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Safety risks arising from icing in flight operations

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Abstract: The paper treats a hazard of the icing in the flight operations. In the first part of the work, a description of the meteorological aspect of the icing can be found. At the beginning, the phenomenon of icing is defined. The work continues by defining the types of icing. Subsequently the process of icing identification is described by the meteorologists on the one hand and by the pilots on the other hand. It provides the definition of the products and the equipment used for the icing identification. In the next part of the work, an influence of icing on the flight operations (on the airframe, on the instruments and on the propulsion system) is analyzed. Chapter V identifies the areas representing the highest risk for the flight operations. The rest of the work elaborates on the safety risk analysis of the icing in flight. In Chapter VII an attempt to find out the ways how to increase the safety level and how to decrease the hazard of icing related occurrences is proposed. Finally, the last improvements in icing forecasts are described in the work.

Keywords: Icing, Ice, Frost, Freezing rain, Freezing drizzle, Freezing fog, Ice crystals, Supercooled water, Supercooled Large Droplets, anti/de-icing

JEL Classification: Z00

1. Introduction

The aviation industry is dependent on the several sources of information to maintain current level of safety. One of the most important sources is a meteorological service. It supplies aviation personnel with the most accurate forecasts, reports, charts and other available information about the weather conditions. Icing is one of them.

The icing reduces aircraft performance in a number of ways. Unfortunately, it´s proven by a fact that 30 % of accidents in commercial aviation are caused by icing. (Labyt, D., 2008) In the United States of America the airframe icing resulted in 583 accidents and more than 800 fatalities between years 1982 and 2000. (J Petty, K., 2000)

It is difficult to forecast icing. As it´s written in a book of Aeronautical Meteorology from ENAC (Ecole Nationale de l'Aviation Civile) the biggest problem of icing is that it´s not as obvious as other meteorological phenomena (visibility, precipitations, strong wind…) If you are not prepared, trained or you forget to think about the risk of icing, it can surprise you violently and quite often very late to recover it.

Icing is a specific form of contamination that consists of a deposit or coating of ice on an object such as an aircraft or part of it. Contamination means any deposit of lithometeors (dry particles suspended in the atmosphere such as dust, haze, smoke, and sand) or hydrometeors (any of various forms of water in liquid or solid form) on a surface.

2. Types of Icing

It exists more kinds of icing classification. Depending on the weather conditions we can define the basic types of airframe icing as hoar frost, rime ice (soft ice), clear ice (hard ice, glaze ice) and several specific types of icing as mixed ice, rain ice (glazed frost) and pack snow.

A. Hoar frost

Hoar frost appears in the conditions when the air temperature reaches the saturation point and a surface of the aircraft is cooled to the freezing temperature. It is the only type of icing that can occur in clear air if we don´t speak about the ice crystals icing. Hoar frost is a white crystal deposit in a form of needles, scales or feathers which make it quite brittle. It is very similar to the frost on the ground.

B. Rime ice

Inside the clouds, the rime ice is formed by rapid freezing of the supercooled drops or by very small cloud droplets in contact with a surface at negative temperature. A fast freezing of small water droplets causes that air bubbles contained in the water are trapped in the ice. The rime ice has an opaque, white appearance that is making it fragile and brittle due to trapped air bubbles.

C. Clear ice

Opposite to the rime ice, the clear ice formation is connected with a slow freezing process of supercooled water droplets. As it is a slow process, ice has enough time to spread over airframe surface, to create homogeneous layer without the air inclusion. Clear ice forms a transparent layer of ice without air inclusion. It can be characterized as homogeneous, smooth, clear, compact and very solid. It can spread over big airframe surface.

D. Ice crystals

A hazard of ice crystals icing exists in high altitudes where a strong convection activity lifts an important quantity of the water. The warm moist air, which contains high water quantity, cools while it climbs. The water condenses and freezes subsequently while it is forming small ice particles – the ice crystals. In high altitudes, in the tropopause layer, strong winds (jet-streams) move ice crystals far away from the clouds where they are formed. Ice crystals don´t form a deposit on a smooth and clean airframe. Ice crystals can be trapped by the droplets freezing on the contaminated surfaces in clouds. When warm surface is hit by ice crystals, they can melt and stick aft of the warm surfaces. If a big amount of ice crystals is present, it can result in probes blockage or engines problems. (Duvivier, E., 2010)

3. Identification of Icing

A. Identification by meteorologists

Meteorologists identify the icing by evaluating an ice potential of the atmosphere. The ice potential is directly proportional to the total quantity of supercooled water, to the size and to the distribution of the water drops or of the droplets. It depends on the temperature and on the vertical movements of the air. It is not easy to forecast icing conditions because precise meteorological forecasting model doesn´t exist. We are able to identify and forecast the ice potential just based on a good knowledge of the physics of icing, radar data, satellite imagery and thanks to the numerical forecasts.

B. Weather products used in icing identification

- Satellite and radar images

  Satellite and radar images can provide valuable help in identification of the icing areas. However, it is not possible to observe the icing while using the satellites and the radar data only. Even if the most modern radars can provide us with the information about the temperature of precipitation, it´s still complicated to forecast icing.

- Forecasts, charts and reports
  - AIRMETs
  - SIGMETs
  - PIREPs
  - Freezing level charts
  - Current Icing Potential (CIP)
  - Forecast Icing Potential (FIP)
- ACARS data usage
  Commercial airplanes provide over 130 000 meteorological observations per day nowadays, including measurements of the temperature, winds and in some cases the planes observe of the icing, humidity, vertical wind gusts or eddy dissipation rate (turbulence). (Moninger, W. et al., 2003)

C. Identification by pilots

- Weather radar
  The main reason of radar presence on board is to enable the navigation of the pilots around the thunderstorms, to avoid dangerous turbulences and the icing as well. However, it is not in the capabilities of the radar to directly identify the icing. The problem of radar is that it reflects poorly when liquid water is not present. It´s not able to reflect off the water vapor, the micro sized droplets that form majority of clouds and it reflects poorly ice crystals, ranging from the snowflakes to the hail stones.
- Ice detectors
  Ice detectors are used to verify that the ice accretion on the most vulnerable parts of the aircraft is acceptable. Otherwise use of de-icing/anti-icing equipment or escape from icing conditions are necessary. Several types of icing detectors exist and are used on board of the aircraft (Smiths ice detector, Vibrating ice detector, Napier ice detector…)

4. Influence of Icing on Flight Operations

A speed of the aircraft and its aerodynamic shape are very important factors in aircraft icing. They have important influence on the surface temperature of the airframe through aerodynamic heating. For example, an aircraft flying at FL100, where standard air temperature is -5°C, cruising at Mach 0,6 will have the temperature of 12,8°C at the point of impact and the average temperature of the wing surface section will be 11°C.

Some parts of the airframe are more sensitive to the icing than the other parts. The most sensitive parts to the icing are the sharp components such as the leading edges of the wing, the empennage, the engine intakes, the propellers, the spinners, the antennas, probes, the windscreen wipers.

A. Airframe icing

1. Mass increase

Variation of the mass caused by icing will have more significant effect on a light aircraft that has generally less excess of power then on a heavy aircraft type.

2. Modification of balance

Ice deposits will not often be uniformly repartitioned across the airframe. This will modify a distribution of mass, CG position will be modified and finally it may cause a loss of stability. (Oxford, 2008)

3. Aerodynamic effects

The ice accumulates firstly on the leading edges of an airfoil. It disrupts the laminar air flow on the wing and significantly reduces a lift. This causes an increase of drag and reduction of the stall angle. Ice modifies the handling characteristics and the aircraft performance.

4. Problems with controls

a) Wing stall

Ice deposit on a wing affects the lift negatively. It decreases the critical angle of attack while drag and weight increase.

b) Roll upset

It is an uncommanded and uncontrolled roll phenomena. Ice ridge, which builds up on an unprotected surface of the wing, disrupts laminar flow of the air. Airflow separation on the wing induces self-deflection of the ailerons and degraded roll handling characteristics.

c) Empennage stall

When the ice deposit on the tail plane becomes excessive and the horizontal stabilizer reaches critical value of angle of attack the tail plane stall occurs. Natural nose down tendency produced by the center of lift of the main wing will not be compensated by tail plane any more. The plane will react by pitching down uncontrollably.

B. Instruments icing

1. Probes icing

The pressure probes on the passenger aircraft are heated during all the flight. Without the heating, the pitot tubes can be very easily blocked by the ice, even in light icing conditions.

2. Antennas icing

A sharp shape and the position of the antennas makes them very vulnerable to the ice formation. Antennas must be equipped with anti-icing protection to do not disturb the radio communication.

C. Propulsion system icing

1. Engine icing

The ice deposits on the engine intakes disrupt an airstream and degrade the thrust. When the ice formation is excessive or if the de-icing of the engine inlet is operated improperly, big ice blocks can be ingested by the engine. This can damage the blades of the compressor or it could lead to the engine stall or sometimes the engine destroy.

2. Propeller icing

The propeller will start to vibrate because of the ice sometimes. The severe icing can cause a destruction of the propeller. To overcome it, the anti-icing systems are mounted on the propeller.

5. Areas Representing the highest Risk for Flight Operations

A. Areas under influence of front passage

1. Influence of Cold front

Two different air masses exist one over the other, separated by the front line. This state is perfect for the icing formation. Precipitations that are formed in the warmer air, in form of the rain, fall to the colder air. In these conditions severe icing is very probable. Ice accumulates so quickly that almost every aviation industry manufacturer advises that none of its products, even those certified for known icing, are design and certified to fly in the freezing rain.

2. Influence of Warm front

Similar situation as we have seen at the cold front area happens with the warm front passage. The air temperature increases first at higher altitudes as the front passes. If a temperature of the colder air is negative, the freezing rain forms again. In case of the warm fronts, the areas under the influence of the freezing rain is much wider in comparison with the cold front. The freezing rain forms only in case that rain drops are falling on a short distance threw the colder air (with the negative temperatures). Otherwise, water is transformed into ice and drops become ice pellets.

B. Inversion in an altitude

Strong temperature inversion in the altitude of a few thousand feet or the wind shear can block all the updrafts in the air. The water lifted up from the ground to the inversion layer starts to accumulate near the top parts of the inversion. If this phenomena takes places in a higher altitude, where the temperature drops under 0 °C, the probability of the icing is quite high. Statocumulus clouds imply the presence of the temperature inversion very often. Closer to the top of Stratocumulus we are flying, higher icing severity is possible.

C. Orographic lifting

The humidity is transported to a high troposphere by an orographic lifting. It results in the formation of the clouds above the mountains. These clouds contain supercooled water. It represents the potential icing conditions in combination with the cold air.

D. Inter-Tropical Convergence Zone

Inter-Tropical Convergence Zone is an area of a significant weather that circles the globe near the equator. This zone is well known for pilots because of massive thunderstorm development. Ice crystals icing is very probable in the Inter-Tropical Convergence Zone

E. Icing conditions at high altitudes

There exists high possibility of ice crystals icing in the upper troposphere. The most vulnerable parts of the plane threatened by the ice crystals are the engines and the probes. The problem with ice crystal icing is that our knowledge about it is not sufficient. We don´t have enough precise data about the volume of ice crystals in the upper troposphere.

6. Safety Analysis of Icing in Flight

This chapter summarizes the last major safety events which happened during the flights of commercial aircraft and that have something in common with the icing. Each accident/incident is described by a table, summarizing the effect of the icing on the occurrence. In this table, I try to define related hazards, trace the consequences of these hazards and evaluate the existing barriers. To assess a risk of the hazard related consequences, the safety risk index will be assigned to each occurrence, as it is defined in ICAO Doc 9859 - Safety Management Manual. In each case, the most suitable value from the Table 1 will be chosen to approximate the likelihood or the estimated frequency of the safety occurrence.

Table 1 - Safety risk probability

Likelihood	*Meaning*	*Value*
Frequent	Likely to occur many times (has occurred frequently)	5
Occasional	Likely to occur sometimes (has occurred infrequently)	4
Remote	Unlikely to occur, but possible (has occurred rarely)	3
Improbable	Very unlikely to occur (not known to have occurred)	2
Extremely improbable	Almost inconceivable that the event will occur	1

Source: (SMM, 2013)

The values/characters form the Table 2 will be used to characterize the severity of each occurrence.

Table 2 - Safety risk severity

Severity	*Meaning*	*Value*
Catastrophic	— Equipment destroyed — Multiple deaths	A
Hazardous	— A large reduction in safety margins, physical distress or a workload such that the operators cannot be relied upon to perform their tasks accurately or completely — Serious injury — Major equipment damage	B
Major	— A significant reduction in safety margins, a reduction in the ability of the operators to cope with adverse operating conditions as a result of an increase in workload or as a result of conditions impairing their efficiency — Serious incident — Injury to persons	C
Minor	— Nuisance — Operating limitations — Use of emergency procedures — Minor incident	D
Negligible	— Few consequences	E

Source: (SMM, 2013)

A. Major accidents/incidents caused by icing in flight

1. Clear ice accretion, ATR 72

- Date: 31 October 1994
- Location: near Roselawn, Indiana (United States of America)
- Type of occurrence: Fatal accident

Table 3 - Clear ice accretion, ATR 72

Type of operation or activity	*Generic hazard*	*Specific components of the hazard*	*Hazard-related consequences*	*Existing defenses to control safety risk(s)*	*Safety risk index*
Flight in significant weather	Approach /holding in an area of supercooled precipitations	Severe rime and clear airframe icing	Degraded aerodynamic performance – roll upset, stall	De-icing boots	4A

2. Wing stall, Cessna Citation V Ultra C560 U

- Date: 2 January 1996
- Location: near Augsburg, Bavaria (Germany)
- Type of occurrence: Accident

Table 4 - Wing stall, Cessna Citation V Ultra C560

Type of operation or activity	*Generic hazard*	*Specific components of the hazard*	*Hazard-related consequences*	*Existing defenses to control safety risk(s)*	*Safety risk index*
Flight in significant weather	Precision approach in freezing fog	Wing icing - clear ice	Stall	Operational procedures	3B

3. *Stall caused by icing, Embraer 120RT Brasilia*

- Date: 9 January 1997
- Location: near Monroe, Michigan (United States of America)
- Type of occurrence: Fatal Accident

Table 5 - Stall caused by icing, Embraer 120RT Brasilia

Type of operation or activity	*Generic hazard*	*Specific components of the hazard*	*Hazard-related consequences*	*Existing defenses to control safety risk(s)*	*Safety risk index*
Flight in significant weather	Descent through the layer of clouds	Wing icing - glaze/mixed ice	Degraded aerodynamic performance – roll upset	De-icing boots	4A

4. *Frost accumulation, Cessna 208 Caravan Amphibian*

- Date: 28 December 1999
- Location: near Abbotsford Airport, British Columbia (Canada)
- Type of occurrence: Accident

Table 6 - Frost accumulation, Cessna 208 Caravan

Type of operation or activity	*Generic hazard*	*Specific components of the hazard*	*Hazard-related consequences*	*Existing defenses to control safety risk(s)*	*Safety risk index*
Preflight-check	Condition of the surface of an aircraft	Frost deposit on the airframe	Degraded aerodynamic performance – MTOW exceeded, stall	Ground de-icing	4B

5. *Engine flame-out, Shorts SD3-60*

- Date: 13 January 2000
- Location: near Marsa el-Brega (Libya)
- Type of occurrence: Fatal accident

Table 7 - Engine flame-out, Shorts SD3-60

Type of operation or activity	*Generic hazard*	*Specific components of the hazard*	*Hazard-related consequences*	*Existing defences to control safety risk(s)*	*Safety risk index*
Flight in significant weather	Descent from colder air to warmer air	Ice accretion on the engine inlets	Engine flame-out	De-icing	3A

6. *Blocked elevator controls, BAe 146-300*

- Date: 12 March 2005
- Location: en-route, between Frankfurt and Stuttgart
- Type of occurrence: Serious incident

Table 8 - Blocked elevator controls, BAe 146-300

Type of operation or activity	*Generic hazard*	*Specific components of the hazard*	*Hazard-related consequences*	*Existing defenses to control safety risk(s)*	*Safety risk index*
Ground anti-icing	Application of thickened anti-icing liquid	Accumulation of anti-icing liquid residues on an airframe	Controls blockage	Pre-flight check, unthickened anti-icing liquids	5D

7. *Airspeed indicator error, Airbus A320-200*

- Date: 24 January 2007
- Location: in climb from Nuremberg to London
- Type of occurrence: Serious incident

Table 9 - Airspeed indicator error, Airbus A320-200

Type of operation or activity	*Generic hazard*	*Specific components of the hazard*	*Hazard-related consequences*	*Existing defences to control safety risk(s)*	*Safety risk index*
Flight in significant weather	Flight through an inversion layer in freezing temperature	Melting ice deposit	Pressure probes blockage	Pressure probes construction	3D

8. *High altitude stall, Airbus A330-200*

- Date: 1 June 2009
- Location: the Atlantic Ocean, near Brazilian coast
- Type of occurrence: Fatal accident

Table 10 - High altitude stall, Airbus A330-200

Type of operation or activity	*Generic hazard*	*Specific components of the hazard*	*Hazard-related consequences*	*Existing defenses to control safety risk(s)*	*Safety risk index*
Flight operations in Intertropical Convergence Zone	Cruise flight in the upper troposphere	Ice crystal icing	Pitot tubes blockage	Pitot-tubes de-icing	3A

7. Recommendations to Increase the Level of Safety

A. Safety analysis outcome

To identify the safety risk index of each occurrence, I tried to discover all other situations where the aircraft´s safety margins were reduced by the same hazard related consequences. After this analysis I was able to set down the probability index of the occurrences.

To move the safety analysis forward, the safety risk assessment matrix must be defined. It contains all the combinations of the severity and the probability indexes.

Table 11 - Safety risk assessment matrix

Risk probability		Risk severity				
		Catastrophic A	Hazardous B	Major C	Minor D	Negligible E
Frequent	5	5A	5B	5C	5D	5E
Occasional	4	4A	4B	4C	4D	4E
Remote	3	3A	3B	3C	3D	3E
Improbable	2	2A	2B	2C	2D	2E
Extremely improbable	1	1A	1B	1C	1D	1E

Source: (SMM, 2013)

The final task is to define the tolerability region of the risk in the matrix. For this purpose a new diagram showed in the Table 12 - Safety risk tolerability matrix is used.

Table 12 - Safety risk tolerability matrix

Tolerability description	Assessed risk index	Suggested criteria
Intolerable region	5A, 5B, 5C, 4A, 4B, 3A	Unacceptable under the existing circumstances
Tolerable region	5D, 5E, 4C, 4D, 4E, 3B, 3C, 3D, 2A, 2B, 2C, 1A	Acceptable based on risk mitigation. It may require management decision.
Acceptable region	3E, 2D, 2E, 1B, 1C, 1D, 1E	Acceptable

Source: (SMM, 2013)

The tolerability regions defined in this diagram must fulfil the criteria defined by a person/an organization responsible for the safety risk analysis. In a case of the safety analysis of the icing in my work, I preserved the tolerability regions as they are defined in the ICAO Doc 9859. I think that it corresponds quite well with a required level of safety for the operations in the icing environment.

The ultimate task of the safety risk analysis is a safety risk management. The aim of the safety risk management is to evaluate the safety risk and to find the way how to decrease the risk to the minimal tolerable or acceptable region. The safety risk analysis of the icing in flight contains five occurrences classified in the Intolerable region. All the occurrences in the Intolerable region require immediate mitigation action. In case of the occurrences described, the mitigation actions have been already taken as the reaction on the safety investigation. However, there are still existing some issues where the safety level can be improved. I try to describe these opportunities in the next paragraph. The safety risk of the occurrences from the Tolerable region is acceptable but a strategy to prevent the risk may be developed. We always need to mitigate the risk until it reaches the acceptable region.

B. Severe icing conditions

The most complicated issue is to recognize the state when icing starts to critically influence the flight safety. In case of probable severe icing conditions, pilots used to turn off the autopilot and they control the aircraft manually to discover any abnormal flight characteristics caused by icing as soon as possible. If the de-icing equipment of the aircraft can´t eliminate icing accretion, emergency procedures must be applied. Emergency procedures depend on the type of aircraft and are always specified in the flying manual.

C. Training improvements

High frequency of accidents caused by icing caused that the FAA expand the regulation in this area. The first step was an amendment of training procedures to better prepare pilots for flight in icing conditions. New training rules focus on four main issues: general icing and meteorological information, ground de-icing, type-specific operations, company operations and procedures.

D. Modification of operational requirements

The FAA updated the Part 121 requirements for operations in icing conditions. New rules state that after October 21, 2013 "no person may operate an airplane with a certificated maximum take-off weight less than 60,000 pounds in conditions conducive to airframe icing unless it complies with requirements defined in Part 121.

E. Update of aircraft certification requirements

In November 2014, new icing certifications standards were published in the FAR Part 25 (transport category aircraft) and they are effective from January 2015 for all new-designed planes (no retroactive application) with Maximum Take-off weight under 60 000 pounds equipped with reversible flight controls. Certification standards in the Part 25 were completed by the requirements for flight in freezing drizzle and freezing rain conditions.

8. Conclusion

In the field of icing identification, the meteorologists and the other specialists on the icing have still a lot of work. The most complicated issue is to forecast the freezing drizzle or the freezing rain. Thanks to the supercomputers, the numerical weather models can work with much denser grid of data inputs than before. It means that the probability of the forecast accuracy is increased and icing conditions can be discovered more easily. Precise information about icing will improve the quality of the flight planning and it will increase the flight safety level. The prevention of the safety occurrences in aviation is an ultimate goal of all this effort.

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