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Jet Engine: Evolution, 3D Printing Applications, and Future with Clean Energy

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Abstract:
The development of jet engines is the key to driving the development of the aviation industry and changing the military, economic, and social landscape. This article reviews the evolution of jet engine technology, from early piston engines to modern turbofan engine systems, emphasizing their role in achieving higher speeds, altitudes, and fuel efficiency. It explored key innovations such as 3D printing, with practical applications including GE Aviation, Rolls Royce and Pratt & Whitney's 3D printing components, demonstrating potential to reduce weight, material waste, and production time. However, challenges such as component consistency and scalability still exist. In addition, this article also investigates clean energy alternatives, particularly hydrogen. It can eliminate carbon emissions, but its application still faces challenges such as high combustion rates, high-temperature nitrogen oxide emissions, and high resource and economic costs. Through a review of existing research, this article emphasizes the transformative impact of jet engines and identifies future development directions, including advanced manufacturing and sustainable energy solutions, to provide guidance for the sustainable development of the aviation industry.

Keywords: Jet Engine; Additive Manufacturing (AM); Aviation; Environmental Protection.

1. Introduction

In 1903, the Wright brothers' "Flyer 1" successfully launched, marking the beginning of the aviation era for humanity. The invention of airplanes not only completely changed the mode of transportation, but also triggered profound changes in military, economic and social aspects, becoming one of the key technologies that have influenced human development since the 20th century. In terms of military aspect, the Air Force is already an independent branch of the military that is equally important as the Navy and Army. The various experiences of modern warfare have also demonstrated the importance of air superiority. In terms of economy and society, airplanes have led the transformation of transportation. In the

19th century, crossing the ocean took several weeks, but now it only takes a few hours. At present, billions of people travel by civil aviation every year, and the globalized trade chain cannot do without the support of air cargo, not to mention the employment and development promotion brought by the aviation industry. It shows that the development of airplanes is very important.

The engine, as the heart of an aircraft, provides the necessary thrust for flight, and the development of airplanes cannot be separated from the update of airplane engines. The earliest airplanes used piston engines. This type of engine generates thrust by driving the propeller through the crankshaft, with a simple structure but low power density. This resulted in early aircraft speeds generally being below 200km/h. At the same time, due to physical limitations such as low temperature and low air density in high altitude, as well as a sharp drop in efficiency when the propeller tip speed approaches the speed of sound, propeller engine including turboprop and piston engine will encounter insurmountable bottlenecks at flight altitude and maximum speed [1]. When it comes to 1940s, with the invention of jet engines (Turbojet), the aviation industry entered the jet age. This type of engine works continuously through the compressor combustion chamber turbine, directly ejecting high-speed airflow to generate thrust, with a power density far exceeding that of piston engines [2].

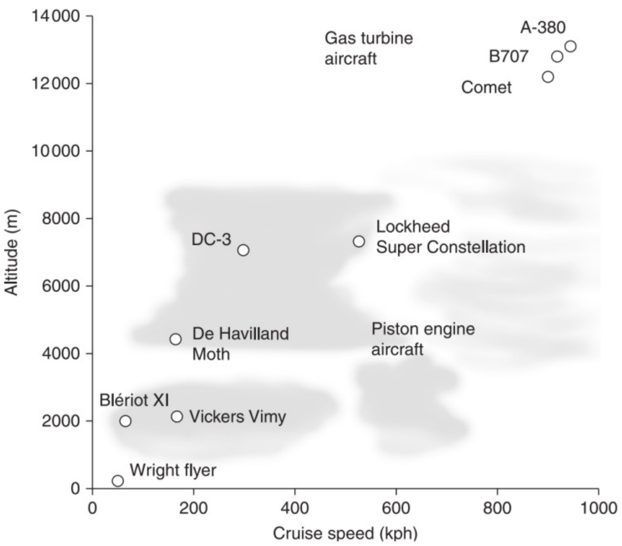

Fig. 1 Flight altitude and speed of different aircraft [1].

From Fig. 1, it shows that compared to piston engines, jet engines enable aircraft to break through limitations with higher speeds and flight altitudes. Jet engines can even accelerate gas to supersonic speeds through special nozzles (Laval nozzles), allowing the aircraft to break through the barrier of sound speed. In 1960s, due to the unsatisfactory efficiency of the turbojet engine, the turbofan was invented to solve this problem. This engine significantly improves fuel efficiency and reduces noise by adding a large-diameter fan outside the core engine to drive a large amount of low-speed airflow. Its appearance greatly reduced the fuel cost of aircraft flight and increased the flight distance. This undoubtedly promotes the popularization of aviation, transforming the civil aviation industry from “luxury travel” to “mass transportation” and driving the formation of a global logistics network.

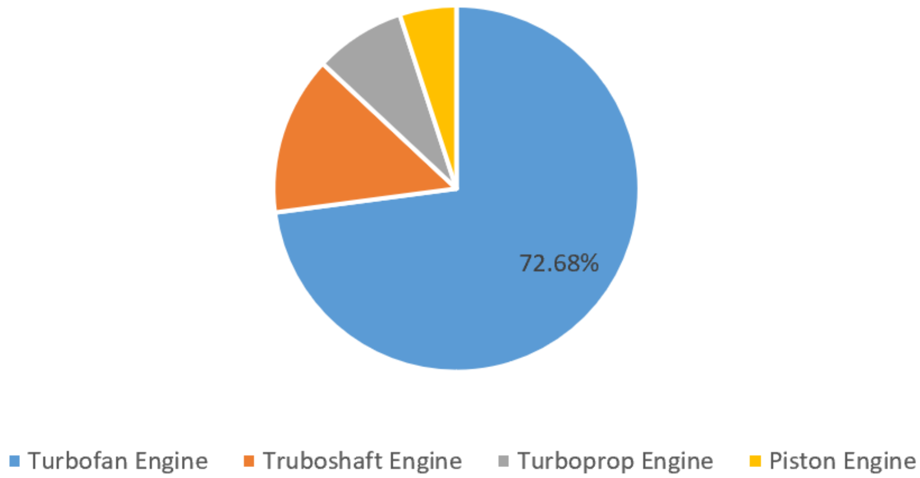

Fig. 2 Global Aircraft Engine Market Share, By Engine Type, 2023.

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At present, turboprop and propeller engines are only used on some training aircraft and regional civil aviation aircraft due to their inherent limitations. In contrast, jet engines are currently the mainstream of aviation engines, providing power for various civil and military aircraft. As Fig. 2 shows, in the 2023 Global Aircraft Engine Market, Turbofan accounts for 78.68%, far higher than the overall proportion of other engines [3]. It can be said that the development of jet engines has dominated the entire aviation industry. That's why reviewing existing research on jet engines and clarifying their future development directions are so important.

2. Results and Discussions

2.1 Jet Engine and 3D Printing

Additive manufacturing also known as 3D printing, is currently a popular field in the manufacturing industry. It is the process of manufacturing objects from 3D model data by stacking materials layer by layer. Unlike traditional subtractive manufacturing, AM does not require fixtures and cutting tools and can directly produce complex parts, leading to its huge advantages [4]. Firstly, in terms of design freedom and complex structure manufacturing, 3D printing can produce complex structures that are difficult to achieve with traditional methods, such as turbine blades for jet engines and complex hollow structures designed for lightweighting. This will reduce the difficulty of manufacturing and allow for more freedom in design work. In terms of cost control, compared to traditional building materials manufacturing that requires the removal of a large amount of materials, 3D printing can increase material utilization and reduce raw material costs by stacking materials layer by layer. According to Lim et al.'s investigation, through 3D printing, it is possible to produce aircraft parts with a weight reduction of 30-55%, while saving nearly 90% of materials [4]. In terms of product development, 3D printing does not require molds or specialized tools, and can quickly manufacture prototypes or functional parts from CAD models, accelerating the product development cycle [5]. For example, the development time for the Airbus A350 bracket has been reduced from 6 months to 1 month. Finally, in terms of production flexibility, 3D printing technology is highly suitable for flexible small-scale production. When it is necessary to produce discontinued or rare parts, 3D printing can achieve rapid manufacturing through models without the need to build corresponding assembly lines, saving supply chain time.

From the numerous advantages of 3D printing, it indicates that its combination with jet engine has a bright future. In fact, 3D printing technology has already been applied to the production of Jet engines. GE Aviation produces chrome alloy engine fuel nozzles through laser selective melting technology, integrating the traditional nozzle consisting of 20 parts into a single 3D printed component, successfully reducing the weight by eliminating connectors. The parts they produce have passed aviation certification and are being mass-produced, and their target is to produce 100000 pieces by 2022 [5, 6]. Pratt & Whitney integrated 3D printing technology into the development and manufacturing of the compressor stator and synchronizing ring bracket for the PW1500G engine, successfully shortening the development cycle and reducing engine weight [7]. Rolls Royce has successfully shortened the manufacturing time by incorporating electron beam melting technology into the titanium alloy front bearing housing of its Trent XWB-97 engine [8]. In China, according to Xinhua's report, "China successfully completed the maiden flight of a domestically developed ultra-lightweight miniature jet engine, which was entirely manufactured using 3D printing technology [9]." It indicates that the current application of 3D printing in the field of jet engines has a clear direction. The integrated manufacturing of complex components can be achieved through 3D printing technology, reducing the weight of components by reducing the number of connecting parts, thereby providing high fuel efficiency.

However, 3D printing is not perfect, and there are still many problems that need to be addressed to fully promote its application in jet engines. Firstly, 3D printed components may have internal porosity and lack of fusion defects, resulting in lower fatigue life. At the same time, residual stresses in the components can also easily cause deformation or cracking. Secondly, aviation components such as jet engines have strict standards for parts, and parts made using 3D printing technology may have poor consistency, resulting in some batches of parts not meeting the requirements. Finally, due to the limitations of printing equipment, 3D printing is difficult to manufacture large-sized parts. Although 3D printing can shorten the research and development cycle, it is still inferior to traditional processing methods in terms of manufacturing cycle and mass production [5]. More researches are needed in these parts.

2.2 Jet Engine and Clean Energy

Why do people always focus on the fuel efficiency of engines when discussing related topics? This is not only because higher fuel efficiency means a lower cost, but also because such engines are more environmentally friendly. Faced with global environmental degradation and limited fuel resources, clean energy has always been an important research direction. The main component of traditional aviation fuel is hydrocarbons ($C_xH_γ$), which undergo oxidation reactions with oxygen (O_2) in the engine combustion chamber generating Carben oxides (CO_x). At the same time, 78% of the air took in by the combustion chamber is nitrogen (N_2). It reacts with oxygen at high temperatures producing nitrogen oxides (NO_x). Their reaction process is shown in Fig. 3.

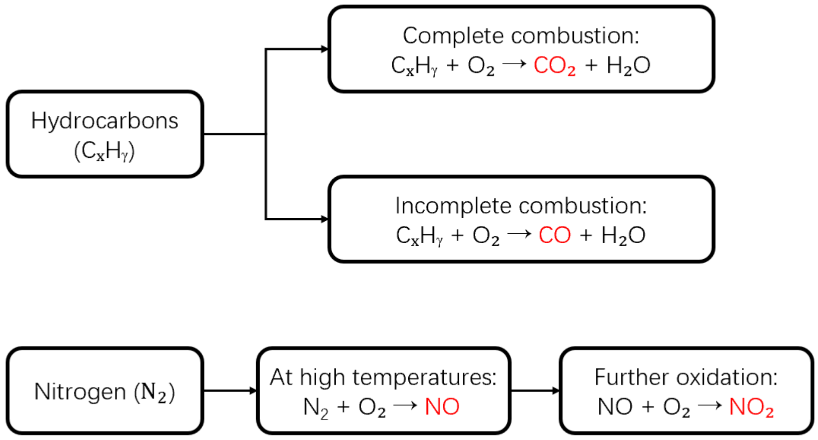

Fig. 3 The generation principle of CO_x and NO_x pollution in jet engines.

In the case of complete combustion, fuel combustion generates traditional aviation fuel to produce CO_2. As a greenhouse gas, it can strongly absorb long wave radiation from the ground, hinder the dissipation of heat into space, and form the "greenhouse effect". This will lead to an increase in global average temperature, triggering a series of environmental problems such as glacier melting, rising sea levels, and frequent extreme weather events. Under incomplete combustion, traditional aviation fuel can even produce carbon monoxide (CO), a toxic gas that causes significant harm to the human body. Meanwhile, the NOx generated in the combustion chamber can also cause environmental damage. After NOx is emitted into the atmosphere, it reacts with water, oxygen, and other substances to produce nitric acid (HNO_3) and nitrous acid (HNO_2). These acidic substances fall to the ground with the precipitation, forming acid rain, acidifying soil, corroding buildings, and damaging the ecological environment. NO_2 is a greenhouse gas that can absorb long wave radiation from the ground, enhance the greenhouse effect, and indirectly cause global warming. Moreover, the diffusion of NOx emitted from jet engines at high altitudes can also lead to the destruction of the ozone layer, further exacerbating environmental problems.

It can be seen that whether it is carbon oxides or nitrogen oxides, their emissions cause great damage to the environment. However, research has shown that under current technological conditions, the impact of aviation on the climate faces a trade-off between carbon emissions and nitrogen oxide emissions [10, 11]. This is because the emission reduction measures taken by the industry, such as advanced engine technology, sustainable aviation fuel use, route optimization, etc., often exacerbate the impact of another type of factor when reducing the impact of one type of factor. If low NO_x emission engine technology is adopted, it can reduce fuel efficiency by controlling the possibility of increasing CO_2 emissions, resulting in a trade-off between CO_2 and NO_x emissions.

2.1.1 The advantages of hydrogen energy

To address the problems above, hydrogen energy holds great potential as a clean energy source. Compared to traditional fossil fuels, liquid hydrogen combustion in the combustion chamber only produces harmless H_2O without carbon emissions as shown in the following chemical formula.

$$H_2 + O_2 \rightarrow H_2 \quad (1)$$

In the current context of global warming, this is undoubtedly very important. Meanwhile, due to its combustion without the generation of carbon oxides, hydrogen energy shows an important direction in breaking through the trade-off between carbon emissions and nitrogen oxide emissions. In theory, traditional fossil fuels for aviation should be replaced by clean fuels.

2.1.2 The problems faced by hydrogen fuel

There are many obstacles to the application of hydrogen energy in jet engines. Firstly, the combustion of hydrogen is difficult to control. The combustion speed of hydrogen is extremely high, with a maximum combustion speed of up to 280 cm/s, much higher than fuels such as ammonia (about 6-8 cm/s) and methane (about 40 cm/s) [12]. This high combustion rate causes hydrogen to react extremely violently during the combustion process, making it difficult to control and increasing the instability of the

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combustion process. Meanwhile, hydrogen has a wide flammable range, which means that combustion can occur within a wide range of fuel to air mixing ratios, further increasing the risk of explosion and posing challenges for its storage, transportation, and use. To solve this problem, Li proposed a solution in their research to control the combustion rate of hydrogen ammonia mixed fuel for more stable combustion [12]. The introduction of ammonia undoubtedly increases the emission of nitrogen oxides. However, in this method, the fuel NO_x generated by ammonia combustion dominates, while the thermal NO_x generated at high temperatures can be ignored, providing direction for controlling emissions. Garai demonstrated the possibility of this control by studying the nitrogen oxide emissions of hydrogen ammonia fuel with different equivalence ratios at different residence times [13].

Even pure hydrogen fuel cannot solve the problem of NO_x emissions. According to NASA's research, thermal NO_x increases exponentially with increasing fuel temperature [14]. The combustion temperature of hydrogen fuel is about 2254 ℃, which is higher than that of traditional aviation fuel Jet-A. The use of hydrogen fuel can lead to an increase in thermal NO_x emissions. For this issue, Skottene's research has shown us some possible directions. The generation of thermal NOx can be achieved by controlling the flame temperature, adjusting the combustion equivalence ratio, controlling the pressure, and optimizing the reaction mechanism [15]. However, this study only demonstrated the theoretical feasibility of these methods. If it is to be applied in practice, more research support is needed.

The current mainstream navigation still uses traditional navigation fuels. This is not only due to the lack of breakthrough progress in the two major issues mentioned above, but also from a broader perspective, the current hydrogen energy is not as environmentally friendly as expected. Altuntas' research can explain the reasons. It quantifies the environmental damage caused by the use of Jet-A (traditional aviation fuel) and liquid hydrogen in GE-J85 engines to compare which fuel is more environmentally friendly. In order to achieve quantification, the author defined two new indicators, Specific Fuel Consumption Impact (SFCI) and Thrust Environmental Impact (TEI). SFCI is given by the following formula, which measures the full lifecycle environmental impact of unit fuel consumption and is used to quantify the environmental efficiency of different fuels.

$$SFCI = \frac{b_f}{\dot{m}_f}(mPts / kg) \quad (2)$$

where b_f is the weighted environmental impact value of the entire lifecycle of fuel calculated using SimaPro software, with units of mPts, and $\dot{m}_f$ is fuel flow. TEI is the full lifecycle environmental impact generated by a unit of thrust, used to evaluate the balance between engine thrust and environmental performance.

$$TEI = \frac{b_f}{T}(mPts / N) \quad (3)$$

where b_f is the same as above, and T is the engine thrust. Through calculations, he concluded that Jet-A has a higher SFCI in the ecosystem and human health categories, while liquid hydrogen has a higher SFCI in the resource consumption category. This is because the combustion of Jet-A directly generates pollution emissions, while liquid hydrogen consumes more in production and storage. The calculation of TEI shows that the thrust environmental impact of Jet-A (33.52 mPts/N) is much higher than that of liquid hydrogen (13.78 mPts/N) [16]. SFCI demonstrates the advantages of hydrogen energy in pollution emissions and the disadvantages in resource consumption. The consumption of resources is greatly linked to the cost of use, which is currently one of the main obstacles to the promotion of clean energy jet engines. However, the comparison of TEI demonstrates the absolute advantage of clean energy in terms of thrust and environmental efficiency, indicating the great potential of clean energy.

3. Conclusion

Jet engines play an important role as the cornerstone of modern aviation. Its development continuously drives social, military, and economic progress. It iteratively updates time and time again, pursuing faster speed, higher altitude, and higher efficiency. There are two major directions with great potential in the research of jet engines. On the one hand, 3D printing technology provides a new way for manufacturing processes to make engine components lighter and more complex, while reducing material waste and production time. However, challenges still exist in terms of consistency in processing and material properties. On the other hand, clean energy, especially hydrogen, provides a promising path for sustainable aviation by replacing traditional fossil fuels. However, it still faces obstacles in terms of stability, nitrogen oxide emission control, cost, and resource consumption.

With the development of the aviation industry, the future of jet engines lies in combining advanced manufacturing with environmentally friendly propulsion systems. By addressing these challenges, the next generation of jet engines will not only improve performance, but also contribute to a more sustainable and efficient aviation era.

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