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The future of aviation in the global warming environment

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Abstract. Today, greenhouse gas emissions caused by human activities have led to rising global temperatures, increasing extreme weather events, and rising sea levels, posing a threat to human society and ecosystems. People are also taking some active measures to mitigate these impacts. Therefore, in order to make a positive response in the aviation industry, this paper studies how to reduce greenhouse gas emissions brought by aircraft engines under the environment of energy conservation and emission reduction, mainly from two aspects of improving large bypass ratio engines and adopting new environmentally friendly fuels. Then the two major aspects, respectively, the origin and advantages and disadvantages of their analysis, for the current needs of the theory and the problems encountered in the actual production, how to solve and apply. After synthesizing the previous studies and reorganizing the previous studies, this paper expounds these two aspects in more detail.

Keywords: Aviation emission reduction, High bypass ratio engine, New fuel

1. Introduction

Although the aviation sector contributes a relatively small proportion to global emissions, it can have a significant impact in specific regions and time periods, especially on busy hubs and high-density routes. The aviation sector contributes about 2 to 3 percent of global greenhouse gas emissions, which includes greenhouse gases such as carbon dioxide (CO2) emitted by aircraft exhaust. However, in some areas, such as around busy airports, the proportion of exhaust emissions from air transport can be higher, with a greater impact on local air quality and the environment. In addition, because of the increasing demand for air travel, carbon emissions from the aviation industry are also growing. Therefore, reducing tailpipe emissions from the aviation sector remains an important effort to reduce greenhouse gas emissions. It can also start from two aspects. First, to improve the conversion efficiency of traditional engines, so that more energy can be used for the power of aircraft, thereby indirectly reducing exhaust emissions. On the other hand, people can seek to use cleaner energy as engine fuel, which will greatly reduce the content of greenhouse gases or other harmful gases in the exhaust. If these two things can be achieved at the same time, not only could the passenger experience in civil aviation be significantly improved, but even more resources could be saved, and the goal of zero carbon emissions by 2050 could be achieved.

2. High bypass ratio engine

2.1. Economic demand
The long-term stable development of things must achieve the requirements of high quality and low price. Aircraft as a high-tech and high-investment means of transportation, its large construction cost, fuel consumption and maintenance costs seriously restrict the progress of aviation industry. Therefore, the global aviation industry has been pursuing economic and durable type of large aircraft engines, mainly focusing on reducing fuel consumption and extending service life in two aspects [1]. After solving the most basic economic benefits, how to make civil aircraft more environmentally friendly has become the most concerned point at present. In the future development, low energy and environmental protection have become mandatory requirements for various industries, especially in the field of large aircraft engines. At the beginning of the 21st century, civil turbofan engines such as GP7200, GE90 and PW4084 have made remarkable progress in environmental protection, effectively reducing noise pollution and low-energy emission technology to meet environmental protection requirements [2]. In order to further improve the environmental performance of aircraft engines in the future, the United States and European Union countries have carried out a series of technical research programs, committed to reducing emissions and reducing emissions of harmful substances green aircraft engines, and developed a "green engine" in the whole life of the engine to the social ecological environment and the health and safety of the crew related staff to minimize the impact of the "green engine".

2.2. Encountered problems
In order to improve the fuel efficiency of the civil large bypass engine, it is necessary to continuously improve the bypass ratio and strengthen the cycle power of the core engine. This will lead to the high pressure compressor to bear a larger aerodynamic load, which is manifested by the reduction of the series and the increase of the pressure ratio. Taking the CFM56 engine as an example, its stage 9 high-pressure compressor has achieved the pressure ratio of the CJ805 engine's stage 17 high-pressure compressor. GE's latest GE-9X engine even achieves a high pressure compressor ratio of 27 to 28, with an average stage ratio of 1.35 to 1.40. To make matters more challenging, high-pressure compressors not only need to withstand high loads, but also need to have a broad stable operating range to meet the various requirements of aircraft engines, including acceleration, performance degradation, and the inhalation of rain and hail. Usually, the stable operating range of high-pressure compressors is measured by surge margin, which is required to be greater than 20% to 25% in the full speed range. In addition to the above indicators, the flow rate is also an important representative of the flow capacity of the high-pressure compressor [3]. Modern civil high-load aviation high-pressure compressors usually have the characteristics of high-pass flow, and their flow is related to density, axial speed and circulation ring area.

Table 1. Pressure ratio of typical high-pressure compressors [4]

Model number		Series total pressure ratio	Average stage pressure ratio	Years
CJ805	17	12.5	1.16	1950
CF6-50	14	13.0	1.20	1973
CFM56	9	12.0	1.32	1980

In the design process, it is necessary to comprehensively consider the change of the area of the flow channel, the change of the pressure ratio and the speed triangle at all levels, and also the impact of the import and export hub comparison performance and stability. As shown in Table 1, the compressor efficiency is very difficult to improve, under normal circumstances, about every ten years to increase by one percentage point [4].

2.3. Factor considered
Therefore, in order to improve the performance of civilian high bypass ratio turbofan engines, several key factors need to be considered. First of all, in terms of aerodynamic runner design, the height and

ring area of the runner affect the speed and performance of the blade. The inlet stage of high pressure compressor requires special design to reduce shock wave and blade profile loss. The rear stage usually adopts the flow channel design in the form of equal inner diameter to reduce the load in the blade end area, and the concave pit at the root of the blade is designed to reduce the blade load. Secondly, the tangential velocity and pressure ratio distribution is also critical. The tip tangential velocity represents the rotor's ability to do work, but a balance is needed to flow Mach numbers and losses. The tip tangential velocity of high pressure compressors is usually controlled between 400 and 450 m/s, while the pressure ratio distribution decreases step by step from inlet to outlet. Multiple rows of adjustable stator blades are used for surge margin regulation at low RPM. Finally, in blade design, a small aspect ratio design and a highly three-dimensional curved-sweep design are used to control loss and end-zone efficiency. Features such as refined leading edge design, free mid-arc and arbitrary thickness distribution help to reduce blade profile losses. The "J" or "S" shape is used to control the flow separation of the end area along the radial stacking of the blades. The Angle at both ends of the blade is increased to enhance the ability to do work and resist the pressure loss in the end area. It should be noted that the flight status of civil aircraft is relatively stable, so the change of tip clearance of high-pressure compressor blades is small. In the long-term working state, a smaller tip clearance can be used to improve efficiency, but for high-load compressors, the adjustment of tip clearance has a sensitive impact on efficiency.

Because the civil large culvert part of turbofan engine has been pursuing high pressure ratio and high efficiency, it has also caused a series of problems, including the reduction of outlet stage size, Reynolds number effect, outlet stage blade leading edge thickness and large chamfering radius. Literature puts forward some solutions, including adopting advanced optimization algorithm to improve blade design and power distribution, so as to improve the matching performance between stages and blade root tips. In addition, it is also suggested that reasonable arrangement of bleed position and suction volume, design of high precision and high reliability stator blade adjustment structure, control radial clearance leakage flow, control blade profile tolerance, reduce compressor performance decline and other measures. The key to realize high load and high efficiency compressor is to control the boundary layer of blade channel, secondary flow and shock wave interference to the boundary layer. Some innovative methods have been proposed and preliminarily verified at home and abroad. These methods are worth further study to explore their application possibilities in high-pressure compressors and lay a solid foundation for future engineering applications [5].

2.4. Terms of settlement

In order to solve the above problems, there are two ways to improve the total pressure ratio of compressors: First, people keep the series unchanged and improve the average stage pressure ratio of compressors; Second, by increasing the series to improve the total pressure ratio. To achieve this goal, advanced optimization algorithms are used to explore the load potential of the 3D curved, swept and twisted blade, while combining the development of the boundary layer in the fusion control corner area of the flow channel and blade to increase the average stage load level. However, the use of large tangential velocity, incoming Mach number and blade Angle, although it can improve the pressure ratio and load, may adversely affect the efficiency [6]. In addition, reasonable design stage reaction force and control of rotor power distribution are also important considerations. Compared with military aircraft, the performance of high-pressure compressors of civil aircraft can be improved by taking into account the thermal and aerodynamic loads borne by the casing, the thermal, aerodynamic and centrifugal loads borne by the rotor, and accurately estimating the deformation between the hot state and the cold state within the working range of the compressor under relatively stable flight conditions. For multi-stage high-pressure ratio axial flow compressors, it is the primary problem in aerodynamic design to ensure the matching between the various stages in the full working range. In the design process, some simplifications, such as handling the static interface, chamfering, interstage static sealing cavity and manufacturing assembly errors, will cause deviations. As the stages increase, these deviations become more significant and may cause the compressor to deviate from the design and fail to meet the predetermined performance goals. In order to cope with these problems, a block or stage design

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approach can be adopted, but this requires highly accurate boundary conditions and accurate estimates of design deviations, which often rely on experience [7]. In addition, there is a high degree of unsteady flow in the compressor channel, which is closely related to compressor performance and aerodynamic stability, involving complex problems such as statics interference, generation, development and disappearance of vortex system, prediction of surge boundary and gas-solid thermal coupling, which affect the accurate estimation of compressor performance and strength level. However, the verification process of such multistage high-load compressors is both challenging and requires significant time, cost and test resources.

3. New fuel

3.1. Fuel composition

At present, most civil aircraft use jet kerosene, so in order to achieve the ultimate goal of energy saving and emission reduction, the development of sustainable aviation fuel is very important. Jet fuel is a complex mixture made up of hundreds of different hydrocarbons with carbon atoms ranging in number from 8 to 16. The fuel is similar to gasoline and diesel, and has a boiling point that partially overlaps with gasoline and is almost exactly the same as diesel [8]. Refiners often choose to produce different types of fuel based on market demand and policy, leading to fierce capacity competition between renewable aviation fuel (SAF) and renewable diesel. To treat SAF on a par with jet kerosene, performance, operability and compatibility need to be considered. Performance factors include mass energy density, volumetric energy density, particulate emissions and thermal stability, among others, which determine the performance of SAF in aviation engines. Operability is concerned with ensuring the safe availability of fuel under harsh conditions, such as cold start and high-altitude reignition, and often requires the use of an original Equipment manufacturer (OEM) test facility for certification [9]. Compatibility means that SAF can be applied directly to existing aircraft and engine products without the need for large-scale tweaks. The composition of SAF has expanded from the early normal and isomeric alkanes to four hydrocarbon families including aromatic and cycloalkanes. Other components in traditional aviation kerosene, such as oxygen-containing molecules, heteroatom-containing molecules, unsaturated olefins and metal atoms, have been excluded from the SAF specification standards due to poor thermal stability, low freezing point and easy formation of pollutants. Normal alkanes and isomeric alkanes typically make up 55 to 60 percent of conventional jet fuel, but while the former can be part of the SAF, it does not meet the freezing and flash point requirements of the ASTM D1655 standard and has no unique performance properties. Unlike this, iso-alkanes have advantages such as high quality energy density, good thermal stability, and low freezing point.

Table 2. Typical SAF that has been approved by ASTM [5]

name	Ingredients	Upper mixing volume
Fischer-tropsch Synthetic paraffin Kerosene (FT-SPK)	Municipal solid waste, agricultural and forest waste, energy crops, etc	50%
Paraffin kerosene synthesized from hydrogenated ester and fatty acid HEFA-SPK)	Animal and vegetable fats, oils and greases	50%
Hydrofermentation of sugars to isomeric alkanes (HFS-SIP)	saccharide	10%
Fischer-tropsch synthetic paraffin kerosene with aromatic hydrocarbons (FT-SPK/A)	Solid waste, agricultural and forest waste, wood , energy crops, etc	50%
Alcohol spray Synthetic paraffin Kerosene (ATJ-SPK)	Starch, sugar, cellulose and other biomass	50%

Table 2. (continued).

Paraffin kerosene synthesized from hydrogenated hydrocarbons, esters and fatty Acids (HHC-SPK)	Hydrocarbons, fatty acid esters and free fatty acids of biological origin	10%
Catalytic Hydrothermal synthesis of kerosene (CH-SK)	Animal and vegetable fats, oils and greases	50%
Co-processing of renewable raw materials and crude oil middle fractions	Renewable lipids (plant and animal fats)	5%

The energy density of aromatic hydrocarbons is lower, and their combustion is not as clean as that of alkanes, which is the main source of particulate matter emissions in aviation kerosene, and it is easy to cause wear and tear of the internal structure of the combustion chamber. Cycloalkanes complement isomeric alkanes in some ways, providing a similar sealed expansion function as aromatic hydrocarbons. Therefore, the trend has become clear to reduce the aromatic content by adding high quality isoparalkanes, and eventually to replace them, which can both minimize pollution emissions and further improve the energy characteristics of the fuel. As of early 2021, there are already eight SAF production processes certified by ASTM, usually with a maximum blending ratio of no more than 50%. Among them, the hydrogenated ester and fatty acid (HEFA) process is one of the most feasible ways to prepare SAF, which forms hydrocarbons by hydrogenating industrial waste oil and vegetable oil after deoxidation reaction. The technology maturity of this process has reached 8 to 9 in 2017, and it is also expected to use oily algae as feedstock in the future. Fischer-tropsch synthesis is another method, which gasifies wood fibers from municipal solid waste into a mixture of carbon monoxide and hydrogen, which is then further converted into SAF. This method has achieved a technical maturity of above level 7 in 2019 and is the only preparation process approved to incorporate aromatic hydrocarbons into the fuel, with better compatibility [10]. In addition, there are constantly improving and developing production processes such as alcohol spray synthesis, catalytic hydrothermal decomposition and direct synthesis of sugars. As shown in Table 2, part of the SAF has been approved so far [11].

3.2. Future development

In 2019, the global aviation industry consumed about 360 billion liters of fuel and is expected to continue to increase at a growth rate of about 3% per year. However, the annual production of sustainable aviation fuel (SAF) is currently only 50 million litres, less than 0.02 per cent of the total. The capacity of SAF must be significantly increased in the coming years to meet market demand, despite the challenges of feedstock availability and mass production. Sources of industrial waste and exhaust gases are limited, while the production of other biomass feedstocks requires large amounts of land and water resources. The most viable long-term technological solution is to utilize the Fischer-Tropsch process, which combines industrially produced hydrogen, such as those produced by electrolysis, with atmospheric carbon dioxide to synthesize hydrocarbons for the preparation of fuels. However, this would also create a huge demand for renewable electricity[10]. In addition, the world does not yet have a fully developed SAF infrastructure, and additional investment is needed to equip conventional refineries with feedstock processing capacity and to build specialized SAF plants outside the existing supply chain, along with pipeline transportation and storage systems. In order to minimise carbon emissions, SAF should ideally not be mixed with conventional fuels. However, current production techniques mainly replicate some of the components in jet kerosene, resulting in a lack of comprehensive understanding of the performance characteristics of SAF in the industry, limiting the blending of SAF in commercial applications to no more than 50%. While Boeing's latest tests have shown acceptable performance when using 100 percent HEFA fuel on Boeing 777 aircraft, caution remains as to whether aromatic hydrocarbons can be completely replaced in older aircraft and engine systems without sufficient research and trial data. Future engine combustion systems may need to be redesigned to achieve optimal operational performance. ASTM D4054 is the core standard for evaluating new aviation fuels and fuel additives and is designed to ensure that aircraft using alternative aviation fuels can operate safely and reliably. This certification process is led by the aviation manufacturer and typically consists of 4 major steps, which is an iterative and extremely rigorous evaluation process. However, the current SAF certification takes three to five years and costs over US $5 million, with the full process costing up to US $10 million to US $15 million, which is a heavy burden for many emerging fuel suppliers. Therefore, reducing the time and cost of certification has become a necessity. Although a fast-track certification annex to ASTM D4054 was approved in January 2020, the maximum mix of SAFs certified through this annex is still limited to less than 10%. It is important to note that while there is room to streamline the ASTM certification process, the requirements for SAF performance specifications will only become more stringent, not less, as the technology advances.

4. Conclusion

Through innovative engineering and the adoption of sustainable fuels, we can expect aircraft engines to dramatically reduce carbon emissions. Advanced materials and design improvements will increase combustion efficiency, while a new generation of engines will reduce emissions of nitrogen oxides. This development will have a positive impact on the sustainability of the global aviation industry and help us better protect the environment.

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