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Experimental study of the gaseous and particulate matter emissions from a gas turbine combustor burning butyl butyrate and ethanol blends

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HIGHLIGHTS

- Study on the emissions of butyl butyrate based biofuels in a GT combustor.
- PM number emissions at cruising and idling states were studied.
- Comprehensive emissions and ion analysis of PM were conducted.

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ABSTRACT

This paper reports the gaseous pollutants and Particulate Matter (PM) emissions of a gas turbine combustor burning butyl butyrate and ethanol blends. The gas turbine has been tested under two operational conditions to represent the cruising (condition 1) and idling (condition 2) conditions of aero engines. Aviation kerosene RP-3 and four different biofuels using butyl butyrate (BB) and ethanol blends were tested and compared to evaluate the impact of fuel composition on CO, NO_x, unburnt hydrocarbon (UHC) and PM emissions under selected two operational conditions. The PM number (PN) concentration and size distributions were measured by a scanning mobility particle sizer (SMPS). The compositions of filter borne PM were analysed by ion chromatograph technique. The concentrations of CO, NO_x and UHC were detected and analysed by a gas analyser. Results indicated that under idling and cruising conditions the CO emissions from butyl butyrate and ethanol blends were higher than that of RP-3 due to the relatively lower combustion temperature of the biofuels compared with that of RP-3. Results of the NO_x emission comparison indicated the biofuels produced less NO_x than RP-3 and the increase of ethanol content in the biofuels could reduce the NO_x and UHC emissions. The particles smaller than 20 nm played a dominant role in PN emissions at condition 1 with the range from $2 \times 10^6/cm^3$ to $4 \times 10^7/cm^3$. There was a peak value of particle number concentration with the particle size ranging from about 25 nm and 40 nm. The PN emission index at condition 1 was higher than that at condition 2 for the biofuels, whilst the trend was opposite to that of RP-3. The ions analysis indicated Ca^{2+} and SO_4^{2-} were the two dominant ions in the PM emissions of biofuels.

1. Introduction

The gaseous pollutants and particulate matters (PM) from burning fossil fuels have attracted ever increasing research attentions on the development of new fuel formulations [1–3], advanced engine design and calibration methods [4–6], and effective after treatment technologies [7,8]. Increasingly strict emission regulations have been proposed and adopted including Euro V and VI requiring a non-volatile particle number (PN) emission limit of 6×10^{11} particles/km to complement the mass-based limit for PM emissions from light-duty diesel vehicles [9,10]. Similar to vehicular emission regulations, the Committee on Aviation Environmental Protection (CAEP), a technical committee of the International Civil Aviation Organization (ICAO) Council has recently proposed amendments of number-based particle limits regarding the non-volatile Particulate Matter Standard [11]. The studies on aviation emission characteristics and their mitigation technologies are much limited compared with vehicular emissions. It is conceivable that the emissions from aviation gas turbine engines will

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become a hot topic in the light of the upcoming aviation emission regulations.

The main gaseous pollutants from aero-engines are carbon monoxide (CO), nitrogen oxide (NO_x) and unburnt hydrocarbon [12,13]. Fu et al. and Kyprianidis et al. [14,15] employed lean-burn combustors in aero-engines and obtained significant NO_x reduction. Zhang et al. [16] introduced a novel double-vortex combustor for gas turbine engines burning kerosene and lower emissions of CO, NO_x and UHC especially at high inlet temperature have been achieved. Numerical study was conducted by Hamed et al. [17] in order to figure out the method to reduce NO_x emission of aero-engine combustor. Results indicated that the increase of the axial distance of the stabilizer and the number of holes could significantly hinder NO_x generation in the combustor [17]. Xing et al. [18] also summarised researches on reducing NO_x with increasing thermal efficiency via flameless combustion technologies. However, these methods of reducing gaseous emissions depend on retrofitting current aero-engines, which increase the costs of commercial application.

Another major pollution from aero-engines is the PM emissions including soot and volatile particles, which now contribute about 4.9% of total anthropogenic PM emissions, which have drawn increasing attentions in recent years [19,20]. Ultrafine particles (smaller than 100 nm) are harmful to human health because they can penetrate deeply in the lung and alveoli [21,22]. The size distributions and chemical compositions of PM emissions from gas turbines or aero-engines are the main research topics of scientists at present. The formation of ultrafine particles is highly correlative with fuel properties and engine operational conditions [13,20,23]. Lobo et al. [20] studied PM emissions of a JT8D-219 engine burning kerosene Jet A at various conditions. Results demonstrated that the mean diameter increased with increasing engine thrust and the PN emissions experienced a U shaped line when the engine power raised from about 4% to full level. Huang et al. [23] tested the aviation kerosene JP-8 and several renewable fuels in a jet engine. Higher PN concentrations were found at 85–100% power level than that of 4–7% power due to a higher fuel air ratio and the presence of aromatics content [23]. Timko et al. [24,25] also demonstrated that PM emitted from aero-engines during take-off and landing played a dominant role in the ultrafine particle emissions (4–100 nm). And the majority of total PN concentrations was the nucleation mode particles (5–50 nm) [24,25]. However, in terms of engine operational parameters, previous researches have focused more on heavily sooting conditions (such as take-off, climb) and conditions that primarily affect the airport air quality (such as landing, taxiing). Limited researches have been conducted on the PN emissions under cruising and ground idling conditions, which represent the two longest durations of engine operation time.

The ion analysis can identify the water-soluble inorganic component such as metal ion, sulphate, nitrate and ammonium, which are the chemical source of toxicity in PM [26,27]. Popovicheva et al. [28] tested kerosene with the sulphur content of 0.11% in an aero-engine and reported that sulphates (SO_4^{2-}) and organic ions dominated the water-soluble fractions of soot emissions. Kinsey et al. and Mironova et al. [29,30] demonstrated that $SO4^2$ was the largest single component ion in particle emissions from aero-engines. Cl^-, NO^{3-}, NH_4^+, K^+, and Na^+ as well as other metal elements were also found and their sources were considered the compositions of kerosene, engine lubrication oils and abrasion from engine wearing components [31,32].

Biofuels are recognised as alternative energy resources for aero application, which could effectively mitigate the pollutant emissions from gas turbines or aero-engines. Chiaramonti et al. [33] tested diesel fuel, vegetable oil and biodiesel in a modified micro gas turbine and found that the combustion of vegetable oil generated comparable emissions with diesel fuel [33]. Habib et al. [34] tested four types of biofuels and their blends with Jet A in a gas turbine engine and demonstrated that biofuels decreased thrust-specific fuel consumption, CO and NO_x emissions. Mendez et al. [13] selected butanol as a typical biofuel and observed less NO_x and CO emissions. Seljak et al. [35] investigated the emissions of liquefied lignocellulosic biofuels in a gas turbine and found out the NO_x and PMs are both reduced but the CO and UHC are increased. Nevertheless, a number of biofuels have shortcomings such as high viscosity, high surface tension and poor thermal stability, which may exert a negative impact on atomisation and combustion [36]. Jenkins et al. [37] and Chuck et al. [38] examined certain properties of several single-composition biofuels and compared with fossil fuel counterparts. Results suggested that butyl butyrate as a qualified biofuel surrogate, has similar viscosity, flash point, distillation profile and low temperature behaviour to kerosene (Jet A) [37,38]. Thus the butyl butyrate has the potential to be used in a blend and fully compatible with aviation kerosene. However, experimental work on the combustion performance in gas turbine burning butyl butyrate-based biofuels has been rarely found in the literature.

In summary, gaseous and particulate matter (PM) emissions from gas turbine engines, which are highly correlative with the fuel compositions and operating conditions of engines, are drawing concerns due to the adverse effects on health and environment. However, most research work has not mentioned the information on PM number (PN) concentration at cruising state and idling state of aero-derivative gas turbine engines. In addition, biofuels have the advantage in reducing most pollutant emissions, yet most of them have poor viscosity, distillation profile and low temperature behaviour, which have negative impacts on atomization and combustion. Given the above considerations, a series of experiments on a gas turbine combustor were conducted to analyse the characteristics of CO, NO_x, unburnt hydrocarbon (UHC) and PM emissions of biofuels consisting of ethanol and butyl butyrate, which has closed thermal properties to aviation kerosene. Two conditions of the combustor were operated to represent the cruising state and idling state of a gas turbine engine respectively.

2. Description of the test rig and methodologies

2.1. Test rig and measurement instruments

The gas turbine combustor consists of a high-pressure air source, a low-pressure air source, a combustion chamber, a fuel delivery system, and a cooling system. The schematic of the test combustor rig is show in Fig. 1. The pressure of air source is from 0 to 7 MPa and the air temperature can be heated up to 600 K. The fuel supply system with the injection pressure at 2 MPa consists of a main feed line and a secondary feed line respectively for the primary combustion and pre-combustion. The K-type thermocouples are employed to measure temperatures and pressure transmitters are used to measure the air pressures. The measured temperature and pressure conditions are used to calculate the air flow rate, which has the relative errors within 1.5%. Two Coriolis mass flow meters are used in the fuel supply lines to measure the fuel mass flow rate with the relative error of 1%.

The combustor in the combustion chamber is fabricated based on an aero-engine, whose section view is shown in Fig. 2. The case of the combustion chamber is 172 mm high and 325 mm long with the thickness and width of the case wall at 11 mm and 145 mm, respectively.

A sampling tube inserted inside the exhaust pipe of the combustion chamber was connected with an auto-controlled dilution system, which provides a precise control over the dilution condition (e.g. dilution ratio, dilution temperature, and residence time).