Research on High-Temperature Cooling Flight Test Technology of a Certain Type of Civil Aircraft Generator

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Abstract. The high-temperature special flight test is one of the important special meteorological flight tests for civil aircraft airworthiness certification flight test, and generator high-temperature cooling flight test is also very important as the key flight test subject of high-temperature special flight test. The purpose of this paper is to summarize and study the airworthiness background, technical research, technical preparation, technical implementation, and data analysis results of a certain type of civil aircraft generator high-temperature cooling flight test, to provide guidance and help for subsequent civil aircraft generator high-temperature cooling flight test.

1. Introduction
At present, the engine cooling system and the generator cooling system of large trunk civil aircraft operate independently. Different from the previous regional civil aircraft, its engine cooling, and generator cooling are the same system. Therefore, this paper is the first domestic flight test airworthiness verification of generator cooling system technology research and test flight implementation summary.

2. Generator high temperature - cooling seaworthiness background
The power supply system of civil aircraft needs to verify the function of the power supply system in high temperature environment by a high-temperature and cooling test flight of the generator, and the cooling performance of the generator meets the requirements of CCAR25.1401 and CCAR25.13639(b). CCAR25.1401 requirements under the condition of the land, water, and air to run and parking in engine or auxiliary power unit or both normal after the power unit and auxiliary power unit cooling facilities, must be able to make the liquid used in the power plant parts, engine and the auxiliary power unit and the liquid temperature, keep on these parts and within limits set by the liquid temperature. CCAR25.13639(b) requires that flight tests be performed for each flight condition that cannot be properly simulated in the laboratory or through aircraft ground tests [1].

3. Generator high-temperature cooling technology research
Two frequency-conversion three-phase alternators with a continuous capacity of 120kVA are used as the main power supply for a civil aircraft. The generator is driven by the engine. The generator is mainly composed of a permanent magnet generator, excitation generator and generating parts, etc. They are installed on the same rotating shaft and driven by the engine accessory gearbox. The generator lubricating oil cooling system consists of the generator’s internal lubrication and cooling structure, the external lubricating oil pipeline, and two lubricating oil-air coolers. The lubricating oil pipeline, joints and air coolers are made of fireproof stainless steel. As shown in Figure 1, after cooling and lubricating the structure inside the generator, the lubricating oil flows out of the outlet of the generator, flows into the air cooler through the lubricating oil pipeline, cools the lubricating oil under the action of the air contained outside the fan, and then the lubricating oil returns to the generator through the lubricating oil return pipeline to complete a working cycle.

![Fig. 1 Working principle of generator oil cooling system](image)

According to the Supplementary Clause CCAR25.1043(a) of CCAR25.1041, generator cooling test flight must be conducted under critical operating conditions on the ground and in the air. Considering the working principle of the generator lubricating oil system comprehensively, the main influencing factors on the cooling performance of the generator are external ambient temperature, generator power, generator lubricating oil quantity, generator speed, and engine nacelle ambient temperature [2]. The following is a detailed analysis of the above factors.

### 3.1. External ambient temperature
After the generator oil enters the air cooler, it is cooled by the air bypass outside the engine fan cover. The ambient temperature has a great influence on the cooling performance of the generator. According to CCAR25.1043(b), the maximum ambient temperature corresponding to sea level conditions must be at least 37.8 °C, i.e., ISA+22.8 °C. Therefore, the ambient temperature of the test airport shall meet the requirements of ISA+22.8°C, and the influence of the ambient temperature at different flight altitudes on the cooling of the generator shall be fully considered during the test.

### 3.2. Generator power
The generator is designed with a voltage regulator to keep the output voltage stable, so the greater the load of the generator, the higher the output current. The increase of current increases the temperature of the generator stator winding, thus increasing the heat dissipation of the generator [3]. Therefore, it is necessary to make the generator work at full load as far as possible in the test process.
3.3. Generator oil quantity
The oil can take away the heat generated by the mechanical friction inside the generator and the hot parts. Therefore, the amount of lubricating oil will have a great impact on the cooling performance of the generator. Therefore, before the start of the test, the lubricating oil quantity should be set at the critical position under the test safety conditions.

3.4. Generator speed
The higher the speed of the generator, the faster the flow rate of generator oil, which can effectively improve the cooling efficiency of oil. However, the increase of the generator speed will also lead to the increase of the internal magnetic field of the generator and the increase of the armature iron loss. At the same time, the increase of speed will also directly increase the heat generated by mechanical friction and improve the heat output of the generator. As the generator is driven by the engine accessory gearbox, the speed of the generator is positively related to the thrust of the engine. Therefore, it is necessary to consider the influence of maximum continuous thrust and slow engine thrust state on generator cooling during the test.

3.5. Engine nacelle temperature
Because the generator is installed in the engine nacelle, the thermal performance of the generator is closely related to the temperature of the engine nacelle. There are many factors affecting engine nacelle temperature. It mainly includes external environment temperature, engine thrust status, nacelle anti-icing/wing anti-icing/air intake working status of air conditioning package, aircraft speed, etc. Therefore, the influence of the above factors on generator cooling should be considered comprehensively in the test process.

4. Generator high-temperature cooling technology preparation
CCAR requirements related to high temperature cooling test flight of integrated generators, flight test guidelines for certified transport aircraft, and major factors affecting cooling performance of generators. The high-temperature and cooling flight profile design of the generator is shown in Figure 2, and the configuration setting of the air intake is shown in Table 1:

![Fig. 2 High-temperature-cooling flight profile for generators](image-url)
The idea of designing the cooling high-temperature flight profile and the intake air configuration of the generator is to consider the adverse factors on the cooling performance of the generator as far as possible to investigate its cooling capacity. The generator was kept full load throughout the test, and the special test equipment for the power supply was turned on throughout the test, and the exhaust gas configuration was turned on during the test as required. When the ambient temperature is greater than ISA+22.8°C and the relevant cooling parameters (oil temperature, generator component temperature) are stable, the aircraft takes off. The take-off configuration of the aircraft is the state of the front center of gravity and the maximum take-off weight. Test generator corresponding TO engine TO/GA thrust, another slow engine. After climbing for 10 minutes at V2, the aircraft changed to the maximum continuous thrust climbing of the test engine and climbed to the single engine climbing limit. After the cooling temperature stabilizes, the maximum continuous thrust of the two engines is climbed to the double engine lift limit. After the cooling parameters are stable, descend to the waiting level at maximum service speed. After the cooling-related parameters are stable, the simulated go-around operation is performed, the aircraft lands normally, and the data are recorded for 60min after the shutdown or 30min after the peak temperature parameter of the radiator inlet is monitored, and the test ends [4].

To complete the above test flight procedures, the following technical difficulties need to be tackled.

4.1. Analog electrical load technology
The generator load needs to be connected to the external analog electrical load box so that the generator can reach the full load state. Considering that the whole section of the generator cooling test flight needs to make the generator fully loaded, the test time is about 5 hours long and the loading power is large. Therefore, the cooling capacity and integrity of the simulated electrical load system are highly required.

For the cooling of a high-power load system, water circulation cooling and heat dissipation technology is generally adopted, which involves the need to bring a large number of cooling water tanks (tonnage) on the machine, as shown in Figure 3. Therefore, on the one hand, it is necessary to consider the influence of aircraft attitude on water circulation cooling function, on the other hand, it is necessary to consider the influence of airflow on water circulation cooling function.

### Table 1. Generator high-temperature-cooling test flight air-entraing configuration

| Height (ft) | Left hair Citation | Right hair Citation | APU Citation | Left PACK | Right PACK | Cross-cutting Citation | WAI | NAI left | NAI right |
|------------|--------------------|---------------------|--------------|-----------|------------|------------------------|-----|---------|-----------|
| AGL ≤31000ft | open Closed Closed Open Closed AUTO Closed Closed Closed On request |
| >31000ft | Open Closed Closed Open Open Open Closed Open On request |
hand, it is necessary to consider the influence of water seepage safety hidden danger and a large number of cooling water installations on aircraft performance stability and stowing.

![Water cycle cooling system](image)

**Fig. 3** Water cycle cooling system

Generators take a long time to load to full load, which requires the electrical load system to have high tolerance overload protection function and a stable automatic load-following function. At the same time, a large amount of heat will be generated in the cabin and EE cabin with a full load for a long time. Therefore, the heat dissipation in this part should be dealt with emphasis on in-flight tests under high-temperature weather.

Based on the technical difficulties and risks of the above simulated electrical load, it is necessary to conduct a comprehensive inspection and test flight of the simulated electrical load system before starting the high-temperature and cooling test flight of the generator, and compile monitoring pictures to carry out real-time safety monitoring on the ground for the key parameters such as generator power, water tank temperature, and pan box temperature.

4.2. Special test technology for power supply
In addition to verifying the cooling ability of lubricating oil, the generator high-temperature cooling test flight also needs to check that the relevant voltage, current, and power parameters of the generator are normal during the test.

Therefore, a set of special power test equipment and analysis software is needed to collect and analyze high-frequency power test flight data.

4.3. Risks of heavy takeoff and high-speed descent
The test requires the maximum take-off weight to take off, and there is a risk of the aircraft returning to the field and landing with a large weight due to an accident. Therefore, it is necessary to calculate the runway length and brake performance of the airport in advance and make an emergency plan with the airport for brake overtemperature.
The test required the aircraft to descend to holding level at maximum use within the twin-engine lift limit. Therefore, the relevant flutter/ASE envelope extension test flight needs to be completed in advance.

4.4. Judgment of oil parameter stability
In multiple stages of the test, it is necessary to judge the relevant parameters of cooling (oil temperature, generator component temperature) to reach stability before executing the next stage of operation. In CCAR 25.1045, "for cooling tests, when the temperature change rate is less than 1.1 °C per minute, the temperature is considered to be stable". The least-square method can be used for data processing to obtain the temperature change rate to meet the requirements of test criteria. The calculation of temperature change rate is as follows:

\[ \bar{t} = \frac{1}{60n} \sum_{i=1}^{60n} t_i \]  
(1)

\[ \bar{T} = \frac{\sum_{i=1}^{60n} T_i}{60n} \]  
(2)

\[ m = \frac{\sum_{i=1}^{60n} (t_i - \bar{t})(T_i - \bar{T})}{\sum_{i=1}^{60n} (t_i - \bar{t})^2} \]  
(3)

where the \( t_i \) indicates the time of the record \( \text{(unit: min)} \). \( T_i \) represents the temperature recorded at the time \( t_i \) \( \text{(in °C)} \). \( n \) 60 indicates the number of times the temperature is collected within \( n \) minutes.

4.5. High-temperature airport survey
Under CCAR25.1043(b), the maximum ambient temperature corresponding to sea level conditions must be at least 37.8 °C or ISA 22.8 °C. Besides, the temperature data of the generator radiator should be corrected to the right boundary of the aircraft temperature packet line according to CCAR25.1043(c) requirement. The revised formula is as follows:

\[ T = T_{sc} + (T_{hot} - T_S) \]

\[ HP \leq 15000ft; T_{hot} = 15 - 0.00198 \times HP + 40 \]

\[ 15000ft < HP < 39800ft; \quad T_{hot} = 15 - 0.00198 \times HP + 35 \]  
(4)

Among them:
\( T \) -- the corrected temperature, °C.
\( T_{sc} \) -- the actual measured temperature, °C.
\( HP \) -- air pressure height, ft.
\( T_{hot} \) -- ambient temperature in hot days at different air pressure heights, °C.
\( T_S \) -- Ambient temperature, the temperature of the outside atmosphere when the maximum temperature of the component or liquid under test first appears, °C.
The test process requires the ambient temperature to be greater than ISA+22.8°C for 5 hours. Domestic alternative airports include Turpan Jiaohe Airport, Hami Airport, and Chongqing Jiangbei Airport. In the comprehensive airspace resources and airport resources and other aspects of consideration. Turpan Jiaohe Airport has more interest in the development of the experiment. Turpan's weather is changeable, affected by the Tianshan convection, the airport in the evening to the early night, there will be strong wind weather. It was hot during the day and the plane was exposed to the sun. Therefore, adequate aircraft protection measures are needed. In addition, to conduct test flights in a high-temperature airport, it is necessary to fully evaluate the impact of high-temperature environment on aircraft equipment and aircraft take-off and landing performance in advance.

5. Technology implementation
In the implementation process of high-temperature and cooling test flight of the generator, there are the following technical details:
A) Relevant parameters need to be cooled to reach a stable state before the aircraft takes off. In order to ensure that the take-off configuration is the maximum take-off weight. Therefore, it is necessary to match the parameter stability time and fuel consumption rate and confirm the fuel amount in advance.
B) The airport temperature is high in high temperature, and the initial water temperature of the load water tank is high after exposure, and the loading time in subsequent tests is long. Therefore, it is necessary to take into account the high-temperature meteorological period and the cooling performance of the electric load on the day before the test and select the machine to temporarily inject low-temperature water. If the water injection time is too early, the rising water temperature will affect the loading time of the system and thus affect the flight time of the test subject. If the water injection time is too late, the high-temperature window period required by the test subject may be missed.
C) During the test, the generator was in a full load state, and the engine exhaust gas configuration was changed as required by the test program. During the test, the load management protection function may be triggered to unload part of the load equipment, which has certain safety risks.

6. Test data processing
The overall situation of the generator cooling - high temperature test flight is shown in Figure 4-6 below. The test lasted for 5 hours, and the average power of the test generator was 117kVA. Air intake configuration and anti-ice configuration at all stages of the aircraft were set as required, and the right generator was shut down for the whole process. In the simulated single-engine take-off and climbing stage, the altitude is about 6000ft and the speed maintains V2 for 5min, the oil temperature at the inlet and outlet of the generator radiator reaches the peak value of 109 °C and 126 °C, and the peak value of 130 °C and 147 °C after temperature envelope modification. The take-off weight is 71.4t (IAS+25°C limit take-off weight is 71.6t), the center of gravity of takeoff is 18.1%MAC, the single-engine lift limit height is 27000ft, the double-engine lift limit height is 37000ft, and the double-engine lift speed meets the VMO/MMO requirements while waiting for the level flight altitude (10000ft). After landing at 16:53, the test engine operated slowly for 3 minutes as required (16:56) and the engine was shut off. After that, the data were recorded for 1.5 hours and the test was finished at 18:30. After the test started, the temperature at the radiator inlet
and outlet of the generator continued to drop, and finally dropped to about 53°C. There was no alarm information related to generator oil during the whole test.

Fig. 4 Temperature variation curve of external environment

Fig. 5 Temperature and change rate of inlet and outlet of the radiator
Fig. 6 Complete section of generator cooling test flight
Based on the comprehensive analysis of the temperature data of the oil at the inlet and outlet of the radiator of the test generator, the following conclusions can be drawn:

A) The opening of the engine air intake, wing anti-icing, and nacelle anti-icing will increase the temperature change rate of oil at the inlet and outlet of the radiator of the test generator, but the overall effect on temperature is small.

B) The test of generator radiator, inlet oil temperature in simulated single take-off climb (TO/GA thrust, maximum continuous thrust) in the process of rapidly rising and fall in the VMO/MMO speed (slow train thrust) in the process of declining rapidly, in the 10000 ft simulation overshoot (phase TO/GA thrust) continue TO rise, can derive the engine thrust on the test generator radiator, inlet oil temperature influence for positive correlation.

C) The oil temperature at the inlet and outlet of the radiator of the test generator increases rapidly and continuously in the warm-up stage (full load of the generator) and decreases rapidly and continuously in the landing and stop stage (unloaded generator). It can be deduced that the influence of the loading amount of the motor on the temperature of the radiator of the generator is positively correlated.

D) The oil temperature at the inlet and outlet of the radiator of the test generator continued to rise during the re-entry and landing at a height of 10000ft. It can be deduced that the influence of the ambient temperature on the radiator temperature of the generator is positively correlated.

The influence degree of main factors on temperature is as follows: engine thrust grade and generator load have great influence, external environment temperature has a certain influence, engine intake air configuration, wing anti-icing, and nacelle anti-icing state have little influence.

7. Concluding remarks
The airworthiness background and technical principle of the high-temperature cooling test flight of generator are described in this paper. Based on the terms and technical principles, the main influencing factors of the generator cooling performance are analyzed in detail, and the train of thought of the test-oriented flight method is given. Finally, based on the experience of a high temperature-cooling test flight of a certain type of generator, the difficulties of test flight technology, the preparation of test flight technology, the problems encountered in the implementation of the test flight, and the results of test flight data are summarized and analyzed.

Reference
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