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Investigation of Fire Protection Certification for Aircraft Engine Components

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Abstract: Fire protection performance is one of the most important capabilities for aircraft engine, since the result may be hazardous in the case of a fire condition. According to fire protection regulation CCAR 33.17 of China Civil Aviation Regulations, fire-proof tests of a specific pipeline, a fuel tank and a fuel filter assembly were carried out. Test conditions include inlet fluid temperature, fluid pressure, fluid volume flow, fire temperature and heat flux density. The average flame temperature during the fire tests is 2000 degrees Fahrenheit, the heat flux density is $116kW/m^2 \pm 10kW/m^2$ and the distance from burner exhaust to the test area is 100mm in these fire tests. Fire test of pipe passed, but the fire test of oil tank failed because of the failure of the oil circulation system and the melting of plastic pipe material in the ventilation pipe separately. The first fire test of the fuel filter failed because of design defect of one oil drainage path, but after design change of the oil drainage path, the second one succeeded. Based on the fire protection tests and results analysis, three essential factors of fire protection performance and type certification were presented: 1. Volume of medium retained in test parts; 2. Mass flow of medium; 3. Pressure in the test parts cavity.

Keywords: Aircraft Engine, Fire Protection, Airworthiness

1. Introduction

Fire protection performance is a critical requirement for civil aircraft engines, an it is one of the most essential factors for basic safety requirements and airworthiness regulation compliance [1]. There were many flight accidents in the aircraft transport service history because of engine fire events, which caused hazardous effect on social safety and huge economical loss. As a result of that, engine fire protection performance is of great importance for aircraft safety.

According to the investigation of engine fire protection regulation CCAR 33.17, which is of China Civil Aviation Regulations Part 33 *Airworthiness Standards: Aircraft Engines*, the design and construction of the engine and the materials used must comply with the fire protection requirements, such as the pipe and tank which contains flammable fluids.

The fire protection design of pipe and firewall is mature and full of experience. However, the fire protection design of oil tank and fuel filter assembly is relevant difficult, since the structure of these components is complicated and there are many accessories integrated in them, such as fuel pump, sensor and fuel metering units etc. The internal fluid routes are also complex with high fluid temperature, pressure and mass flow. The failure causes may be complicated and the result of a fire event may be severe.

In the last few years, much research were carried out in aircraft and engine fire protection field [2-9], but the research about engine components fire protection performance is not enough. The experience of showing compliance to fire protection regulation is also not sufficient.

In this paper, fire-proof tests will be carried out on pipe joints and box parts of an aero-engine. Combining with test data analysis, fire-proof performance of aero-engine parts will be studied. On this basis, the airworthiness certification elements of engine fire protection are explored.

2. Fire Protection Regulation

CCAR 33.17 requires that the design and construction of the engine and the materials used must minimize the probability of the occurrence and spread of fire during normal operation and failure conditions, and must minimize the effect of such a fire. In addition, the design and construction of turbine engines must minimize the probability of the occurrence of an internal fire that could result in structural failure or other hazardous effects. A tank, which contains flammable fluids and any associated shut-off means and supports, which are part of and attached to the engine, must be fireproof either by construction or by protection unless damage by fire will not cause leakage or spillage of a hazardous quantity of flammable fluid.

Simply speaking, the primary objectives of CCAR 33.17 are to contain, isolate and withstand a fire; to prevent any source of flammable material from feeding an existing fire; to perform those engine functions intended to be performed in the case of fire, and not to result in a hazardous condition [10, 11].

The definitions of fireproof and fire resistant are as follows:

1. Fireproof: The capability of a part or component to withstand, as well as or better than steel, a 2000 °F average flame temperature (± 150 °F individual thermocouple tolerance) for a minimum of 15 minutes, while still performing those functions intended to be performed when exposed to a fire.
2. Fire Resistant: The capability of a part or component to perform those functions intended to be performed while exposed to the heat and other conditions that are likely to occur at the particular location, and to withstand a 2000 °F average flame temperature (±150 °F individual thermocouple tolerance) for a minimum of 5 minutes.

The 5 minutes fire resistant means a reasonable time period for the flight crew to recognize a fire condition, close the appropriate fuel shutoff valve (s), and shut down the appropriate engine, thereby cutting off the fuel source. The 15 minutes fireproof includes 5 minutes reaction time and 10 minutes fire fighting time. In the later 10 minutes, although the engine is shut down, the oil may still circulate because of the continued rotation. It is not difficult to understand why fuel-related components require five minutes of fire resistance, while lubricant-related components require 15 minutes of fireproof.

3. Fire Protection Test

Taking pipe, oil tank and fuel filter assembly fire tests as examples, this paper researches the fire protection performance of engine parts, and discusses certification elements of aero-engine parts fire test.

3.1. Fire Test of Pipe

The structure of engine pipe is relatively simple. Stainless steel is generally used in actual design and use of engine pipe. For stainless steel sheet with thickness over 0.381 mm, it can be assumed that it has fireproof capability by default and does not need fireproof test [12]. The wall thickness of fuel and lubricating oil pipelines of aero-engine is generally larger than this scale. Therefore, when conducting fire prevention test for such pipeline parts, the joint is usually chosen as the critical test area.

The test piece chosen in this paper is a fuel booster tube from one type aero-engine. The material of pipe and joints is stainless steel. The structure of test piece is shown in figure 1. The structures of joint A and B are shown in figure 2. And the interface is sealed by O-type rubber sealing ring, in which the A-end joint is sealed by conical embedded seal and the B-end joint is sealed by surface seal.

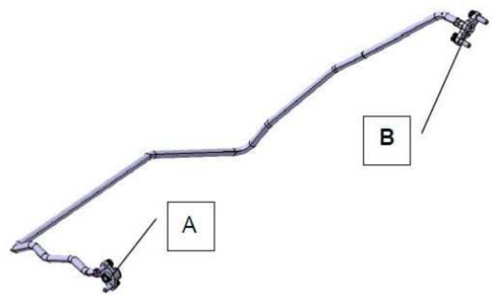
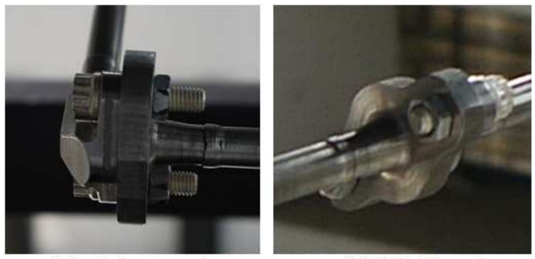


Figure 1. *Structure of fuel booster tube.*



(a) Joint A-end (b) Joint B-end

Figure 2. *Structure of tow joints.*

The conditions of 5 minutes fire resistant test for two joints separately are as follows:

1) Inlet fluid temperature: 135°C ~137°C;
2) Fluid pressure (gauge pressure): 5500kPa~5600kPa;
3) Fluid volume flow: 30L/h~31L/h;
4) Burner standard: ISO2685;
5) Heat flux density: $116kW/m^2 \pm 10kW/m^2$
6) Distance from burner exhaust to the test area is 100mm.

After the flame temperature, heat flux and flow parameters in the pipeline were stabilized, the fire resistance test was started

During the test, there was no fuel leakage and no damage at both ends of the pipeline, and there was no residual flame after the test.

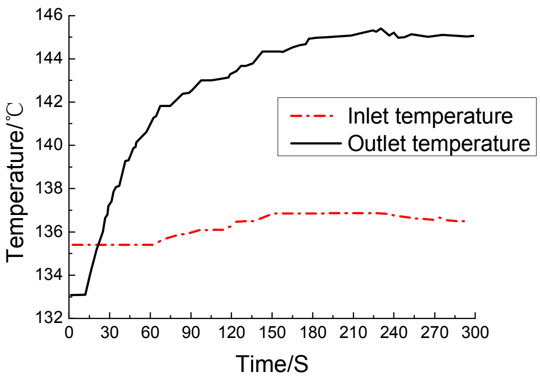
After the test, the decomposition inspection of A and B end joints are shown in Figure 3 and Figure 4, respectively.

Figure 3 shows that the A-end joint is free of deformation, the sealing structure is complete, and the O-ring is not carbonized or damaged;

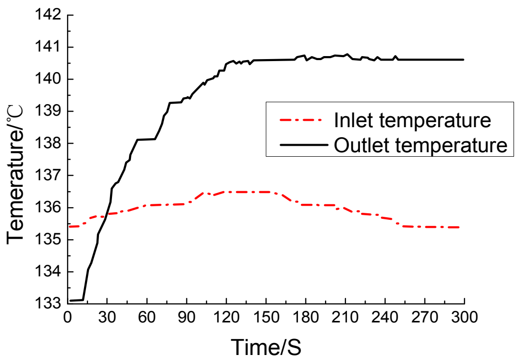
Figure 4 shows that the B-end joint is free of deformation, the sealing structure is complete, but the O-ring is carbonized and damaged;

Figure 3. *Structure of A-end after test.*

Figure 4. *Structure of B-end after test.*



(a) Fire resistant test of A-joint



(b) Fire resistant test of B-joint

Figure 5. *Change of inlet and outlet temperature.*

The temperature changes at the inlet and outlet of the pipeline test pieces are shown in Figure 5. Figure 5 (a) shows that the inlet temperature of the pipeline has been maintained between 135°C and 137°C during the 5-minute fire-resistant test on the A-joint, and the outlet temperature has risen from 133°C to 145.5°C and tends to be stable. During the test, the temperature difference between the inlet and outlet of the pipeline reaches 9.5°C.

Figure 5 (b) shows that the inlet temperature of the pipeline has been maintained between 135°C and 137°C during the 5-minute fire-resistant test on the B-joint, and the outlet temperature has risen from 133°C to 140.5°C and tends to be stable. During the test, the temperature difference between the inlet and outlet of the pipeline reaches 5.0°C.

3.2. Fire Test of Oil Tank

The oil tank in this test is a component of one aero-engine; the structure is shown in Figure 6.

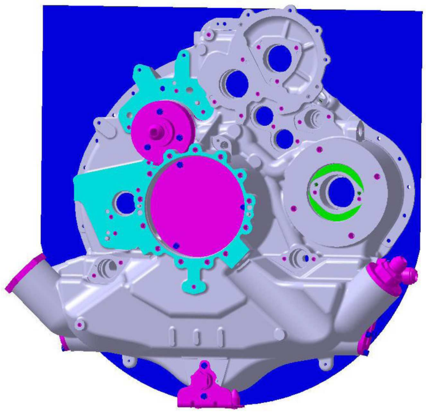


Figure 6. *Structure of oil tank.*

The main structural material of the test box body is aluminum alloy. Other components include wire threaded sleeve, locating pin, oil return pipe, bolt, O-ring and oil drain valve.

Test condition of 15 minutes fire-proof test is as follows:

1) The first 5 minutes: fluid volume flow is 225L/h～232L/h. Gauge pressure in tank is 181kPa～201kPa. Fluid temperature is 157°C～159°C. At least 2.9L oil maintained in the tank.
2) The later 10 minutes: simulate engine shut down condition and the oil is not circulating, the pressure in the tank equals to atmosphere pressure.

The schematic diagram of the first fire test is shown in Figure 7. The oil enters the oil tank from the left intake port and pumps from the right suction port. It is planned that the oil volume in the tank will be maintained at 2.9L by coordinated control of the import pump and the outlet pump.

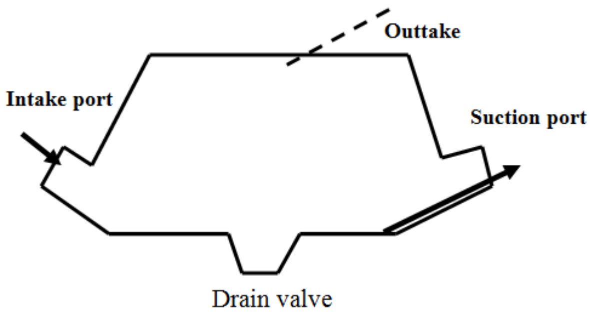


Figure 7. *Schematic diagram of oil tank.*

The first test failed with tank breakage. Analysis indicates that the oil in the tank is much less than 2.9L during the test. The root cause is the failure of the oil circulation system. The mass flow of suction port is larger than the intake port.

In the second test, the suction method is improved. The fulid level is rised to the 2.9L location and maintains to exact 2.9L oil in the tank during the test.

However, the second test also failed. At the 14th minute and 55 seconds, the flame mass in the lower right part of the tank becomes larger. At the end of the 15th minute, the flame is removed. After removing the flame, there is residual flame in the lower right part of the tank. After 1 minute and 14 seconds, the residual flame extinguishes.

The inlet fluid mass flow, temperature and pressure are shown in Figure 8, Figure 9 and Figure 10.

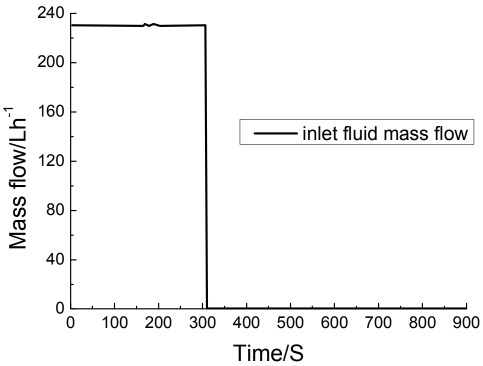


Figure 8. *Fluid mass flow.*

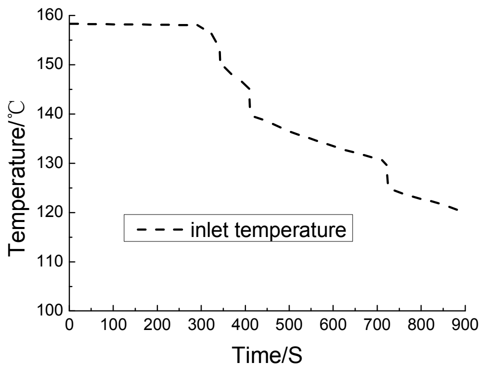


Figure 9. *Inlet fluid temperature.*

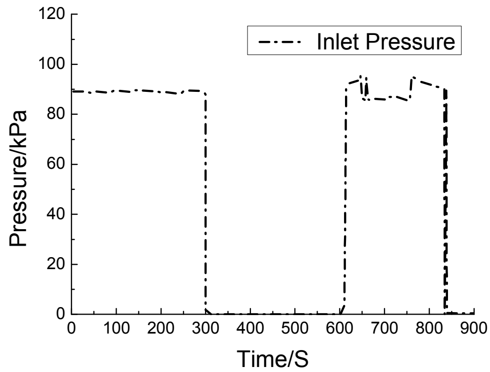


Figure 10. *Inlet fluid pressure (gauge pressure).*

Figure 8 shows that the flow rate of fluid keeps 227 L/h in the first 5 minutes, and no flow of fluid in the last 10 minutes. The flow condition meets the test requirements.

Figure 9 shows that the inlet fluid temperature is kept at 158°C for the first 5 minutes, and the flow stops after 5 minutes. The fluid naturally decreases with the cooling of air, and the inlet oil temperature meets the test requirements.

Figure 10 shows that the gauge pressure of the oil tank is 89.4kPa in the first five minutes, which meets the set pressure range. Then the outtake pipe is opened and the gauge pressure is 0 kPa. During the period from 600 seconds to 840 seconds, there is a sustained and fluctuating increase of about 92kPa. During the period from 840 seconds to 900 seconds, the gauge pressure returns to 0 kPa.

Figure 11 shows that after decomposition inspection, a crack of about 70 mm appears in the lower right side of the tank. The widest crack is about 5 mm.

Figure 11. *Inspection after test.*

Except above, there is no leakage of liquid oil or steam in other parts. The valve at the bottom of the tank is in good condition, and the remaining oil in the tank is 220 ml. The O-ring on the drain valve, oil level indicator and oil return pipe have been carbonized, but there is no oil leakage in each position, and the clearance meets the design requirements.

After cutting off the ventilation pipe, it was found that there was a melting defect in the inner plastic structure of the pipeline. It is due to the melting of plastic pipe material in the ventilation pipe, the blockage of the ventilation tank, and the continuous and oscillating pressurization in the tank, which results in the intermittent ejection of liquid lubricant and oil vapor from the tank through the ventilation pipe in the test, thus greatly reduces the lubricant in the chamber of the test piece. The position uncovered by the fluid cannot withstand the high flame temperature and the rupture occurs.

3.3. Fire Test of Fuel Filter Assembly

A 15 minutes fire-proof test of fuel filter assembly was carried out.

The first test failed and a residual flame appeared after the test. The reason is that one of the oil drainage paths is blind pipe design, causing oil accumulation in the fire test process, and it has not been involved in the flow and heat transfer, which leads to the increase of oil temperature and seal failure at high flame temperature.

Later, aiming at this problem, the unreasonable redundant drainage circuit in the test sample is deleted, as shown in the red oil circuit in Figure 13. The second fire test was successful.

Figure 12. *Fire test of a fuel filter assembly.*

Figure 13. *Design change of blind pipe.*

4. Fire Protection Performance and Certification Elements

4.1. Fire Protection Performance

Through the fire test of the above pipeline and oil tank, the fire protection performance of engine parts is studied. The following key factors are summarized: 1. Volume of medium retained in test parts; 2. Mass flow of medium; 3. Pressure in the test parts cavity.

In the fire test, the working substance retained in the components can effectively absorb the heat transferred from the flame to the test piece, and take away the heat through the flow of the working substance to protect the test piece. The first test of the tank fire test failed because of the lack of retained oil. Ten minutes after the fire test, the liquid does not circulate, and heat is only taken away by the gasification and volatilization of the remaining liquid. This puts forward a requirement for the design of parts: no dead chamber is allowed to exist in order to avoid liquid vaporization and pressurization in the case of flame attachment and explosion danger.

In fire test, the flow of working substance in the test piece can absorb and take away heat. The fire protection performance will be better with larger flow of working substance. And the blind pipe design should be forbidden.

Another key factor in the fire test is the chamber pressure of the components. Firstly, the pressure inside the chamber affects the pressure-bearing performance of the parts. Excessive pressure will destroy the sealing of the parts and cause leakage or even rupture, which will lead to the failure of fire prevention of the parts. On the other hand, if there is non-design pressurization inside the parts, it will lead to the damage of the fire protection performance of the parts, which is due to the abnormal discharge of working substances in the cavity and the damage to the parts themselves.

For the fire test of parts, the sealing form at the interface has an important influence on the fire performance of parts, and it is also an important factor.

4.2. Fire Protection Certification Elements

The pass criteria of fire protection test includes as follows:

1) Maintain the ability to perform those functions intended to be provided in the case of fire.
2) No leakage of hazardous quantities of flammable fluids, vapor or other materials.
3) No support of an existing fire event by the constituent material of the test article or by flammable fluid or material leaking from the test article.
4) No residual fire.
5) No failure of a firewall.
6) No other hazardous conditions.

It is very important to maintain the ability to perform the function intended to be provided. For example, the Engine fuel control components must not cause a hazardous condition while continuing to operate, but must allow or may cause a safe shutdown of the engine at any time within the required exposure time period.

The definition of hazardous quantities is directly related to the hazardous condition [13]. Therefore, it is not forbidden to leak in any form or amount in fire test. As long as the leakage does not reach the dangerous amount, it is still considered that fire protection requirements are met.

When the residual fire is concerned, a rapid self-extinguishing flame and no re-ignition after test flame removal is generally acceptable. The acceptability of such a test result will be determined on a case by case basis, and the type and function of the component under test will also be considered.

5. Conclusion

In this paper, the fire-proof tests of a certain type of engine pipe, an oil tank and a fuel filter assembly were carried out. The fire-proof performance of engine parts was studied through test analysis, and three key factors affecting the fire-proof performance were summarized, which were volume of medium retained in test parts, mass flow and pressure in the test parts cavity. The sealing form of component interface also has an important influence on fire protection performance, which needs further study.

This paper also discussed the fire performance of engine parts and the elements of fire test certification, which can be used as a reference for the type certification criteria of fire protection regulation.

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