will tend to pick up ice quicker than a larger wing of exactly the same aerofoil section. Not only that, but the adverse effects of the same amount of ice accretion are more severe in smaller wings than in larger wings. These scale characteristics partly explain why there are relatively few inflight icing accidents involving large airplanes.

Clearly, the hazard associated with flight in icing conditions is dependent on the exposure time. In general, icing conditions are more prevalent at lower altitudes. Propeller-driven airplanes generally cruise at altitudes conducive to icing conditions. Furthermore, they have limited excess power to enable them to climb out of icing conditions, should the need arise. This problem is more acute for single engine versus multi-engine airplanes.

On the other hand, multi-engine turbojets spend limited time climbing through icing conditions, and cruise at altitudes well above icing conditions. On an exposure basis, propeller-driven airplanes are at a much greater risk.

Due to the adverse aerodynamic effects of ice accretion, critical surfaces must be protected to ensure operating safety in icing conditions. However, as noted above, depending on the size and design of the airplane, not all aerofoil surfaces need to be protected. It is common for the entire wing leading edge, the horizontal stabilizer leading edge and the vertical stabilizer leading edge to be protected for small turbojets (e.g. Cessna Citation II) and most propeller-driven airplanes (e.g. Bombardier DHC-8). For larger business jets (e.g. Bombardier Challenger CL-604), the horizontal stabilizer may not be protected. For large turbojets (e.g. Airbus A320), it is common for the wing leading edge not to be protected inboard of the wing-mounted engine nacelles.

There are many design issues associated with whether or not to protect a surface. For example, a manufacturer may choose to protect the leading edge of a horizontal stabilizer with the attendant issues associated with the protection system design and operating cost. Or, the manufacturer may choose to simply incorporate a larger and/or redesigned stabilizer surface that does not need to work at as high an AOA to balance the airplane, and hence, is less likely to stall.

Ice protection systems are generally classified as either de-icing systems or anti-icing systems. A de-icing system is intended to remove ice once it has accreted, whereas an anti-icing system is intended to prevent ice accretion in the first place.

The most common de-icing system, especially on propeller-driven airplanes and small turbojets, is pneumatic boots. The boot covers the leading edge and is comprised of a number of air chambers that are kept flat by applying suction to the air chambers. When pulsed, the tubes are inflated with high-pressure air. The physical expansion in the shape of the leading edge fractures the ice, and dynamic pressure overcomes any remaining adhesive bond between the smaller fragments and the surface. Most of these systems work on a timer that periodically cycles through different surfaces or parts of a surface.

Pneumatic boot de-icing systems should be able to keep the protected surfaces free from large amounts of ice buildup. However, there will always be ice accretion between boot cycles while the airplane is in icing conditions. In addition, it is rare for all accreted ice to be removed without repeated boot cycles. Hence, normal operation will result in a small amount of ice on the protected surfaces, commonly called residual ice.

One problem that has been identified with this type of protection is that the chordwise extent of the boot protected area may not have considered the full operational range of flight and icing atmosphere variables, thus resulting in ice accretion aft of the protected area. This can be particularly hazardous when a residual ridge of ice is left just aft of the boot on the upper wing after boot operation to break off ice (see Figure 8).

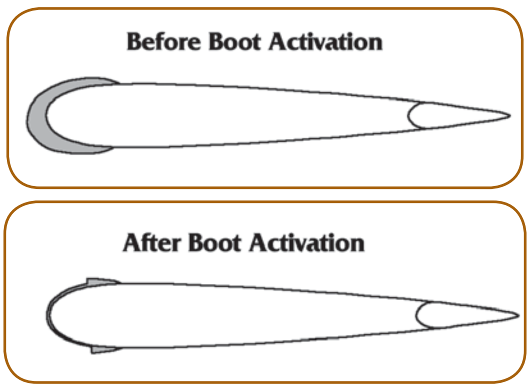

Figure 8: Residual icing ridge formed aft of boot protected surface due to boot inflation

The most common protection system used on large turbojets is thermal anti-icing, using engine compressor bleed air. The bleed air is ducted to the wing, directed to the inside of the leading edge from holes in the ducting tube, and then vented overboard. The temperature of the leading edge is regulated to maintain adequate thermal performance, without compromising the structural strength. The hot surface prevents ice accretion by either vaporizing the supercooled water droplets, or by heating them to a temperature above freezing. In the latter case, the water will form droplets that "run back" from the leading edge due to the airflow. Once beyond the heated area, these droplets can then freeze on the cold upper or lower aerofoil surfaces. In general, this "run back" ice forms chordwise streaks, and is not as hazardous to flight characteristics as the spanwise ridge that can form aft of pneumatic boots.

Although designed to operate effectively with a defined envelope, thermal anti-icing may not be effective in real life icing environments that exceed the certification envelope. The ice protection systems for some components, such as pitot/static pressure sensors and the windshield, are always operated in flight. However, for economic and other reasons, airframe (and engine) ice protection systems are not normally operated when not in icing conditions. Hence, there can be ice accretion during the period from entering icing conditions, recognition of icing conditions, activation of airframe ice protection and the ice protection system working effectively.

In this regard, the incorporation of ice detection systems has helped to reduce both the exposure time and the amount of ice accretion during this transition time interval. Depending on the design, when ice is detected, an alert is provided to the flight crew and the ice protection systems are activated by the flight crew. In some systems, the ice protection systems are automatically activated by the ice detection system.

For those airplanes without ice detection systems, significant ice accretion can occur prior to operation of the ice protection systems, either through lack of awareness of the icing condition (e.g. night), or through non-adherence to the AFM procedures.

Another cause of ice accretion on protected surfaces is system failures. Depending on the sophistication of the design, not all failures may be indicated to the flight crew, nor readily detected. The most critical of the protected surfaces that cannot be readily observed from the flight deck is the horizontal stabilizer leading edge.

In summary, although the critical surfaces of an airplane may be provided with ice protection, there are a number of reasons why ice can be accreted on these surfaces, which ultimately can affect flight safety.

With an understanding of the adverse effects of ice accretion and why ice can occur, not only on unprotected surfaces, but also on protected surfaces, the technical reasons for icing accidents become apparent. In general, there are four main types of accidents: wing stall, tailplane stall, lateral control overbalance, and uncontrolled descent/landing.

Wing stall

Due to ice accretion on the airframe and, if applicable, ice accretion on propeller blades, the airplane begins to slow down from its initial steady state condition. Stall occurs at a much higher speed than expected due to the increased weight of the airplane and the decrease in maximum lift coefficient. Aerodynamic stall can occur prior to operation of stall protection systems intended to prevent aerodynamic stall because of the decrease in stall AOA. If the decrease in stall AOA is large enough, a stall can also occur prior to activation of stall warning with little or no natural stall warning.

A common element in this type of accident is that the airplane is climbing with the autopilot engaged in pitch or vertical speed mode, or that the airplane has just levelled out from a descent with the autopilot engaged in an altitude hold mode. Without an autothrust system, airspeed is not controlled, and the flight crew does not readily identify the speed decrease. As the airplane slows down, it will usually develop some sideslip and will be out of trim. The immediate stall characteristic is a rapid wing drop. The autopilot generally disengages during the departure from controlled flight, with accompanying aural alerts; the stall warning may or may not function and the stick pusher, if applicable, may or may not activate. The departure takes the flight crew completely by surprise, as one moment the airplane is in autopilot controlled normal flight, and the next moment the airplane has departed controlled flight. In some incidents, the flight crew has managed to recover, but with significant altitude loss. Unfortunately, in quite a few cases, control was never regained prior to impact with the ground.

Tailplane stall

This type of accident is due to ice accretion on the leading edge of the horizontal stabilizer. The horizontal stabilizer in a conventional airplane provides a net downward force to maintain the airplane in longitudinal balance and works at a negative AOA. The AOA that the horizontal stabilizer experiences is dependent on many factors, such as:

a) The greater the wing flap extension, the greater the (negative) AOA at the tail.

b) The higher the airplane speed, the greater the (negative) AOA at the tail.

c) A nose-down pitching manoeuvre also generates a greater (negative) AOA at the tail.

d) Power effects (from propellers) are also important with increasing power causing increased slipstream effects at the tail.

With ice accreted on the horizontal stabilizer, it is possible to stall the tail due to the AOA exceeding the stall AOA. This has two immediate effects. First, stalling the tail reduces the net downwards force on the tail, resulting in the airplane pitching nose down. This exacerbates the stall, as the nose-down pitch further increases the negative AOA on the horizontal stabilizer. Second, the stalled horizontal stabilizer creates significant hinge moment anomalies on trailing edge elevators. For unpowered elevators, this can result in the elevator self-deflecting to the airplane nose-down stop (elevator trailing edge down). Again, this further increases the negative AOA.

A typical scenario for this type of accident is when the flight crew selects full landing flap late in the approach, usually close to the flap limiting speed and while making a pitch-down correction to recover to an instrument landing system (ILS) glideslope. Elevator control pulsing is experienced, and the airplane continues to pitch down despite corrective control inputs. The control column is then suddenly snatched from the pilot's hands and goes to the forward stop. The flight crew is unable to recover from the nose-down pitch attitude prior to impacting the ground.

Due to widespread training information on this phenomenon, there is now an abundance of training material available to help flight crews identify and recover from tailplane stall. In general, the material suggests retracting the flaps, reducing power, and applying maximum airplane nose-up elevator control. Unfortunately, these very procedures are those that would tend to induce or deepen an airplane wing stall. As some of the characteristics of the two types of departures are similar, it is easy to see why flight crews could be confused.

Although accidents due to tailplane stall are associated with airplanes with unpowered elevators, incidents have been reported with trimmable horizontal stabilizers and fully-powered elevators. In general, the flight crew has noted either an inability to maintain trim on landing approach, or running out of airplane nose-up trim authority.

Lateral control overbalance

This type of accident has not been as common as the first two types. It has occurred due to ice accretion on the wing upper surface, just aft of the leading edge and in front of the trailing edge ailerons. Conventional ailerons are balanced, that is, in normal flight with the lateral control centred, the hinge moment in one direction on one aileron is compensated by the hinge moment on the opposite aileron. The net force on the pilot's lateral control wheel is very low. However, should the compensating hinge moment on one side change significantly, the ailerons will automatically self-deflect to roll the airplane.

In one accident of this type, the airplane was in autopilot control during a hold, with the flaps partially extended. The flaps were then retracted. The increase in the wing AOA due to the flap retraction caused a flow separation at the wing tip due to the ice accretion. There was perhaps a partial stall of the wing at the wing tip. The flow separation caused a hinge moment discontinuity at the aileron, which in turn caused the ailerons to self-deflect to full deflection. The autopilot was unable to correct the overbalance, and the airplane had a lateral departure from which recovery was not accomplished.

It is important to note that in this scenario, the autopilot is not able to give any indication of the impending potential for the overbalance occurrence. That is, until the flow on one wing tip is disrupted, the ailerons are still reasonably balanced, and the autopilot is not holding a sustained out-of-trim condition.

Uncontrolled descent/landing

If the drag increase and/or thrust decrease due to ice accretion is excessive, continued level flight may not be possible, and a descent will be required in order to maintain airspeed. This has resulted in controlled flight into terrain (CFIT) types of accidents in mountainous areas. There has also been some recent evidence to suggest that the inability to maintain the glide path during approach to landing has been a factor in accidents. In general, uncontrolled descent/landing accidents have been more prevalent in non-transport category airplanes, particularly reciprocating twin-engine airplanes.

Conclusion

The hazards associated with inflight icing are complex, with many independent variables. Ice accretion on critical airplane surfaces, both protected and unprotected, continues to be a contributing factor in many accidents. With better knowledge of these adverse effects, and with improved design procedures, ice protection systems, ice detection systems and certification criteria, airplanes will be better equipped for inflight icing in the future.

However, it is not practicable to redesign and re-certify current airplanes. Flight crews, particularly of propeller-driven airplanes with pneumatic boot de-icing systems, should always try and avoid icing conditions when it is reasonable to do so, exit icing conditions as quickly as is reasonably possible, and always operate the airplane in accordance with the flight in icing conditions procedures outlined in the AFM.

Particular care should be taken to always maintain minimum recommended operational speeds for flight in icing, avoid climbs with the autopilot engaged in vertical speed or pitch modes, monitor airplane speed closely with the autopilot engaged in altitude hold mode, avoid abrupt pitch down manoeuvres in the approach and landing configurations, and generally be aware of the hazards of flight in icing conditions. △

MAINTENANCE AND CERTIFICATION

Independent Check of Flight Controls

by Steve MacNab, Regional Manager, Aircraft Maintenance and Manufacturing, Prairie and Northern Region, Transport Canada

During recent oversight activities involving aircraft operators and aircraft maintenance organizations (AMO), it was noted that there has been an increase in findings pertaining to independent checks of flight and engine controls. The records reviewed show an inconsistency in performing checks, as well as errors in documenting activity.

All of us should note several things:

The maintenance release cannot be signed until after any required independent check has been completed and the technical record contains the signature of both persons who conducted the independent check. The regulatory chain is clear on this:

- *Canadian Aviation Regulation* (CAR) 571.10(1) requires that all requirements specified in section 571.10 of the *Airworthiness Manual* be met before the maintenance release is signed.
- Subsection 571.10(4) of the CARs Standard, item "d" of the "Types of Work" table, requires an independent check and completion of the technical record with both signatures.
- Every technical dispatch system should ensure that flight crews know if maintenance has been done, and if it has, a reasonable outline of what maintenance was done. The journey logbook is the most common source of maintenance information to flight crew. However sophisticated the technical dispatch system, the logbook makes information available to flight crew if they are to satisfy the regulatory requirements.