Comprehensive Journal of Science
Volume (10), Issue (39), (March, 2026)
ISSN: 3014-6266

مجلة العلوم الشاملة
المجلد (10) العدد 39 مارس 2026
ردمد: 3014-6266

Aircraft Aerodynamic Effects by Ice Accretions

Hatem Ahmed Abdulmula
Technical College of Civil Aviation and Meteorology, Esbea, Libya
hatemabdulmula@gmail.com
Hweda Muftah Sharif
Technical College of Civil Aviation and Meteorology, Esbea, Libya
hwedasharif@gmail.com
Salim Ali Shawesh
Technical College of Civil Aviation and Meteorology, Esbea, Libya
Akshaweshsalim2@gmail.com

تاريخ الاستلام:2026/01/12 –تاريخ المراجعة: 2026/02/07 – تاريخ القبول: 2026/02/19 – تاريخ للنشر:2026/03/20

Abstract

To research how ice accretion affects an aircraft's aerodynamic properties. Ice accretion has long been regarded as a serious threat to aircraft aviation safety since it can drastically change the transient response of jet airplanes. Additionally, by changing pitching moments and decreasing control surface responsiveness, ice accretion can negatively impact aircraft stability and controllability. Asymmetric ice accumulation can cause roll imbalances and dangerous flying conditions in extreme situations. The type, shape, thickness, and atmospheric conditions of the ice all affect how much aerodynamic degradation occurs. A/C use anti-icing and de-icing systems, which include thermal, pneumatic, and chemical techniques, to lessen these effects. These systems are made to stop or eliminate ice buildup.

Keywords: aircraft icing sys. , aerodynamic parameter sys. parameter identification

Introduction

The phenomenon of ice accumulation on an aircraft is known as aircraft icing. Aircraft icing will alter the airflow surrounding the lift surface, lowering the aircraft's performance and control capability. The safety of flight characteristics is threatened by severe icing because it will cause air separation on the airfoil in advance, leading to a stall [1]. An anti-icing system is typically installed on the crucial lifting components of contemporary aircraft to prevent the dangerous effects of icing. Nevertheless, flights with ice accumulation on the aircraft are still inevitable, and the accidents are typically brought on by ice protection systems malfunctioning or operating incorrectly. According to the data given by National Transportation Safety Board (NTSB) [2], from 1981 to 1988, about 542 aircraft accidents are caused by aircraft icing. According to the statistics of the International Civil Aviation Organization (ICAO), the death rate of passengers in aircraft icing accidents reached 39% in the early 1990s [3]. Aircraft icing is still a big problem for flight safety and the studies on this area are attracting more attention. In addition to the basic military and industrial operations, airplanes have been extensively used in different areas such as aerial trip, investigation, relief operations, residential plane ride, and so on as the purpose of aircraft has expanded. As a result, aircraft must fly typically in all weathers in order to complete the anticipated missions. Even though some precautions are considered to prevent dangerous wind conditions as much as plausible, such as hourly sequential reports, node estimates, and the lower - level windshear alarm systems. Nevertheless, flight collisions caused by airplanes flying in adverse weather conditions. For example, strong winds, thunderstorms, tropospheric vorticity, freezing rain, hail, severe weather, rain, and ice accumulation have already been revealed year after year ever since the invention of commercial airliners. Climate is responsible for more than half of commercial flight collisions, and it continues to remain the most uncertain component in aircraft operation, particularly unseasonal weather, which can cause a slew of issues in flight operations, drawing people's attention to an issue [4]. Since the previously stated adverse weather, icing has piqued people's interest. The Ice accretion on the surfaces from some parts of an aircraft experiencing an icing meteorological circumstance is known as aircraft icing. Ice accretions can alter the airflow structure of an aircraft, altering the airflow domain and lead to an increase in drag and a reduce in lift. Deterioration of the airflow efficiency of wings, tails, propellers, inlets, and other surface irregularities due to the contamination in any type can have severe repercussions, especially if it is not recognized and compensated for.

Resulting damage all through combat operations from foreign substances lobbed up off the ground or confrontations with systems and equipment, as well as a variety from in sources such as interactions with hail, birds, insect pests, and other pests, are all common pollutants causes. Ice accretions on such substrates, on the other hand, have unquestionably gotten the most focus. Experiments have shown that even minor ice factors generally at strategic points can lead to large decreases in highest hoisting abilities and linear actuator potency, control surface discrepancies, perceptible rises in drag, and, in some instances, lowered fuel efficiency and consistency. Centuries of practical experience have identified multiple circumstances in which glaciers can accumulate on "ice-protected" airplanes, both in flight and on the earth [5]. Flight accidents can occur as a result of severe ice accumulations. Over the last several centuries, icing-induced aircraft collisions have indeed been mentioned across the globe. In the United States, statistics from 1973 to 1977 showed that icing-induced collisions accounted for 2.56

percent of all flight collisions, and icing-induced fatal crashes accounted for 4% of all fatal accidents. Despite the fact that most planes are installed with anti- and/or de-icing structures, it would still be tough to prevent flights with ice interpolations due to varying icing circumstances, ice accumulation severity, and anti- and de-icing framework working situations. As a result, research into aircraft aerodynamic performance, consistency, control, and flight effectiveness in icing conditions is critical. Much study has been undertaken in this area, and substantial progress has been made [6].

1-Ice Formation On Aircraft.

From our daily experience we know that water freezes to ice below 0 °C (32 °F) and melts again above 0 °C. When it comes to aircraft icing, we learn that this need not be so. Below (!) 0 °C, tiny droplets may still be in the liquid phase. Although very tiny and pure droplets may reach temperatures as low as -40 °C (-40 °F) and still be liquid, the majority of droplets will have turned to ice below -20 °C (-4 °F). All of the water in the air will eventually freeze below -40 °C. Super cooled water is defined as (liquid) water that is below 0 °C. Because the water has been completely undisturbed during cooling—nothing has caused it to turn to ice—supercooled water is possible. However, the droplet receives the input required for the phase change and turns to ice when an aircraft strikes it. When the droplets are supercooled water, the heat extraction has already occurred, but the phase transition from water to ice typically requires some latent heat extraction. Compared to the supercooled water a moment ago, the ice will be marginally warmer.

In summary, the interaction with the aircraft causes supercooled water to instantly turn into ice. If the aircraft's surface is below 0 °C, ice will accumulate on it. Thus, aircraft icing is feasible if:

1. Air contains water (clouds are an indication of water in the air)
2. Air temperature is below 0°C.
3. Air temperature is above -40°C.
4. Aircraft surface is below 0°C.

In addition to the conventional method just covered, there are additional icing mechanisms:

- If the aircraft encounters humid air, even at temperatures above 0 °C, icing will occur during the descent from high altitudes. A lengthy flight at high altitudes will cause the aircraft surface to be below 0 °C [7]. Additionally, the wings' fuel will be below freezing. The integral fuel tank design puts the fuel in close proximity to the skin. The fuel will probably stay below 0 °C until landing because it does not warm up quickly.

- Carburetor icing occurs in temperatures from -7°C to 21°C (20°F to 70°F) when visible moisture or high humidity is present, resulting from fuel vaporization cooling combined with the expansion of air flowing through the carburetor.
- Water or slush picked up during taxi can freeze at altitude, with detrimental effects.
- Frost, ice, and snow that have accumulated on the aircraft while on the ground must be removed prior to takeoff. Ground deicing equipment and procedures are available for this purpose (see AC 135-16). [21]. The two basic forms of ice built-up on the aircraft surface are clear ice and rime ice as showed that in the Fig. (1).
- Clear ice typically forms between 0 °C and –10 °C from larger water droplets or freezing rain. It can drastically alter the shape of the leading edge and spread across surfaces.
- Mixed ice typically forms at temperatures between −10 °C and −15 °C. It is a combination of clear ice and rime ice, inheriting the hazardous properties of both, and can accumulate very quickly.
- Rime ice forms at temperatures between −15 °C and −20 °C when small supercooled droplets freeze instantly upon contact with the aircraft surface. This type of ice appears rough and brittle, with a milky white color.

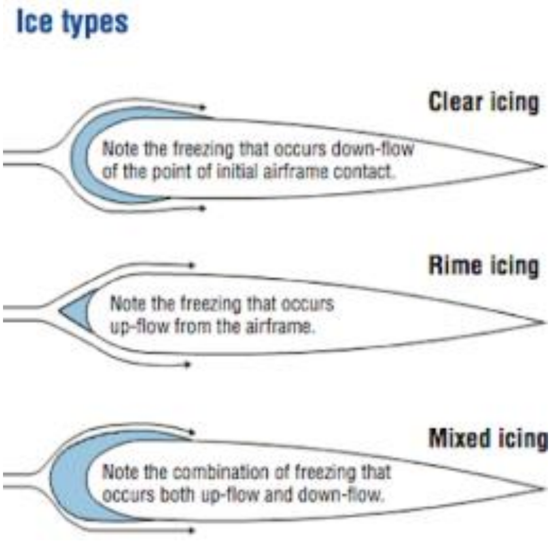

Figure 1: The Ice shapes on the leading edge of airfoils

2- Ice Effects on Aircraft Aerodynamics.

Contamination of aerodynamic surfaces (wings, tails, rotors, inlets, etc.) can have serious consequences, particularly if the contamination is unknown or unaccounted for. Typical sources include damage from foreign objects or ground support equipment during ground operations, as well as in-flight sources such as hail, birds, and insects. Undoubtedly, the most extensively studied source is ice accretion. Experimental results show that even relatively small ice accumulations at critical locations can cause substantial reductions in maximum lift and control effectiveness, control surface anomalies, marked drag increases, and, in some cases, degraded engine performance and stability. Figure 2 illustrates the effect of ice.

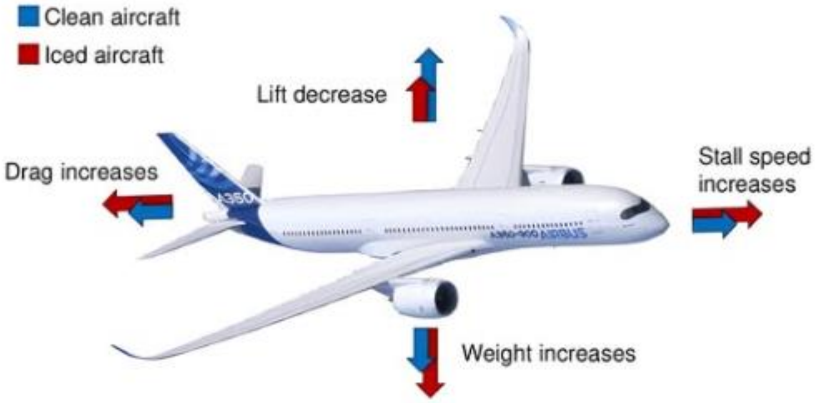

Figure 2: The Effect of Ice on A/C Performance

Decades of operational experience have identified numerous situations both in flight and on the ground where ice can accumulate on aircraft equipped with ice protection systems. These include:

- Certain areas or components that are vulnerable to ice accretion may be left unprotected. This may result from their lower aerodynamic criticality or from design trade-offs that balance the cost and resource demands of ice protection systems against alternative solutions, such as increasing aerodynamic surface size.
- The presence of initial, residual, or inter-cycle ice accumulations associated with the operation of de-icing systems.
- Delays in activating anti-icing or other ice protection systems.
- Runback ice forming behind anti-iced areas when water droplets are not fully evaporated, either by design limitations or during severe icing conditions.
- Ice buildup caused by water droplets impacting areas aft of leading-edge ice protection systems.
- Frost or ice accumulation on upper surfaces due to exposure to adverse weather while the aircraft is on the ground.
- Frost or ice forming on both upper and lower wing surfaces near fuel tanks when an aircraft is parked in high humidity conditions after the fuel has been significantly cooled during flight (“cold soaking”).

Over the decades, much has been learned about the varied forms of ice accretion on aircraft surfaces. Insights gained from natural icing encounters in flight and on the ground, from aircraft flying behind water-dispensing tankers that simulate icing clouds, and from extensive icing tunnel, tests have shown that ice can accumulate in numerous locations, sizes, and shapes, with a range of surface roughnesses.

The size of in-flight leading-edge ice accretions are by-and-large proportional to the liquid water content (LWC) of the icing cloud, the velocity of the aircraft, and the duration of the icing encounter. Conversely, the size of ice accretion generally varies inversely with the dimensions of the aircraft component (such as the leading-edge radius) exposed to icing conditions. Ice formations can range from small, relatively uniform layers to large, highly irregular shapes, including what are commonly referred to as “horned” or “lobster tail” ice formations.

These ice shapes depend on several factors, including the characteristics of the icing cloud, the duration of exposure, and the dimensions of the aircraft surface. Ambient temperature also plays a significant role in determining the final shape. In addition, the degree and nature of surface roughness or irregularity are strongly influenced by droplet size, air temperature, and how effectively de-icing systems remove accumulated ice. Likewise, both runback ice and ground-based ice accretions can vary considerably in form and extent.

Given the wide range of ice shapes and sizes that can form on aircraft surfaces under actual operating conditions, researchers and designers face a significant challenge in reliably defining ice accretion processes and their physical characteristics across various flight and weather regimes. A related goal is to identify which types of ice accretions pose the greatest hazard.

Aircraft certification typically requires limited flight-testing in natural icing conditions to demonstrate the effectiveness of ice protection systems, as well as overall performance and handling. However, relying heavily on such testing is impractical for systematically studying ice accretion characteristics, developing and validating ice protection systems, or accurately assessing aerodynamic effects.

Natural icing flight tests have several drawbacks: high cost, technical complexity, seasonal limitations, and the uncertainty and risk of encountering suitable icing conditions. Additionally, such tests lack the repeatability and comprehensiveness needed for general analysis, and they are not well suited for precisely quantifying performance impacts.

Flight-testing behind tanker aircraft that spray water droplets can address some of these challenges but introduces its own limitations, including droplet evaporation in subsaturated air and constraints on plume size, droplet size, and droplet distribution all of which can affect the accuracy of the icing simulation.

3- How ice affects flight control Aerodynamics.

The aerodynamic effects of accreted ice on the continued safe flight of an aircraft are a complex subject because of the many forms that such ice accretion can take. In certain circumstances, very little surface roughness is required to generate significant aerodynamic effects; as ice-load accumulates, there is often no aerodynamic warning of a departure from normal performance. The stall waring systems are designed to operate in relation to angle of attack of a clean airplane and cannot be relied upon to activate usefully in the case of an ice-loaded airframe as showing in figure (3).

The aerodynamic impact of ice on an airfoil depends on several key factors, including the location of the ice relative to the airfoil's pressure distribution, the ratio of ice height to wing chord length (**k/C ratio**), and the specific geometry of the ice formation. These parameters are extremely difficult if not impossible to accurately assess from the cockpit.

Contrary to earlier assumptions, the effects of icing are not necessarily cumulative in a linear or proportional manner. While large ice formations can significantly affect lift, drag, and pitching moment, decades of research have shown that even small amounts of surface roughness can produce substantial aerodynamic penalties. In all cases, these effects are strongly influenced by the angle of attack, making its control critically important.

One of the most dangerous aspects of icing is that it often provides little to no aerodynamic warning before a deviation from normal performance occurs.

A thin layer of ice roughness often referred to as hoar frost can cause an early, abrupt peak in the lift curve, followed by a sharp decline in lift. The hazardous aspect is that lift behavior may appear normal until the peak is reached and flow separation begins, offering no aerodynamic warning. Additionally, flow separation can occur well before artificial stall warning systems activate.

Test results indicate that drag associated with hoar frost may not increase significantly until the angle of attack approaches the early stall point. Even then, the drag rise may appear manageable.

Hoar frost has been identified as a contributing factor in many accidents. Either this is often due to the flight crew failing to detect the thin ice layer before increasing angle of attack, or delaying ice protection system activation until some accumulation has already occurred.

Larger ice formations can produce similar aerodynamic effects. In some cases, the lift curve peaks at an angle of attack much lower than that associated with hoar frost. These larger ice shapes are typically accompanied by significant drag increases that are strongly angle-of-attack dependent. A particularly dangerous characteristic is that drag can increase far more rapidly with increasing angle of attack than pilots may expect, potentially exceeding available engine power at higher angles of attack.

The FAA research has shown that, for aircraft with pneumatic de-icing system such effects can be experienced with inter cycle ice shapes typical of a mixed rime & glaze condition when the de-ice cycle time was three minutes. Considerably better ice shedding was observed when the de-ice cycle time was reduced to one minute intervals, even in more severe icing conditions. Optimum ice shedding was not achieved until the pneumatic de-ice boot had completed several cycles [9].

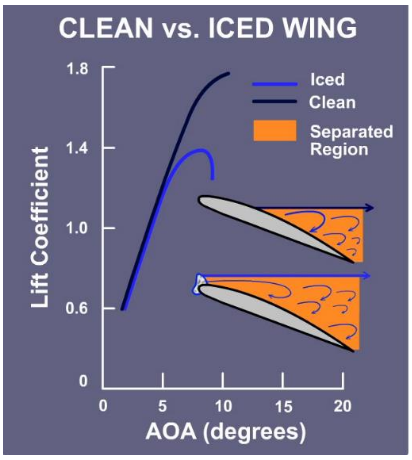

Figure 3: An ice-contaminated wing will stall at a lower angle of attack [10].

4- Aircraft Icing: An Ongoing Threat to Aviation Safety.

Based on nearly two decades of data collected from the Beech King Air aircraft, Ashenden et al. investigated the effects of aircraft icing, particularly under freezing drizzle conditions. Their findings indicated that the rate of flight performance degradation is a strong indicator of icing severity.

Using limited flight data, Leckman estimated the performance characteristics of the Cessna Centurion and Air Overlord aircraft in icing conditions, achieving satisfactory results.

To date, one of the most comprehensive datasets comes from NASA experiments conducted on the DHC-6 Twin Otter. These studies also examined the influence of thrust, flap settings, and angle of attack on aircraft performance in icing environments.

In addition, NASA, in collaboration with the FAA, carried out flight tests under the Tailplane Icing Program. These tests provided valuable insights into aircraft stability and control characteristics, showing that the adverse effects of icing become more pronounced as the angle of attack increases.

Figure 4: A Twin Otter operated in ice condition.

5-Aircraft Icing Influences the Flight Safety in Many Ways.

1. When there is icing, the aircraft's maximum lift coefficient and lift curve slope drop, while the drag and critical stall speed rise. If the pilot does not monitor changes in airspeed and climb rate, the aircraft may approach the stall boundary [17], [16], [15].
2. While tailplane icing may result in a tailplane stall, particularly in flap downwash flows, wing icing can reduce the airfoil stall angle of attack. Both conditions may result in pitch instability and potentially lead to a crash [8].
3. Additional rolling moment can arise from three situations: asymmetric icing, failure of the anti-icing system on one side, and the formation of an ice ridge beyond the ice protection system. The first two may limit lateral control, but the third is particularly hazardous, as it can lead to uncommanded roll and loss of control. A notable example is the ATR-72 crash in 1994. The aircraft was operating in severe icing conditions. The combination of the wing leading-edge electric de-icing system and the natural environment caused an ice ridge to form aft of the protected area, creating a negative pressure zone over one aileron. During a routine turn, this pressure differential caused the aileron to deflect unexpectedly. The aircraft immediately lost control, rolled, and crashed [19].

4. Control efficiency degrades under icing conditions. Flight tests have shown that tailplane icing can increase stick forces by hundreds of pounds, making control more difficult. Icing on the rudder movable surfaces may cause the rudder to become stuck, leading to loss of controllability. Icing on the leading edge of flaps can cause premature airflow separation over the flap surfaces, reducing flap effectiveness [20].

Conclusion.

One important factor influencing an aircraft's aerodynamic performance, stability, and general flight safety is ice accumulation. Ice buildup on aerodynamic surfaces can seriously impair an aircraft's handling characteristics and efficiency by changing the geometry of the airfoils, increasing drag, decreasing lift, and disrupting airflow. Reduced control responsiveness, changed pitching moments, and, in extreme situations, hazardous flight conditions like stall or roll imbalance because of asymmetric ice formation can result from these alterations.

References.

[1]-Whalen, E., Bragg, M.B. "Aircraft characterization in icing using flight test data." J. Aircr. 2005, 42, 792–794.

[2]-Authority, C.A. Aircraft Icing Handbook; Safety Education and Publishing Unit:Lower Hutt, New Zealand, 2000.

[3]- Cao, Y.; Tan, W.; Wu, Z. "Aircraft icing: An ongoing threat to aviation safety." Aerosp Sci. Technol. 2018, 75, 353–385.

[4]- D.Zmic, P. Mahapata, R. Doviak, and V. Mazur, "Aviation Weather Surveillance System": Advance Radar and Surface Sensors for Flight Safety and Air Traffic Management (American Institute of and Astronautics, Inc., Washington, DC,1999)

[5]- Y.Cao, Z. Wu, and Z.Xu, Progress in Aerospace Sciences 71,85 (2014)

[6]- S.P.Baker, J.E. Brady, D.F, Shanahan, and G.Li, AviatSpace Environ MED 80,1001 (2009)

[7]- Panamedia International Flight School (2024), ice-formation-on-aircraft

[8]-CAA Vector, 1997 Issue 3. New Problems with Ice – Dan Manningham.

[9]- FAA Flight Standards Handbook, Bulletin Number HBAT 98-21. Relief of Icing Fuel Penalties Associated with Critical Fuel Calculations for ETOPS

[10]- Handling effect of aerodynamic icing (2016), aircrafticing.grc.nasa.gov

[11]- T.S. "Board Determining the Effects of Weather in Aircraft Accident Investigations", (1986)

[12]-J.R. Nicholson et al. Atmospheric sciences program at NASA Kennedy Space Center. ,(1988)

[13]- E. Mandel Severe weather-impact on aviation and FAA programs in response, (2012)

[14]-G. Forbes et al. Weather support for the space program ,(2022)

[15]-T.P. Ratvasky et al. "Icing Effects on Aircraft Stability and Control Determined from Flight Data," Preliminary Results, NASA TM 105977 (January 1993)

[16]-T.P. Ratvasky et al. NASA/FAA Tailplane Icing Program Overview ,(1999)

[17]- R.J. Ranaudo et al "The Measurement of Aircraft Performance and Stability and Control After Flight Through Natural Icing Conditions," (1986)

[18]-H.E. "Addy Ice Accretions and Icing Effects for Modern Airfoils", (2000)

[19]-M. Papadakis et al "Aerodynamic performance of a swept wing with ice accretions", (2003)

[20]-M.B. Bragg et al. "Effect of Ice Accretion on Aircraft Flight Dynamics", (2000)

[21]- Federal Aviation Administration AC Deicing and Anti-icing Training and Checking, (1994)