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The quest to mitigation of aviation emissions and pollutions

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Abstract. With the aviation industry's continuous development and commercial air travel's growing popularity, the emissions and pollution resulting from air transportation have experienced a rapid surge. In recent years, as environmental awareness has increased and there has been a growing reflection on the pollution caused by technology, the significance of aviation emissions has been increasingly acknowledged. This article aims to summarize achievements and challenges concerning the current state of aviation emissions and the technologies employed for their reduction. It begins by outlining the present state of aviation emissions, followed by an analysis of common pollutants emitted by the aviation sector, such as NO_x, CO, and HC, as well as the mechanisms underlying greenhouse gas emissions and their associated hazards. Furthermore, the article explores several prevalent emission reduction strategies, including applying biofuels, improving combustion chambers, and optimizing flight procedures. Finally, the article provides an outlook on potential future directions for aviation emission reduction technologies.

Keywords: aviation emissions, pollution, clean fuel, engine design.

1. Introduction

With the development of the economy and advancements in the aviation industry, civil aviation has experienced significant expansion. However, the associated issue of aviation pollution has become increasingly impossible to ignore. The emissions from commercial aircraft are becoming a more significant component of the overall transportation emissions inventory. This increase happens when other major sources, both mobile and stationary, significantly reduce their emissions, thereby emphasizing the growth in aircraft emissions. The Federal Aviation Administration (FAA) recently reported that commercial air carrier flights are projected to increase by 9% from 2002 to 2010 and 34% from 2002 to 2020 [1]. To effectively control exhaust emissions from aircraft engines, the United States Environmental Protection Agency (EPA) introduced pollutant emission standards in 1973, and the International Civil Aviation Organization (ICAO) issued aircraft engine pollutant emission standards in 1977.

Emissions from aircraft engines generally include smoke and gaseous pollutants. The gaseous pollutants include HC, NO_x, SO_2, CO, CO_2 and PM2.5 [2]. The mechanisms by which these different pollutants are generated vary, as they originate from different sources and reaction pathways in aviation emissions. These pollutants are also emitted at different locations. Some pollutants are directly released into the atmosphere from the aircraft's exhaust outlets, while others may undergo atmospheric chemical reactions at high altitudes before settling down to the ground. Additionally, pollutants can accumulate in the lower layers of the atmosphere near airports, leading to regional air quality issues [3]. The impacts on human health and the environment vary depending on the nature and concentration of the pollutants. Therefore, it is necessary to conduct detailed analyses of the mechanisms by which these different pollutants are generated and implement appropriate emission reduction measures for each pollutant.

Currently, there are several methods available to mitigate aviation emissions. These include adopting more advanced aircraft models to improve efficiency and reduce fuel consumption, utilizing low-emission combustion chambers in aircraft engines, and using cleaner fuels. These methods employ different principles to reduce emissions. However, there is still a need for more effective measures to further reduce.

The article will introduce and analyze the current state of aviation pollution emissions, examine the mechanisms behind generating aviation pollutants, discuss the mainstream methods for emission reduction currently in use, and finally, provide predictions on the future development trends of emission reduction in civil aviation.

2. Key characteristics of aviation emissions

2.1. Composition of aviation emission pollutants

According to the ICAO's "Present And Future Aircraft Noise And Emissions Trends," aviation emissions possess key characteristics. Firstly, the composition ratios of emission pollutants may vary depending on the structure of aircraft engines, but the basic components remain consistent. Jet engines primarily emit exhaust pollutants such as HC, NO_x, and CO [4]. Additionally, greenhouse gas emissions, especially CO_2, should not be disregarded in addressing global warming issues, although not directly harmful to the environment and human health.

2.2. Mechanisms of aviation emission generation

2.2.1. The mechanism of CO formation. CO is a byproduct of incomplete combustion. During combustion, it is primarily formed in the main burning area of the combustion chamber and then converted into CO_2 in the middle region where there is sufficient oxygen. However, in fuel-rich areas with limited oxygen, CO is produced instead of CO_2. Additionally, in high-temperature zones with chemically appropriate or slightly fuel-lean conditions, a significant amount of CO is generated due to the thermal decomposition of CO_2. But this CO is efficiently burned in the downstream oxygen-rich zone, such as in the cooler, rendering its production less meaningful. Therefore, the mechanism of CO production has an absolute advantage during slow-speed and low-thrust conditions [5].

2.2.2. The mechanism of HC formation. Unburned hydrocarbons are typical products of fuel deficiency and incomplete combustion. They consist of low-molecular species, such as methane or ethyne, resulting from the fuel's thermal degradation reactions of hydrocarbons. They are emitted when the temperature and pressure at the inlet of the combustion chamber are low. Some hydrocarbons in the fuel only vaporize and do not have enough time to participate in the combustion reaction before passing through the combustion chamber. As a result, unburned hydrocarbons appear at the exit of the combustion chamber in the form of oil droplets or oil vapor [6].

2.2.3. The mechanism of NO_x formation. The mechanism of NO_x formation is quite complex. Although they are byproducts of combustion and do not directly participate in the actual combustion process, NO_x cannot be ignored due to their *toxicity* and potential impact on the stratospheric ozone layer. Extensive research has been conducted on NO_x. The main mechanisms of nitrogen oxide formation include the following two aspects: i). Thermal NO_x: When the combustion temperature exceeds 1500 ℃, nitrogen and oxygen in the air directly react to produce nitrogen oxides, mainly NO and NO_2. This is the primary pathway for NO_x formation in high-temperature combustion processes [7]. In the actual combustion

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process, due to the reaction between nitrogen and oxygen in the high-temperature environment, the resulting NO is referred to as thermal NO [8]. When the fuel does not contain nitrogen, the NO produced in the combustion environment through mechanisms other than thermal NO is called prompt NO. In the case of fuel containing organic nitrogen, the NO formed during combustion is referred to as fuel NO. Additionally, NO can be transformed from previously generated N_2O under high-pressure conditions. At the exit of the engine's combustion chamber, a considerable portion of the NO formed by the mentioned mechanisms is oxidized into NO_2. ii). Fuel nitrogen conversion: Some fossil fuels, like coal and oil, contain organic nitrogen compounds. During combustion, these compounds undergo complex reactions that result in the formation of NO_x. The exact mechanisms involved are still under investigation and may vary depending on the specific fuel composition.

2.3. Hazards posed by aviation emissions and greenhouse gas

NO_x emissions from aircraft engines contribute to air pollution and have detrimental effects on human health and the environment. They are key contributors to the formation of smog and acid rain. When inhaled, NO_x can cause respiratory problems, cardiovascular diseases, and other health issues. Additionally, it plays a significant role in the depletion of the ozone layer, contributing to the problem of stratospheric ozone depletion.

CO is a toxic gas emitted by aircraft engines. It is harmful when inhaled, as it reduces the oxygen-carrying capacity of the blood, leading to oxygen deprivation and adverse health effects. Exposure to high levels of CO can cause headaches, dizziness, impaired vision, and even death in severe cases. CO_2 emissions from aircraft engines are a major contributor to greenhouse gas emissions. CO_2 is a primary driver of global climate change and contributes to the warming of the Earth's atmosphere. The accumulation of CO_2 in the atmosphere leads to long-term environmental consequences such as rising temperatures, melting ice caps, sea-level rise, and disruptions to ecosystems [9].

3. Measures and principles for controlling aviation emissions

3.1. The research and application of clean fuels

Compared to the CO_2 emissions from automobile exhaust, the greenhouse gases emitted by conventional aviation kerosene burned in aircraft engines are mostly released into the atmosphere, contributing significantly to the greenhouse effect and posing greater harm than other industries, even though the emissions account for only 2% to 3% of the total human emissions [10]. Consequently, countries worldwide are actively seeking alternative aviation kerosene with lower CO_2 emissions to mitigate the exacerbation of the greenhouse effect.

Aviation biofuel has been recognized as a solution to this issue. Several foreign airlines have already conducted test flights using aviation biofuels. Since its research and development in the 1970s, bioenergy has made significant progress and found wide applications in various fields. Among the numerous bioenergy products, bioethanol has been the most mature and widely used biofuel to date [11]. Bioethanol, a first-generation biofuel technology developed using grains and edible oils as raw materials, has evolved into third-generation biofuel technology. Raw materials gradually shift from human food to non-food sources such as straw, animal and plant oils, and marine algae. These non-food materials are ideal choices for biofuel production. Biofuels have gained popularity due to their wide range of raw material sources, environmental friendliness, and alignment with the principles of a circular economy. They play a crucial role in promoting economic development and improving the environment.

The International Air Transport Association (IATA) has made commitments to improve fuel efficiency by an average of 1.5% per year from 2009 to 2020, gradually reduce the growth rate of carbon emissions, achieve zero emissions growth by 2020, and reduce carbon emissions to half of the 2005 levels by 2050. Additionally, by 2020, 2030, and 2040, the proportion of aviation biofuels in aviation fuel should reach 15%, 30%, and 50%, respectively [12]. It is emphasized that using aviation biofuels is a measure to achieve these goals because the greenhouse gas emissions in the lifecycle of aviation biofuels are more than 50% lower than those of traditional fossil fuels [13].

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3.2. The improvement of engine design

Commercial aircraft engine combustion chamber designers face numerous conflicting design requirements and choices. They must ensure maximum thrust during take-off and optimal fuel efficiency during cruising while also considering factors such as not stalling at high altitudes and in heavy rain. Considering environmental regulations, engine certification requirements must also be met [14]. One of the key issues to consider when designing commercial aircraft engines is how emissions are generated and controlled. The emissions that need to be controlled during engine certification processes primarily include NO_x, HC, CO, and particulate matter.

The key to aircraft engine emissions reduction lies in the combustion chamber. The fuel needs to undergo thorough combustion within the combustion chamber to minimize the emissions of CO and HC. Additionally, to mitigate and reduce the production of NO_x, it is necessary to lower the temperature of high-temperature air within the combustion chamber during high-speed engine operation. Major aerospace engine manufacturers currently employ different combustion chamber technologies for large advanced commercial aircraft engines.

The commonly used low-emission combustion chamber technologies in aviation engines include lean premixed pre-vaporized (LPP) combustion, lean direct injection (LDM) combustion, and rich burn-quick quench-lean burn (RQL) combustion.

These technologies have advantages and are chosen based on the specific engine types and application areas. LPP combustion is one of the most widely used technologies due to its ability to achieve lower emissions and higher combustion efficiency in large commercial aviation engines. However, LDM combustion and RQL combustion technologies are also employed in specific engine types and for specific emission requirements.

3.3. Improvement in flight routes, take-off, and landing procedures

In addition to improvements in the aircraft themselves, there are other methods to reduce carbon emissions in aviation by optimizing the aircraft's flight processes, particularly during the take-off and landing phases. Aircraft emissions can be categorized as high-altitude emissions during the cruise phase and near-ground emissions during the landing and take-off (LTO) cycle. While most emissions in commercial aviation occur during high-altitude cruises, the LTO cycle significantly contributes to near-ground pollution [15]. Developing emission inventories specific to airports and understanding the emission mechanisms and characteristics are crucial for setting emission standards and implementing reduction strategies, effectively helping to minimize emissions during the LTO cycle.

Simulating airport emissions, creating aircraft emission inventories, and understanding airport emission mechanisms provide the basis for developing relevant emission standards and mitigation strategies, contributing to reducing emissions during the LTO cycle. Furthermore, optimization measures can be implemented to reduce pollution emissions. Some strategies include: i) Quick take-off and climb: Implementing efficient take-off and climb procedures can reduce engine operation time at ground level and low altitudes, thereby lowering pollution emissions. ii) Continuous climb: Minimizing speed variations and maintaining a stable climb trajectory during the ascent phase helps reduce pollution emissions. iii) Minimize emergency braking: Reducing the use of emergency braking during the landing process can decrease engine operation time and fuel consumption, leading to lower pollution emissions. iv) Extended high-altitude cruising: Cruising at higher altitudes is associated with improved fuel efficiency and reduced pollution emissions. Extending the duration of high-altitude cruising can decrease overall emissions.

4. Future development direction

4.1. Development of new types of fuel

Although biofuels have demonstrated promising prospects in practical test flights, the formation of an industry chain inevitably encounters various bottleneck issues. These include the acquisition of raw materials. Whether using edible or non-edible biomass as feedstocks for biofuels, the safe, efficient, and economically viable acquisition of upstream raw materials is worth contemplating. Similarly, although the use of biofuels does not require engine modification, further design optimization is needed for storage and transportation facilities and equipment for fuel tanks [16]. Long-term storage should aim to minimize issues such as corrosion and microbial proliferation to ensure the cleanliness of aviation fuel.

While addressing the current challenges of biofuels, the development of other types of new energy sources is also crucial, such as hydrogen energy. Hydrogen fuel has an energy density of approximately 120 MJ/kg, three times that of standard aviation fuels. Hydrogen energy in the aviation industry achieves zero CO_2 emissions and effectively reduces the emissions of other pollutants, offering significant advantages [17]. However, the widespread application of hydrogen energy also faces several major challenges, including overcoming key technological bottlenecks in hydrogen combustion, hydrogen fuel, and storage.

4.2. Further improvement of engine structure

Due to continuous improvement and development, the aerodynamic atomization nozzle has become the main approach for achieving lean-burn low-emission combustion. One of the development trends in modern aviation gas turbine engines is the adoption of single annular short combustion chambers for lean-burn combustion, aiming to simplify the head structure of the combustion chamber [18].

Multipoint Lean Direct Injection (MP-LDI) combustion technology is another advanced method currently being researched. MP-LDI offers several advantages: stable and uniform combustion, a short and small combustion zone, allowing for a compact combustion chamber design, direct fuel injection into the flame zone without auto-ignition or flashback issues, no dilution holes on the flame tube, with air entering the combustion chamber either from the head end or as cooling air, rapid and uniform fuel-air mixing, enabling lower combustion temperatures, thorough combustion, and low pollutant emissions, and ease of adjustment through multipoint injection to meet various operating conditions [19]. Although MP-LDI technology has not been directly applied yet, its numerous advantages make it an important direction for developing low-emission combustion technology in engines.

5. Conclusions

With the continuous development of the aviation industry and the increasing emphasis on environmental protection, the standards for aviation emissions have become increasingly stringent. Currently, there is a thorough understanding of the mechanisms behind aviation emissions pollutants, and corresponding emission reduction targets have been established. Tremendous promising technological advancements have been made in areas such as aviation biofuels and advanced low-emission combustion chamber technologies, showcasing significant theoretical advantages.

However, achieving truly environmentally friendly aviation emissions still presents certain challenges. Despite the theoretical advantages, these new technologies face practical issues that need to be addressed. For example, large-scale production and supply of new fuels still face challenges related to raw material sourcing and production costs. Similarly, the actual performance and reliability of novel low-emission combustion chamber technologies require further validation. Therefore, further research and innovation are necessary to overcome these challenges and drive the aviation industry in a more environmentally friendly direction. Through continuous technological advancements and collaborative efforts, we can explore more feasible and sustainable solutions, leading to a sustained reduction in aviation emissions and higher levels of environmental protection.

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