Airworthiness Design and Verification Analysis of Unconventional Thermodynamic Cycle Hydrogen Aero-Turbine Engines

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Abstract. Hydrogen fuel is an extremely ideal aviation power with its characteristics of high power density and zero carbon emission. Hydrogen fuel is stored in a low-temperature liquid state in aircraft, and the liquid hydrogen needs to be warmed up to hydrogen gas by heat transfer before entering the combustion chamber to participate in combustion. Since liquid hydrogen has the traits of low temperature and high specific heat capacity, large amount of heat is required to complete the heat transfer process. And the engine thermal cycle process can be fully utilized for heat transfer of liquid hydrogen. This paper presents the design and verification of unconventional thermal cycle system based on an unconventional thermal cycle configuration for hydrogen aero-turbine engines under the existing airworthiness regulations. This paper can provide support for the airworthiness design and verification of hydrogen aero-turbine engines with unconventional thermal cycle configurations, and provide a reference for the introduction of the airworthiness validation special conditions policy applicable to hydrogen aero-turbine engines.

Keywords: Hydrogen · Unconventional thermodynamic cycle · Airworthiness

1 Introduction

The rapid growth of the air transport industry has made aviation emissions one of the main sources of pollution emissions in the transportation sector, and the impact of aircraft on climate and the environment has become more and more significant, among which carbon dioxide emissions have received the most attention from governments. The United Nations Framework Convention on Climate Change, adopted in June 1992, first proposed comprehensive control of carbon dioxide emissions [1]; the Kyoto Protocol, signed in 1997, began seeking to cut greenhouse gas emissions from aircraft and ships and proposed the idea of carbon trading [2]. The European Union adopted Directive 2008/101/EC in November 2008 to include the aviation industry in the Greenhouse Gas Emissions Trading System (ETS) [3]; ICAO added the "Environmental Technical Paper Annex 16, Volume 3" in March 2017, which specifies the calculation method and limitation standards for aircraft carbon emissions [4]; China's 2021 In the 14th Five-Year

Plan of China, the goal of "double carbon" is also clearly proposed, striving to achieve peak carbon emissions by 2030 and neutral carbon emissions by 2060 [5]; in the newly revised CCAR-34 "Turbine Engine Emissions and Exhaust Emissions" by Civil Aviation Administration of China (CAAC) in 2022 In 2022, "Aircraft Fuel Discharge and Exhaust Emissions Regulations" of the Civil Aviation Administration of China (CAAC) also clarified the calculation method and limitation requirements for aircraft carbon emissions [6].

Under the guidance of a series of civil aviation transportation low-carbon and energy-saving emission reduction requirements, in addition to the continuous optimization of traditional gas turbine engine design and aircraft operating procedures, new aviation power technologies such as hydrogen energy and electric motors have also seen vigorous development. Among them, hydrogen aero-turbine engine has the advantage of high power density because it directly uses part or all of liquid hydrogen as fuel, and can be adapted on the basis of the existing configuration of gas turbine engines, without making disruptive design changes to the current aircraft and aero-engine configuration, so hydrogen aero-turbine engine has a great potential to realize the civil aviation industry's "double carbon" goal in civil aviation.

Hydrogen fuel is stored in ultra-low temperature liquid form in aircraft and needs to be heated to gaseous state by unconventional thermodynamic cycle which is different from that of conventional gas turbine aero-engine before participating in combustion. In this paper, the design and verification of the unconventional thermodynamic cycle configuration of hydrogen aero-turbine engine is proposed based on the safety principle under the existing CCAR33 aero-engine airworthiness regulations.

2   Unconventional Thermodynamic Cycle Hydrogen Power Scheme

The ultra-low temperature (usually below $-260\,°C$) liquid hydrogen fuel in the aircraft storage tank cannot be directly mixed with petroleum hydrocarbon fuel through direct atomization but needs to be transformed into hydrogen gas through heat exchange and warming before entering the combustion chamber. Liquid hydrogen is one of the liquids with the highest specific heat capacity, which is about 5000 J/(kg K), and it consumes a lot of heat in the heat exchange process. In this context, the onboard electric heating supplemented by unconventional thermodynamic cycle engine modification design, so that the hydrogen as a fuel at the same time takes on the cooling function of the engine thermal cycle, can greatly reduce the extra energy consumption of liquid hydrogen heat exchange warming and improve the engine performance [7, 8], and thus improve the economy of the engine.

The purpose of using unconventional thermodynamic cycle hydrogen power scheme is to make full use of the engine thermal cycle to raise the temperature of liquid hydrogen and improve the performance of the engine. The current unconventional thermodynamic cycle schemes that can better heat the liquid hydrogen and significantly improve the engine performance are mainly two kinds of compress flow path pre-cooling (CPC) and turbine cooling gas pre-cooling (TPC).

The core structure of the compressor flow path pre-cooling scheme is the pre-cooler installed on the wall of the booster stage cassette. The lead pipe introduces part of the air

after the fan into the pre-cooler, which is cooled down by liquid hydrogen pre-cooling and then pressurized and discharged into the core. The principle of this scheme is to reduce the total inlet gas temperature in front of the core machine booster pole, increase the total temperature rise of the compressor and thus increase the pressurization ratio of the compressor, thus improve the efficiency of the compressor and reduce the fuel consumption rate. For the gas entering the compressor, the isentropic temperature ratio can be simplified as a relationship with the pressure ratio, see (1).

$$\frac{T_{2S}}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{\kappa-1}{\kappa}} \tag{1}$$

T1 is the inlet temperature of the compressor (K), T2s is the end temperature of the isentropic compression process (K), T2 is the end temperature of the actual compression process (K), and k is the adiabatic index. Considering the specific heat and adiabatic index of the work mass as temperature-independent constants, the isentropic efficiency is therefore given in (2).

$$\eta_{ad} = \left(\left(\frac{P_2}{P_1}\right)^{\frac{\kappa-1}{\kappa}} - 1\right) \Big/ \left(\frac{T_2}{T_1} - 1\right) = \left(\pi_c^{\frac{\kappa-1}{\kappa}} - 1\right) \Big/ \left(\frac{T_2}{T_1} - 1\right) \tag{2}$$

where πc is the total pressure ratio of the compressor and k is taken as a constant value of 1.4.

The schematic diagram of the compressor flow path pre-cooling scheme is shown in Fig. 1.
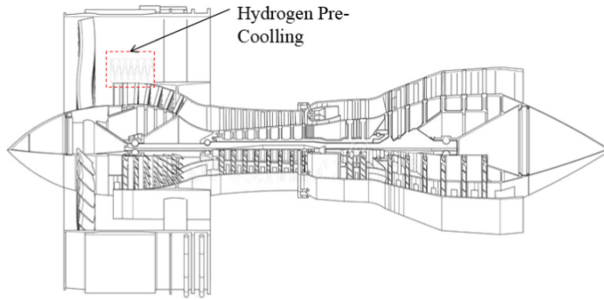

Fig. 1. Compressor flow path pre-cooling scheme

The core structure of the turbine cooling gas pre-cooling solution is an external pre-cooler installed between the high-pressure compressor and the turbine. The lead pipe introduces the turbine cooling gas from the high-pressure compressor into the external pre-cooler, where the cooling gas is further cooled by liquid hydrogen and then used for impact cooling and air film cooling of the turbine blades.

The turbine efficiency is used to measure the extent to which hysteresis isentropic work is converted to actual turbine output work, as shown in (3).

$$\eta_{T4} = N_T/N_{Ts} = N_T/W_4 \frac{k-1}{k} RT_4^* \left(1 - 1/\pi_T^{*\frac{k-1}{k}}\right) \tag{3}$$

where NT is the shaft work, NTs is the stagnant isentropic work, R is the gas constant; πT^* is the expansion ratio; k is the specific heat ratio; W4 is the sum of the mainstream flow and the cold gas flow in front of the blades, and T4* is the total turbine inlet temperature.

Reducing the turbine cooling gas temperature through the heat exchanger can significantly improve the cooling effect of the turbine, allowing the turbine to withstand higher temperatures based on the existing design, increasing the turbine inlet temperature T4* and improving the turbine efficiency ηT4, while reducing the fuel consumption rate (Fig. 2).
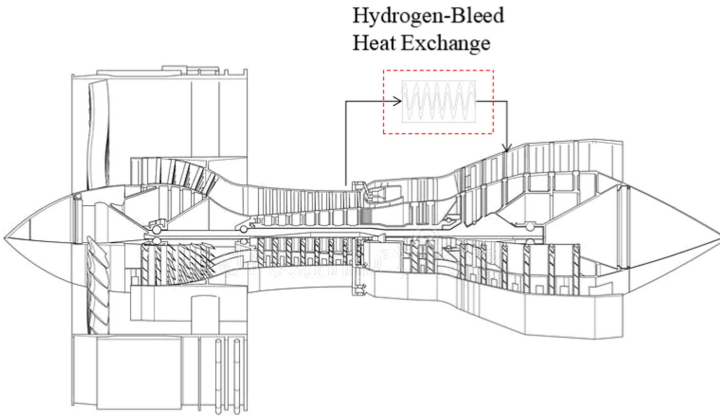

Fig. 2. Turbine flow path pre-cooling scheme

In the European cryogenic civil aircraft project CRYOPLANE, researchers have simulated the performance of a turbofan engine in two hydrogen-fueled unconventional thermodynamic cycle modes based on the performance parameters of a V2527-A5 engine [9]. The result indicates that engine using unconventional thermodynamic cycle has significant improvement on efficiency, as shown in Fig. 3.

The hydrogen turbine engine with unconventional thermodynamic cycle design has excellent performance, however, there are differences in configuration between the modified engine and the pre-modification engine, whether using the pressurized flow path pre-cooling or turbine cooling gas pre-cooling scheme, and the design changes need to be supplemented with the airworthiness design and verification of the unconventional thermodynamic cycle system.

3   Unconventional Thermodynamic Cycle Airworthiness Compliance Design and Verification

According to the two solutions of unconventional thermodynamic cycle hydrogen power, the main differences between the configuration and before modification are mainly in the compressor flow path pre-cooling device and turbine cooling gas pre-cooling device, and
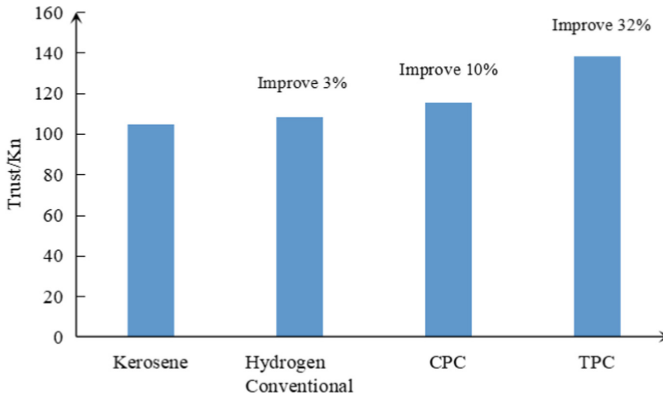
Fig. 3. Performance improvement with unconventional thermodynamic cycle

the airworthiness design should be carried out for the compressor flow path pre-cooling structure and turbine cooling gas pre-cooling structure under the principle of security analysis.

3.1 Design of Pre-cooling Device for Compressor Flow Path

The pre-cooling device of the compressor flow path does pre-cooling on the front end of the engine thermal cycle, and is also installed on the front end of the engine, which bring the influence of icing and foreign matter inhalation into consideration when doing the airworthiness compliance design.

According to the icing requirements of the airworthiness regulations for the intake system, the engine should not have icing conditions on engine components that affect engine operation or cause serious loss of power or thrust during its operation over its entire flight power range. A pressurized flow path pre-cooling device installed in front of the booster pole will make the risk of icing near the manifold ring significantly increased, especially in the high-altitude and low-temperature environment, traditional gas turbine engines often need to install hot gas anti-icing devices to prevent the manifold ring icing, the aero-engine icing phenomenon is shown in Fig. 4.

Therefore, it is necessary to carry out the airworthiness compliance design of the control system for the pre-cooling device of the compressor flow path accordingly, and open the pre-cooling device in front of the booster pole when the total temperature of the inlet air is high to reduce the total temperature in front of the fan booster pole to improve the boost ratio, and keep the pre-cooling device closed when the total temperature of the inlet air drops to a certain threshold. In addition, the total temperature sensor is set at the outlet of the pre-cooling device, and the low-temperature shutdown temperature control logic is also set to automatically shut down the pre-cooling device if the airflow is excessively cooled during the normal operation of the pre-cooling device and the total outlet temperature drops to a level that may cause icing.

In accordance with the requirements of the Airworthiness Regulations for inhalation of foreign objects, no unacceptable mechanical damage, loss of sustained power or thrust,
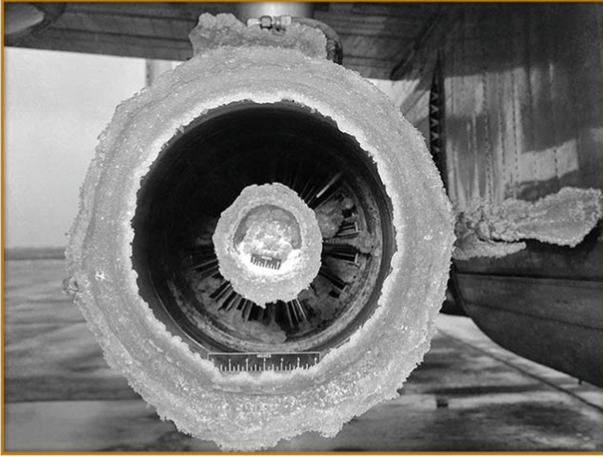
Fig. 4. Aero-engine icing

or engine stoppage shall be caused in the event that flying birds, ice, or large hail are inhaled, the aero-engine suction bird is shown in Fig. 5.

Fig. 5. Aero-engine bird strike

The pre-cooling device of the compressor flow path is installed on the wall of the booster box, and there is a certain probability that birds, ice, and large hailstones will hit the pre-cooling device when it is sucked into the engine, and there is a large amount of liquid hydrogen used for heat exchange in the pre-cooling device, which may cause liquid hydrogen leakage and fire if it is hit by foreign objects. Therefore, it is necessary to design the airworthiness of the pre-cooling device of the compressor flow path for structural strength and conduct strength assessments to ensure that its structure and

installation will not be damaged under the conditions of inhalation of foreign objects as required by airworthiness regulations.

3.2 Turbine Cooling Gas Pre-cooling Device Airworthiness Compliance Design

Turbine cooling gas pre-cooling device to do pre-cooling of the engine thermal cycle of the cooling gas, in doing airworthiness compliance design should mainly consider the impact of the cooling gas temperature range.

According to the airworthiness regulations for engine cooling, the engine must be designed and constructed to provide the necessary cooling under the intended operating conditions of the aircraft. Conventional configurations of aircraft turbine engines usually use a high-pressure compressor intermediate or final stage to induce gas to cool the turbine blades. The gas from the high-pressure compressor enters through the induced gas line from the hollow turbine blade roots and forms a gas film on the turbine blade surface to cool the turbine blades, which can isolate the flame and significantly reduce the temperature of the turbine blade body, the air film cooling structure is shown in Fig. 6.
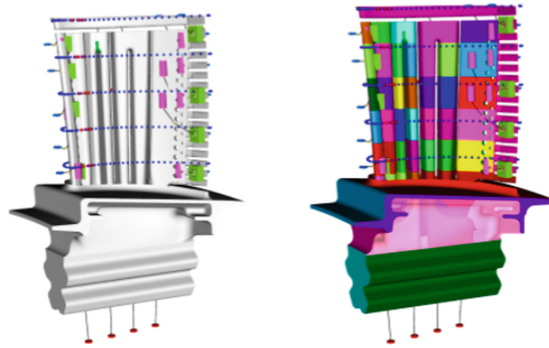

Fig. 6. Schematic diagram of hollow turbine blade air film cooling

The temperature of the air after multi-stage pressurization by the high-pressure compressor has a significant increase, and the total temperature of the high-pressure compressor outlet of large turbofan engines can usually reach more than 350 K. After using the turbo cooling air pre-cooling device to pre-cool the air leading from the high-pressure compressor, the temperature of the cooling air can be effectively reduced to enhance the cooling effect and further increase the temperature before the turbine. However, the turbine cooling air is not allowed to be overly pre-cooled. If the cold air is used directly for cooling the hot end components, it may produce too large a temperature gradient and lead to thermal stress problems in the turbine blades and other hot end components. Therefore, it is necessary to design the turbine cooling gas pre-cooling device to comply with the temperature range of the cooling gas. Determine the temperature range of the cooling gas that can be used for direct cooling according to the temperature field and thermal stress calculation results of the turbine blades and other hot end components.

Then, set the control logic of the turbine cooling gas pre-cooling device according to the determined temperature range of the cooling gas.

3.3 Unconventional Thermodynamic Cycle System Airworthiness Compliance Verification Ideas

The pre-cooling device in the unconventional thermodynamic cycle system designed according to the above principles, as an accessory of the engine, also needs to pass the corresponding environmental test according to the requirements of 33.91. The design and verification of the piping for transporting liquid hydrogen needs to meet the requirements of 33.17 Fire Resistance, 33.63 External Component Vibration, 33.64 Overpressure, etc. Therefore, the design and verification of the unconventional thermodynamic cycle system, represented by the pre-cooling of the compressor flow path and the pre-cooling of the turbine cooling gas, is shown in the Fig. 7.
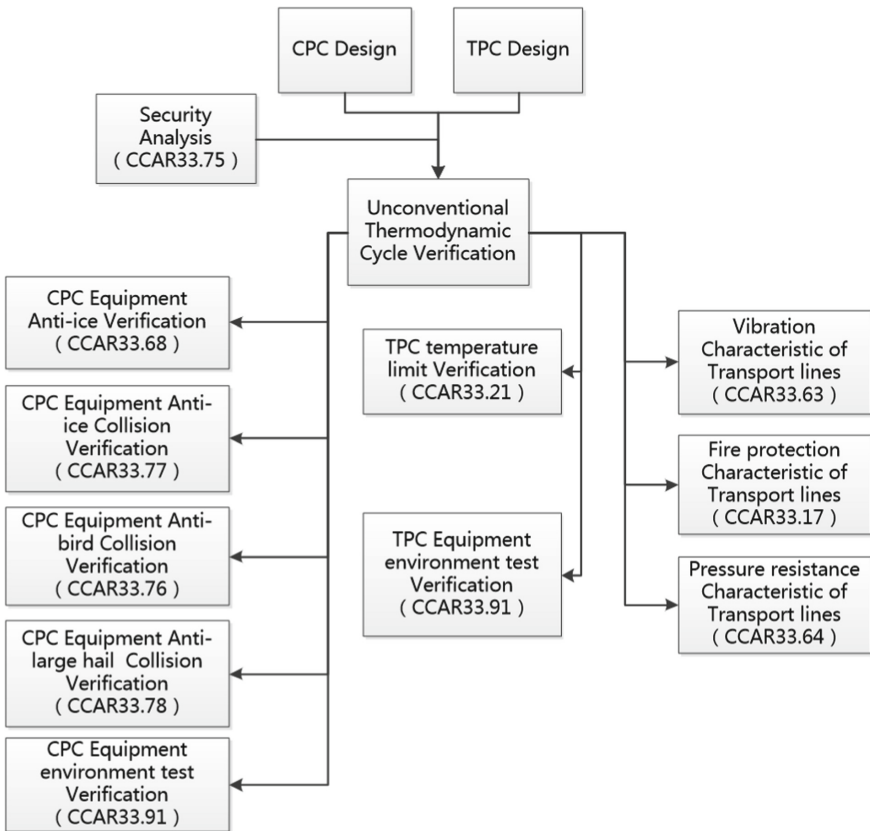

Fig. 7. Unconventional thermodynamic cycle system design and verification ideas

When carrying out airworthiness verification, under the current system of aero-engine airworthiness regulations, the verification of unconventional thermodynamic

cycle systems can fall under the existing CCAR33.68, CCAR33.77 and dozens of other provisions of the conformity work, and the specific conformity verification methods can be determined in consultation with the airworthiness authorities in conjunction with the industrial side's technology maturity assessment and verification strategy. For all evidence of conformity shown to the bureau, it is necessary to prove the validity of the evidence through test verification or validated methods.

3.4 Potential Special Conditions

During the airworthiness review process, the Bureau will establish special conditions for novel and unique design features that do not contain sufficient safety requirements in the regulations. According to CCAR-21 Civil Aviation Product and Component Qualification Validation [10], Section 21.16 of the regulations governs the special conditions as follows (Table 1).

Table 1. Civil aviation administration of China special conditions requirements

Elements			Safety level
Novel or unique design features	The intended use of the product is unconventional	Experience from the use of similar civil aviation products or civil aviation products with similar design features indicate that unsafe conditions may arise	Same as applicable regulation

The design of turbine engines using hydrogen as fuel, especially the unconventional thermodynamic cycle design in this paper, is highly novel, and the physical and chemical properties of hydrogen differ greatly from those of conventional fuel, which is highly flammable and explosive. In the previous paper, we have carried out airworthiness design and verification of unconventional thermodynamic cycle system, taking the verification of piping for liquid hydrogen transport as an example. If not, when the applicant adopts the design of unconventional thermodynamic cycle, the corresponding special conditions should be introduced by the airworthiness authority.

4 Conclusion and Outlook

This paper focuses on the unconventional thermodynamic cycle scheme adopted in conventional aero-turbine engines, and carries out the airworthiness design and verification of the unconventional thermodynamic cycle system, which can provide ideas for the airworthiness of conventional gas turbine engines converted to hydrogen-powered configurations. At the same time, due to storage, transport, ignition, and explosion characteristics, compressibility of hydrogen differ greatly from those of traditional fuel, and there is hydrogen corrosion effect on metal materials, further design and verification of

fire protection, component durability, and operating characteristics of the whole engine are needed in addition to the design and verification for compliance of unconventional thermodynamic cycle systems focused on in this paper, and based on the results of safety assessment, the airworthiness authorities and industry will identify the current novel or unique design features, and timely introduction of the corresponding special conditions.

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