The Research of Aircraft Fuel System Icing Test

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Abstract—When a civil aircraft is flying in high altitude and low temperature environment, once the fuel feed system freezes, the fuel pressure and flow of engine and APU will decrease, resulting in the loss of aircraft power and even the occurrence of flight accidents. In this paper, the icing test platform of aircraft fuel system is set up, the test configuration and measurement system design method are given. By carrying out icing test of a certain type of fuel system, the test results show the safety and rationality of the aircraft fuel system design and test rig design, so as to provide guidance and reference for the implementation of icing test of aircraft fuel system.

1. Introduction
As aircraft were operated at higher altitudes and in colder ambient temperatures, the cooler temperatures make the free water formed and produced ice, valves, pumps, filters and screens become clogged with resulting failure in the aircraft fuel system. In the past, incidents and accidents occurred in the operation of military and civil aircraft which were attributed to the formation of ice in the fuel supply system resulting in intermittent or complete starvation of fuel flow[1].

In order to ensure flight safety, FAR/CCAR25.951(c) requires that the aircraft should prove that the fuel system uses fuel containing supersaturated water and can operate continuously within the expected flight duration. During the flight time and air refueling time designed for the aircraft, it can continuously provide the engine and APU with fuel that meets the pressure and flow requirements[2][3]. SAE also published the icing test guidance documents SAE ARP1401[4] and SAE AIR790[5].

After the flight accident of the Boeing777 aircraft of British Airways Flight 38 on January 17, 2008 due to the icing of the fuel system, the civil aircraft developed in the future were carried out fuel system icing test in accordance with the FAR/CCAR2525.951(c) airworthiness requirements.

The industry has conducted relevant research on the standards and specifications related to aircraft fuel system icing test, and strive to determine the standard test methods and requirements in the industry[6]. In addition, the industry has also research on the method of component icing test and the fuel condition[7][8].

Through the above research, it is found that currently few aircraft fuel icing test documents on domestic and foreign. Based on the above technical research, this paper builds a test rig and establishes a standard test method for icing tests to prove that the designed fuel system is reasonable. It provides theoretical guidance for ensuring flight safety.
2. Test System

2.1. Test Equipment
The main test devices for the fuel system icing test are: conditioning tank, dump tank, circulating boost pump, heat exchanger/fluid chiller, coalescer/water separator filter, re-circulation pump, valve, flow regulating valve, etc. The installation is shown in Figure 1. In addition, there should be liquid nitrogen storage equipment to cool the fuel, liquid nitrogen injection and control devices, etc.

![Fig.1 Facility and Test Setup Schematic](image)

The main test instrumentation includes simulated engine and APU variable frequency pump, water content analyzers, data acquisition equipment, the test fuel tank level control equipment, water injection equipment, moisture titrator, AC power, DC power, etc. Its main testing sensors includes temperature sensors, pressure sensors and flow meters, etc.

2.2. Test Configuration and Measurement
The icing test shall include all engine feed systems with obvious differences in configuration, the scavenge system, suction feed system, transfer system, and APU feed system which connected to engine feed systems, as well as the corresponding part of the fuel supply tank. The fuel supply tank should at least contain the collector tank and partial fuel tank where the test components are installed, such as the fuel tank compartment where the ejector pump and transfer pump are installed.

The installation form, location, and the tube direction, diameter, material and wall thickness shall be consistent with the actual installation of the aircraft. The area at the bottom of the test tank must be consistent with the actual installation. The system components removed from the test tank and the components added by the modification must not affect the flow of fuel and water at the bottom of the tank.

In order to keep the fuel temperature in the test tank, the test tank and the outside tube surface of the tank should be heat-insulated (including the lower wall of the tank), and an empty isolation zone should be formed between the insulation material and the outer wall of the test tank. Liquid nitrogen
gas is sprayed into the isolation area, and the temperature of the isolation area is controlled through a closed loop using temperature sensor and control computer.

The pressure, temperature and fuel flow rate of the key positions components in the test system should be measured and recorded in real time.

The pressure measurement shall at least include the outlet pressure of the engine feed pump, APU feed pump, and the suction screen, besides, the inlet pressure of the simulated engine pump and simulated APU pump also necessary measured and recorded. The pressure sensor should be connected to the corresponding measuring pressure point through pilot tube, and its installation height level should be consistent with the height of the measured point.

![Fig.2 Test Configuration and Measurement Schematic](image.png)

The temperature test should include at least the temperature of the test fuel tank, the isolation zone between the fuel tank and the insulation material, the engine and APU feed tube outside the fuel tank, and the engine and APU simulated pump inlet temperature.

In addition, a flow meter and a flow regulating valve should be installed on the engine feed tube and APU feed tube downstream of the simulated pump to record, display and adjust the engine and APU feed flow.

3. Test Method

3.1. Test Duration and Flow Rate

The aircraft fuel system icing test includes three test temperatures, namely 28°F±2, 13°F±2 and the lowest temperature experienced in flight (or on the ground). The test duration of 28°F±2 and the lowest temperature experienced in flight each accounted for approximately 25% of the total test time, and the test duration of 13°F±2°F accounted for about 50% of the total test time \(^2\). When the fuel temperature is lower than 13°F, the ice/water in the fuel will become solid ice crystals. When the fuel temperature is between 28°F and 13°F, the water begins to turn into ice mud, but it has not completely solidified and is very “sticky”. This ice mud or crystals will adhere to any objects in contact with it, tend to become larger and offer a threat to plugging small openings such as screens, filter, and orifices, so 13°F is the critical temperature for the test. To make the test more rigorous, the test time of 13°F should be longer than 50% of the total test time, and the test fuel volume should also be higher than 50% of the total test fuel volume. The total test time should be equivalent to the longest flight time of the
aircraft, and the total fuel volume of the test should be equivalent to the fuel volume consumed by a single engine in the most flight profile.

Since the icing test assesses the impact of ice accumulation on the system and is a cumulative process, the average fuel consumption of each flight phase should be used, including: take-off, climb, cruise, descent, go-around, etc. In each test stage, the suction feed and APU feed could be also simulated.

3.2. Fuel Conditioning

The icing test should be carried out with the fuel that is commonly used by aircraft. In order to ensure that the test is more rigorous, the test should be carried out with a fuel type with high saturated water content. No matter what type of fuel is used for the test, the anti-icing additive content in the fuel must be measured before the test. During the test, the icing temperature that the anti-icing additive content in the fuel can inhibit should be higher than the first temperature of the icing test by 28°F±2, normally, the content should less than 3.8ppm. Before the test, if the anti-icing additive content in the test fuel is measured to be too high, appropriate water can be added into the fuel conditioning system, and the water in the fuel can be filtered and separated by coalescer/water separator filter after full circulation.

Since the solubility of anti-icing additives and water is better than that of fuel, the anti-icing additives can be separated from the test fuel by filtering water from the fuel.

At 85°F±5°F, the saturated content of water in the fuel is 90ppm (0.3406cc/gal), in order to a more severe icing test state is simulated. Additional 0.75cc water should be added to each gallon of fuel on the basis of saturated water. Therefore, the total water content in the test fuel cannot be less than 288ppm (1.090cc/gal).

The following procedure is recommended for the preparation of the fuel:

1. Place the fuel in the conditioning tank, isolate the coalescer filter and begin circulation from the conditioning tank through the heat exchanger and back into the conditioning tank until the fuel is heated to 85°F±5°F (29°C±3°C).

2. 3.8cc of water per 1gallons of fuel should be added into conditioning tank at a recommended rate of approximately 55cc per minute on the Circulation. After all the water has been added into the fuel, continue circulation for approximately 60 minutes.

3. Following 60 minutes of mixing, the fuel shall be directed through the coalescer/water separator filter (while maintaining the fuel at 85°F±5°F) for a period of 60 minutes minimum or until no more water can be drained from the filter.

4. At this time the filter shall be isolated and three 100 cc fluid samples obtained from the fluid sampling valve while still circulating. Samples shall be contained in 100 cc plastic sample bottles (Caution: do not use glass sample bottles). The sample bottles shall be flushed, filled then drained two times prior to obtaining the final sample for analysis.

5. The samples shall be analysed using Modified Karl Fischer Method. If less than 90 ppm additional water shall be added at 0.00378 cc per gallon per ppm required for 90 ppm total.

6. Once the saturation level has been confirmed, circulation of fuel in the conditioning tank shall be continued and an additional 0.75cc of water per gallon (equals an additional 198 ppm above saturation) shall be metered into the pump inlet at a rate of approximately 50 cc/min.

7. After the required amount of additional water had been added, and while circulating, three fuel samples shall be obtained and analyzed for water content.

The three-sample average should be 288 ppm minimum. The specific average water content is not specified and testing will be commenced provided at least one sample is over 288 ppm.

3.3. Test Procedure

After the fuel conditioning to meet the requirements, the fuel should be circulated and chilled to the required test temperature as soon as possible, but not more than 60°F/h. To prevent water in the fuel from freezing on the walls of the heat exchanger, the difference in temperature between the fuel in the heat exchanger and the refrigerant should not be allowed to exceed 24 °F (13 °C).
The following is the test procedure for each temperature.
(1) The fuel in the conditioning tank shall be chilled to the test temperature (28°F, 13°F, -40°F), and then the test tank shall be filled with enough fuel.
(2) Turn on the AC pump and DC pump.
(3) Turn on the engine simulated pump and APU simulated pump, and adjust the flow rate to the required.
(4) Turn off the AC pump and DC pump.
(5) Adjust the engine simulated pump and APU simulated pump to make the engine feed and APU feed flow rate reach the required data to simulate the suction feed.
(6) Close engine simulated pump and APU simulated pump.

4. Test Result and Analysis
In addition to the suction feed, during the icing test, the fuel pressure at the inlet of the engine and APU in each test state cannot be lower than the minimum pressure required for the normal operation of the engine and APU.

![Figure 3 13°F AC pump outlet and simulated pump inlet pressure](image)

Figure 3 shows the pressure at the outlet of the AC pump and the inlet of the engine during the 13°F test. Turn on the AC pump before 8000 seconds to simulate the engine feed. It can be seen that the AC pump outlet pressure PAC and the engine inlet pressure PENG are greater than 25psi, which is greater than the requirement of the common engine inlet pressure TVP+5psi. The pressures of the three test phases during the test can meet the inlet pressure requirements of the engine and APU, which proves that the fuel system can normally supply fuel to the engine and APU during the entire flight phase, and meets the requirements of FAR/CCAR2525.951(c).

After the test, quickly open the test tank to observe the icing of key components such as AC pump, DC pump and suction screen. And also, quickly disassemble a section of feed tube to observe the icing on the inner wall. Figure 4 shows the icing at the inlet of the AC pump after the test. Through the test device, test system and test method in this article, it is proved that the fuel system of a certain type of aircraft can meet the inlet flow and pressure requirements of the engine and APU under the icing conditions within the entire flight envelope, and prove that the aircraft fuel system can be Ensure the normal and safe flight of the aircraft.
5. Conclusion

Based on the results and discussions presented above, the conclusions are obtained as below:

(1) It is shown that the recommend aircraft fuel system icing test rig, equipment and test method could verify that the fuel system under supersaturated water condition could provide the engine and APU expected the pressure and flow within the expected flight duration.

(2) The recommend test configuration and measurement criteria can well meet the requirements of the Airworthiness Administration.

(3) It is concluded the Tests have shown that the fuel pressure and flow at the inlet of the engine and APU of a certain type of aircraft in each test state can meet the requirements of the engine and APU for normal operation.

Acknowledgments

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