Icing Certification of Civil Aircraft Engines

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Abstract

Aeroengine icing is an unwanted phenomenon which can normally lead to the hazardous effect to the power of aircraft during routine flight. To be on the safe side, each civil aircraft engine model must fully meet the strict requirements of icing operation and ice ingestion in the authoritative certification program, and usually this could be demonstrated by using the experimental approach. Base on a concrete engine model, this paper aims to provide an acceptable method of compliance to the engine icing operation and ice ingestion requirements which are demanded by the US airworthiness standards of aircraft engines, i.e., Federal Aviation Administration 14 CFR Part 33, and introduce the application of critical point analysis and experimental arrangement in engine icing certification. Through the textual description, it would be greatly helpful to the industrial community to evaluate the engine anti-icing capability and conduct the ice-slab ingestion demonstration in engine design process.

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1. Introduction

1.1. Certification requirements for engine icing

Icing is one of the most serious hazards for the aircraft engines. Usually, engine icing comes from the freezing of cloud droplets, or supercooled water droplets which remain in liquid state even at temperatures far below freezing, when they are stuck by the aeroengine during the flight. It can lead to engine operating anomalies such as non-recoverable or repeating surge, stall rollback or flameout when ice accretes on fan or inlet rotating stages, and may also cause the gas path ice blockage in core engine. There are normally two kinds of ice formations that are resulting from the impact of supercooled droplets on the propulsion

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system surfaces, i.e., glaze ice and rime ice [1]. The former is a clean, hard ice, and typically has a non-aerodynamic shape and is more susceptible to aerodynamic forces that result in shedding. The latter is a milky, white ice and typically has greater adhesion properties and lower density than glaze ice. Cloud droplets may freeze instantaneously and form rime ice on unprotected surfaces or run downstream and freeze later forming glaze ice structure. In addition to above, high-altitude ice crystal phenomenon in convective weather are gradually recognized as another icing source to jeopardize the safety operation of aeroengines in recent years. Due to the bounce off, ice crystals do not adhere to the cold airframe surfaces but can partially melt and stick to the relatively warm engine surfaces which may also bring about the engine damage and sustained power or thrust loss [2]. Although it’s quite hard to reveal the inherent formation mechanism of ice crystal until now, more studies have been continuously carried out to unveil the challenging subject.

The current airworthiness standards of aircraft engines in FAR Part 33 have concrete requirements to icing certification. Section 33.68 requests the operational safety for induction system icing, and section 33.77 claims the ice-slab ingestion test in final demonstration. It is very possible to predict that the ice crystal certification requirement will be supplemented into the FAA engine airworthiness regulations in the future.

1.2. Previous work on icing

In the early years of 1960s, few research reports could be found due to the insufficient apprehension of icing accretion process [3, 4]. Beginning in the late 1970s, a few studies began to appear on icing tunnel and flight tests for aircraft, and the simulations focusing on engine icing accumulation were also conducted. Several researchers [5-7] have developed 2-D and 3-D models to predict the ice accretion on aircraft and engine components and to calculate the aerodynamic characteristics of critical surfaces. Macarthur et al. [8] proposed a mathematical model of glaze and rime ice accretion on a 2-D airfoil, and Bragg [9] derived a method to solve the droplet trajectories and impingement characteristics. Based on the original LEWICE code [10] sponsored by NASA, Cebeci et al. [11] and Potapczuk [12] incorporated the viscous and compressible effects to achieve an improved solution. Kwon and Sankar [13] developed a 3-D compressible Navier-Stokes code to study the ice accretion effects and aerodynamic characteristics of a typical wing, and the locally separated flow region was clearly predicted. A significant study involving detailed experimental survey of accreting ice surfaces has been conducted by Hansman [14]. This work described the behavior of liquid flow over the ice surface and the development of roughness on heat...
transfer. Recently, increasing efforts have still been conducted to the aircraft and engine icing protection issue [15-17].

1.3. Objective of this paper

Although a number of studies could be found concerning the icing formation and accretion phenomenon so far, most of them are conducted focusing on the critical surfaces of aircrafts rather than aeroengines. From the type certification’s point of view, this paper aims to present an acceptable means to meet the icing operational requirements of FAR Part 33, Section 33.68 and 33.77, and introduce an eligible icing test for a typical engine in the certification program. It will be directive for the industrial community to further understand the essential icing operational requirements of FAR 33, and prepare well for the final engine demonstration.

2. Methods of compliance to engine icing certification

The FAR Section 33.68 requires each engine with icing protection system could operate throughout its flight power envelope without the accretion of ice on engine components as defined in appendix C of FAR Part 25, and run steadily at ground idle setting for at least 30 minutes under a specific icing condition followed by acceleration to takeoff thrust. To meet the requirement of this section, engine icing test is the exclusive approach for non-derivative engine. During the icing test, the use of auto-recovery system is normally avoided due to its property of back-up devices. As a general rule, engines and induction systems should be shown to operate steadily and continuously in icing. This means that, the test results must exhibit the stabilized ice accretion and engine operation process. To facilitate the test demonstration, the applicant is desired to conduct the critical point analysis (CPA) for icing within the declared operating envelope of the engine. The CPA should include the possible combination of icing conditions and validated by the empirical test data. Some key parameters, such as engine N1, N2, flight speed, inlet air temperature and core pressure ratio, should also be analyzed and recorded. Due to the test facility and weather limitations, it’s sometimes expensive or even impractical for certain engine manufacturers to carry out the icing test. Until now, the FAA only recommended three icing resources for accomplishing the compliance test of section 33.68. These authorized resources include the Air Force’s AEDC and McKinley Climatic Lab in US, and the NRC research center in Canada. Furthermore, the CEPr engine test station is an additional eligible site to implement the icing test.

The FAR Section 33.77 requires each engine must sustain a specific ice-slab ingestion test when operating at its maxi mum cruise or thrust, and the ice quantity is the maximum accumulation on a typical inlet cowl under the condition of 2-minute delay in actuating the anti-icing system. Usually, the ice slab sizes, thickness, density and trajectories aimed at critical engine locations should be considered. This means that the ice accretion and shed characteristics must be fully comprehended in the previous engine icing test. For instance, the 0.25 to 0.5 inch-thick slabs based on the different engine configurations have been often adopted historically. Moreover, the impingement angle of ice slab can also have significant effect on the final test result.

The intent of rule 33.77 is to demonstrate tolerance to ice ingestion both from a delay in nacelle anti-icing activation and also serves to establish limits for ice released from other aircraft surfaces in the aircraft certification program. The ice-slab ingestion test may not cause a sustained power loss or require an engine shutdown, and the caused damage should not adversely affect engine operability and safe flight. Use of auto-recovery systems in this test is allowed since such ice ingestion is considered an abnormal event. If used, the auto-relight system becomes a part of the engine’s type design and incorporates into the dispatch list. The engine installation and operating instructions should provide information on the size and
density of ice slab, and any anomalous behavior during the ingestion test should be described. Execution of the ice slab ingestion test typically involves targeting the slab to the air stream ahead of the fan at the outer diameter of the inlet duct. This is intended to mimic the ice release from the inlet and results in impact on the outer diameter of the fan. The slab is either thrown in or slid into the engine inlet while operating at the critical engine speed, and typically the slab size ranges from about 4 inches by 12 inches for the small diameter engines to 12 inches by 18 inches for large engines. Table 1 illustrates the recommended minimum ice-slab size requirements based on the different engine inlet geometries. As for the engines equipped with other inlet areas, the size of ice slabs could be calculated through linear interpolation.

Table 1. Ice-slab size requirements to engines

| Inlet area (sq inch) | Thickness (inch) | Width (inch) | Length (inch) |
|----------------------|------------------|--------------|---------------|
| 0                    | 0.25             | 0            | 3.6           |
| 80                   | 0.25             | 6            | 3.6           |
| 300                  | 0.25             | 12           | 3.6           |
| 700                  | 0.25             | 12           | 4.8           |
| 2800                 | 0.35             | 12           | 8.5           |
| 5000                 | 0.43             | 12           | 11.0          |
| 7000                 | 0.50             | 12           | 12.7          |
| 7900                 | 0.50             | 12           | 13.4          |
| 9500                 | 0.50             | 12           | 14.6          |
| 11300                | 0.50             | 12           | 15.9          |
| 13300                | 0.50             | 12           | 17.1          |
| 16500                | 0.50             | 12           | 18.9          |
| 20000                | 0.50             | 12           | 20.0          |

3. Engine icing test demonstration

3.1. Engine model overview

Fig. 2. PX6 engine configuration
As shown in Fig.2, a typical two-spool turbofan engine named PX6 with a maximum takeoff thrust of 5600 pounds was chosen for the icing test demonstration. The engine fan assembly rotates counterclockwise while the high pressure (HP) and low pressure (LP) spools rotate clockwise when viewed aft looking forward. Each spool is mounted on two bearings, a ball bearing to react thrust and radial loads, and a roller bearing to support radial loads and to provide for differential axial thermal growth between the supporting structures and the rotating components. An annular splitter located behind the fan serves to separate the fan exhaust air into bypass and core flow to the LP compressor. Air flows from the LP compressor through the HP compressor and is discharged to the annular combustor. Combustion products flow through the HP and LP turbines and exit axially through the engine exhaust duct to provide thrust. The LP rotor spool consists of a four-stage LP axial compressor and a three-stage LP axial turbine, and the HP rotor spool consists of a single-stage HP centrifugal compressor and a single-stage axial turbine. Fuel pump, hydromechanical fuel control, and the lubrication and scavenge pumps are supported and driven by the engine accessory gearbox. The engine control system is made up of a digital electronic control with the existing hydromechanical back-up, fuel pump, surge bleed control and the required sensors.

3.2. CPA of PX6 engine

For this typical engine, components pertinent to icing are the spinner, fan blades, fan blade midspan dampers, bypass duct splitter, and the downstream vanes. Engine operating parameters pertinent to icing are the ambient temperature, ambient pressure, rotate speed, fan blade tangential velocity, and fan discharge temperature. For a given operating condition in the icing envelope, ambient temperature and pressure are constant, while the rotational speed, blade tangential velocity, and fan discharge temperature are variable. Usually, a high fan discharge temperature will result in less downstream ice accretion. The higher rotational speed and tangential velocity could lead to smaller amounts of ice accretion on the rotating surfaces, and smaller ice particles shed from these surfaces. As a result, the icing critical engine power setting is flight idle, when both fan speed and temperature rise across the fan are low. To achieve the satisfied anti-icing requirement, a special icing flight idle schedule with higher fan rotational speed and temperature rise was developed. This schedule is programmed in the Digital Electronic Engine Control (DEEC), and is activated simultaneously with the nacelle inlet anti-icing system upon the pilot command.

Fig. 3. Environmental icing envelope versus CPA
Actually, the potential icing conditions exist over a broad range of altitudes and ambient temperatures. To explore the engine icing envelope, seventeen critical points representing in-flight conditions and one ground idle icing point were studied as shown in Fig.3. At each in-flight icing point, flight Mach numbers of 0.3, 0.4 and 0.5 were analyzed. This speed range is chosen because air speed lower than Mach 0.3 is not a typical flight speed of any PX6 powered aircraft, and speed higher than Mach 0.5 would produce a high enough inlet ram temperature to prevent icing of any engine parts.

Under the special icing flight and ground idle modes, the fan section operating parameters in the CPA are tabulated in Table 2. It can be shown that the ambient conditions include the temperature, altitude and Mach number which cover the entire flight envelope, and the engine operating parameters contain the fan rotational speed (N1), blade hub tangential velocity (V_{hub}), and the fan discharge temperature (T_{fan}). For all the in-flight speeds and ambient conditions studied, the V_{hub} increases with the augmented Mach number, and which is helpful to restrain the spinner ice accretion and shedding characteristics. In addition, high values of T_{fan} imply the ice accretion on the components downstream of PX6 engine is less severe.

Table 2. Fan operating parameters in CPA
3.3. Icing test

Based on the previous analysis of critical operating points, five test points which represent the most rigorous conditions were chosen to conduct the icing test demonstration. Table 3 lists the concrete parameters in these operating conditions.

Table 3. Test points

| Point | A | B | C | D | E |
|-------|---|---|---|---|---|
| Reference point | 10 | 15 | 11 | 12 | 18 |
| Condition | HWC | HWC | HWC | HWC | GF |
| Altitude (Ft) | 15.4K | 8K | 20.4K | 22K | 0.9K |
| \(T_{\text{inlet}}\) (F) | 14 | 14 | -4 | -10 | 29 |
| \(T_{\text{RAM}}\) (F) | 29.2 | 29.2 | 10.6 | 4.4 | 30.0 |
| \(P_{\text{inlet}}\) (PSIA) | 8.16 | 10.9 | 6.64 | 6.21 | 14.2 |
| Mach number | 0.4 | 0.4 | 0.4 | 0.4 | 0.1 |
| Tunnel flow (PPS) | 222 | 296 | 185 | 173 | 210 |
| Engine flow (PPS) | 54.6 | 68.4 | 47.9 | 45.9 | 38.0 |
| Tunnel discharge velocity (FPS) | 427 | 427 | 419 | 416 | 110 |
| Engine inlet duct velocity (FPS) | 267 | 250 | 277 | 280 | 110 |
| Mean droplet diameter (\(\mu\)) | 20 | 20 | 20 | 20 | 40 |
| \(L_{\text{WC-MI}}\) (gram/m³) | 2.20 | 2.20 | 1.70 | 1.50 | --- |
| \(W_{\text{MI}}\) (PPH) | 48.4 | 44.1 | 39.7 | 36.2 | --- |
| \(L_{\text{WC-MC}}\) (gram/m³) | 0.44 | 0.44 | 0.22 | 0.19 | 0.60 |
| \(W_{\text{MC}}\) (PPH) | 9.72 | 8.87 | 5.14 | 4.46 | 3.73 |
| Exposure time –MC (min:sec) | 4.08 | 4.08 | 4.13 | 4.14 | 30 |
| Exposure time –MI (sec) | 37 | 37 | 38 | 38 | --- |
| Number of cycles | 3 | 3 | 3 | 3 | --- |
| Distance from spray nozzle to engine inlet (in.) | 144 | 144 | 144 | 144 | 209 |

Symbol Description

\(T_{\text{inlet}}\) Ambient temperature
\(T_{\text{RAM}}\) Ram temperature
\(P_{\text{inlet}}\) Ambient pressure
HWC High-water catch
\(L_{\text{WC-MI}}\) Liquid water content –maximum intermittent
\(W_{\text{MI}}\) Water catch –maximum intermittent
\(L_{\text{WC-MC}}\) Liquid water content –maximum continuous
\(W_{\text{MC}}\) Water catch –maximum continuous

The five simulated flight test points cover a wide range of flight operation and are the most severe points for the PX6 engine in the icing envelope. Except for these points, all other environmental conditions in the icing envelope are less severe. During the icing encounter, a gradual ice build up was observed on the spinner apex and its immediate downstream external surfaces. Cycles of the sporadic
non-uniform shedding took place. Small amounts of ice accretion formed on the leading edge and the midspan damper of the fan blade. The blade leading edge ice accretion tapered to zero as radius increased. No ice bridging was observed on the fan blade hub section. Some ice accretion was seen on both the bypass and core vane leading edges and the leading edge of the splitter. The icing on these components was visibly more significant as liquid water content increased. However, engine performance was not affected. The shed ice particles, primarily from the spinner apex, were seen to impact the downstream ice accretions and caused sporadic shedding from those surfaces. Upon the engine acceleration, much of the ice disappeared very rapidly. The disappearance was attributed to the higher centrifugal and aerodynamic loadings on the ice as well as the increased frequency of upstream ice particle impact. Furthermore, a higher fan discharge temperature led to melting of the ice downstream of the fan. After finishing the detailed teardown inspection, the dominant conclusions of this test were:

- The engine performed satisfactorily with no tendency to surge, flameout, or experience a significant power loss.
- The engine could accelerate satisfactorily following each icing exposure.
- There was no posttest degradation in engine performance, due to exposure to the icing conditions.
- The engine is suitable for operation in icing conditions with no restrictions.

### 4. Ice-slab ingestion test demonstration

The ice-slab ingestion test was completed with the formal DEEC software version 50.XX.16.04 installed. Flameout-Relight logic remained enabled for the testing but on igniter was disconnected at the exciter for the single channel dispatch ability. The remaining igniter was instrumented for spark detection. Prior to the formal test, all instrumentation used was calibrated in accordance with the previous approved Procedures Manual, Section 2, Metrology. During the test, data was recorded manually, digital acquisition, strip-chart recorders, and magnetic tape.

#### 4.1. Test preparation

![Image of ice slab release fixture](image)

Fig. 4. Test arrange of slab ingestion

As indicated in Fig.4, an ice slab release fixture was used to eject the ice slab into the PX6 engine. To prevent the ice from melting, the ice release fixture compartment was kept cold by packing it with dry ice and alcohol. A thermocouple was installed in the compartment cover and exhibited the compartment
temperature to be -40°F immediately prior to the ingestion test. Based on the inlet area of PX6 engine, an ice slab 29.1-inch long by 2.18-inch wide by 0.2-inch thick was selected to conduct the ingestion test. During the set-up procedure, the ice specimens were formed in the Teflon coated mold with a slightly oversize molding cavity of size 29.17×2.20×0.24 inch than the desired ice slab dimensions. The molding process was repeated until specimens could be consistently produced to the dimensions specified in the test procedures and instructions. The water solution used to make the ice specimen was predetermined and produced by the chemical laboratory. According to the test plan, the specific gravity of ice specimen made with this water was within the desired range of 0.8 to 0.9. Ice specimens were stored in a special low-temperature refrigerator, which was set to 0°F, after ice specimens were removed from ice molds. The ice tray (trap door) was also prechilled in the refrigerator.

![Pretest ice slab dimensional check](image)

**4.2. Formal test**

Prior to conducting the ice ingestion test, the PX6 engine performance calibration was completed. Several check runs were performed before the actual ingestion test to ensure the ice release fixture was functional and the integrity of ice slab was maintained until ingested into the engine.

With the engine installed in test stand Number 7X, the ice ingestion test was carried out. Firstly, the PX6 engine was started and stabilized at the idle setting for one minute. After that, the engine was accelerated to a maximum cruise power setting of 4650 pound thrust, at prevailing ambient conditions and stabilized for one minute. Various engine parameters, such as the inlet temperature and pressure, engine speeds (N1 and N2), turbine inlet temperature (T4.5), thrust (Ff), fuel flow rate (Wf), compressor exit pressure (Pcd), fuel pressure and engine vibration level were manually recorded. The ice slab release mechanism was activated and ice slab was introduced into the engine inlet. The engine continued to operate “hands-off” mode for five minutes following the ingestion, and there was no change in any monitored engine parameters. The same engine parameters, which were logged prior to the ice ingestion, were recorded again. At last, the engine was decelerated to idle setting and shut down. All the recorded data indicated that the engine operated satisfactorily during and after the ice slab ingestion test.

A comparative summary of the performance at maximum cruise thrust setting at 54°F, taken from the pre- and posttest strip-chart data and manually recorded data, and pre- and post performance calibration, is presented in Table 4.
Table 4. Pre and posttest ice ingestion performance summary

| Parameter | Performance based on strip-chart recordings | Performance based on performance calibration |
|-----------|--------------------------------------------|---------------------------------------------|
|           | Pretest | Posttest | Pretest | Posttest |
| Inlet temp F | 54      | 54      | 59      | 59      |
| Fn, lb   | 4800    | 4800    | 4982*   | 4965*   |
| T4.5, F  | 1608*   | 1608*   | 1618    | 1619    |
| N1, rpm  | 19000   | 19000   | 19100   | 19100   |
| N2, rpm  | 29750   | 29750   | 29510   | 29480   |

*Difference within measurement accuracy of ±0.6%*

4.3. Posttest activities

Posttest activities included inspection of the fan and inlet hardware, and the posttest performance calibration of PX6 engine.

Posttest inspection of the engine revealed that it was hard to find any ice slab impact damage on fan blades and vanes, and inlet hardware. However, careful review of the fan rotor showed that there were five blades with a marked leading edge corner (LE), which presented ice impact indications on the outer 1.25 inch LE of the blades. Similar careful review of the fan stator assembly also showed that there were four fan stator vanes which had ice impact indications in the outer 1 inch LE of the vane. Figure 6 exhibits approximately the top half of the fan vane assembly in the engine, with four vanes marked with silver pencil, which had the ice impact indication. The typical ice impact indication on one of the PX6 engine fan vanes is presented in Fig. 7. There were fan rotor LE tip hubs in the inlet housing from 290 degrees to 80 degrees, and from 160 degrees to 200 degrees (forward looking aft, counting clockwise from 0 degrees, at the 12 O’clock position). From 290 degrees to 80 degrees, the rubs were intermittent and had the maximum width of approximately 0.5 inch at the top as shown in Fig. 8. Figure 9 shows the fan rotor tip hub at the 2 O’clock position. Additionally, the rub was from approximately 160 degrees to 200 degrees and was widest (0.26 inch more or less) at bottom dead center, as displayed in Fig. 10.

![Fig. 6. Fan vanes condition after ice slab ingestion](image-url)
Fig. 7. Typical ice impact indications on fan vane

Fig. 8. Fan rotor tip rub at top during ice-slab ingestion test

Fig. 9. Fan rotor tip rub at 2 O’clock (forward looking aft)
5. Summary

Based on a typical turbofan engine, the icing test and ice-slab ingestion test are introduced as the acceptable methods to the US airworthiness standards of aircraft engines, FAR Part 33. Although there’s no official declaration, the icing and ice-slab ingestion tests incorporated the critical point analysis is actually deem as the exclusive approach to meet the requirements of Sec 33.68 and 33.77 in Part 33. The current work aims to provide a useful guideline to the industry community to open up the engine anti-icing capability, and also prepare the final certification demonstration.

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