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Sensitivity analysis of fuel types and operational parameters on the particulate matter emissions from an aviation piston engine burning heavy fuels

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HIGHLIGHTS

- PM emissions from an aviation compression ignition engine were reported.
- Effects of fuel type and engine parameters on PM emissions were quantified.
- Accumulation mode PM obtained from SMPS fit AVL Opacimeter data.
- RP3 and FT fuels exhibited lower PM emissions compared with diesel.

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ABSTRACT

Currently, general aviation aircrafts have growing demand for internal combustion engines burning heavy fuels (i.e. diesel or kerosene) due to the concerns on the safety, costs and availability of aviation gasoline (AVGAS). The application of heavy fuels requires the change of combustion mode from premixed mode to diffusion mode, which will inevitably increase the particulate matter (PM) emissions as incomplete combustion products. In this work, the size-resolved number concentrations of the PM emissions emitted from an internal compression ignition engine burning diesel, RP3 and Fischer-Tropsch (FT) kerosene were studied by a Scanning Mobility Particle Sizer Spectrometer (SMPS). An opacimeter was utilized to measure the opacity of the soot emissions (linearly related to the soot mass), which was in consistent with the SMPS data. Results demonstrated that the FT fuel produced the lowest PM emissions due to absence of sulfur and aromatic contents. Diesel turned out to have the greatest 'sooting' tendency and produced more accumulation mode PM in number than FT fuel by a factor of four, and more PM in mass by approximately three times. Moreover, the effects of fuel types and engine operational parameters were quantified in a systematic manner by adopting the Response Surface Method (RSM) in Design of Experiments (DoE). According to the ANOVA (Analysis of Variance), the DoE derived model was statistically significant and demonstrated that the engine load was the dominant factor for soot generation, followed by injection pressure and fuel types. Relevant combustion parameters and their link with PM emissions were further discussed, illustrating that atomization process had great impact on the ignition delay and thus affected soot generation.

1. Introduction

Aviation has grown faster than any other transportation modes worldwide [1]. Sooting in aircraft engines due to incomplete combustion indicates the decrease of combustion efficiency, and could lead to hardware fouling [2,3]. Ultrafine particles with the size below one micron meter are typical of aviation emissions, and impose high risk on human health since they can penetrate deeper into the lungs, bloodstream and impair cardiovascular and nervous system [4,5]. In terms of military aircrafts, the soot emissions

Abbreviations: AIR, Aerospace Information Repot; ANOVA, Analysis of Variance; AVGAS, aviation gasoline; CA, Crank Angle; CMD, Count Medium Diameter; CN, cetane number; CPC, Condensation Particle Counter; DMA, Differential Mobility Analyzer; DoE, Design of Expert; EC, Electrostatic Classifier; ECU, electronic control unit; EPA, Environmental Protection Agency; FAA, Federal Aviation Administration; FCCD, face-centered composite design; FT, Fischer-Tropsch; HFE, Heavy Fueled Engines; HRR, Heat Release Rate; ICAO, International Civil Aviation Organization; IMEP, indicated mean effective pressure; ISFC, indicated specific fuel consumption; ITE, Indicated thermal efficiency; PM, particulate matter; RSM, Response Surface Method; SMD, sauter mean diameter; SMPS, Scanning Mobility Particle Sizer Spectrometer; SN, smoke number.

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increase infrared exhaust plume visibility, which severely affect and may ruin the training and combat missions [6].

Environmental Protection Agency (EPA), together with the Federal Aviation Administration (FAA), set the first PM standards in 1971, which were updated in 1987, 1997, 2006, and again in 2013 [7]. EPA now focuses on the regulation of the aviation particulate matter emissions with the size less than 1 μm, since ultrafine particles are deemed readily inhalable and thus more harmful than coarse particles [8]. Increasingly strict regulations for mandating vehicular PM emissions make it important to investigate emission mitigation strategies [9] such as clean fuel formulation [10–13], engine calibration [14–16], and emission trap technologies [17,18]. Compared with vehicular PM emissions, the studies on aviation emissions are much scarcer, but it is conceivable that aviation emissions will become a hot issue in the light of the upcoming aviation emission regulations established by International Civil Aviation Organization (ICAO) [19,20]. The conventional smoke number (SN) metric does not address the current challenges to quantitatively measure the mass and number of PM emitted from aircraft engines. Therefore, Aerospace Information Repot (AIR) has been proposed as a primer by the pioneered PM research community to measure the aviation particles on mass and number basis, in order to meet the increasingly stringent regulations [21].

Heavy Fueled Engines (HFE), which have appealing characteristics, such as high economic feasibility, high torque and durability, are widely used in the military by using kerosene and diesel fuels [22–24]. This is in consistent with the 'One Fuel Forward' policy adopted by the US military [25,26], derived from the logic of saving the big logistical cost, but also simplifying the fuel and pipeline systems [27]. Kerosene contains more volatile compositions than diesel and is thus more beneficial for fuel atomization, combustion efficiency and PM emissions [28]. Moreover, the development of derived substitutes for diesel fuel and kerosene, such as Fischer-Tropsch (FT) kerosene fuels, provides more promising solutions, which could improve the engine operations and emission characteristics [29]. The 'iso-paraffinic kerosene' FT fuels firstly produced by Sasol in South Africa from coal, biomass, and natural gas, were allowed for aviation use in blends up to 50% by volume in Jet A-1 in 1999 [30]. Recently, the FY 11, F-15, F-22 aircrafts in the U.S. military have been scheduled to be certified on the FT blends in the forthcoming future, approved by ASTM D7566 specification [31]. Nowadays, FT fuels are becoming commercially feasible in larger quantities and have been adopted in piston engines for aviation power generation, ground transportation, and ship propulsion by the United States Department of Defense, as a means to relieve the dependence on petroleum - based fuels [32,33].

A number of researchers have been exploiting aviation piston engine fueled with diesel or kerosene for small aircrafts market [34–37]. The relevant researches focused more on blends with JP kerosene series, while the literature is scarce to date on the investigation of RP3 kerosene fuels, which are widely used in Asian countries but have discrepancy with JP fuels [5]. Moreover, little research is available that has investigated the feasibility and the performance of neat FT fuel in aviation piston engines. In this study, the neat RP3 and alternative FT jet fuels were used in an aviation piston engine, and the effects of the fuel types and engine operational parameters were systematically evaluated by adopting Design of Expert (DoE), which has been widely used in various fields [38–41]. DoE is a well-established method on the basis of mathematical statistics, for analyzing experimental data and exploring the cause-effect relationships. The Response Surface Method (RSM) in DoE utilizes face-centered composite design (FCCD) to evaluate how the variables affect the response [42]. The objective of this study is to provide a comprehensive analysis of the effects of fuel types, engine operational parameters and their interactions on the PM emissions. The factors influencing the accumulation mode particles have been quantitatively determined via the predictive model proposed by adopting the RSM in DoE.

2. Experimental setup

2.1. Engine test system

The tests were operated utilizing a single-cylinder compression ignition engine modified from a four-cylinder common-rail diesel engine (specification was shown in Table S1). This engine was controlled by using the electronic control unit (ECU) via a program module. The injection parameters including the number of injections, injection pressure, injection quantity and injection timing could be adjusted manually by a PC terminator. The schematic of the engine system was illustrated in Fig. 1. In-cylinder pressure was recorded with a resolution of 0.2 Crank Angle (CA) by using AVL GH14P pressure sensors. The relevant combustion pressure analysis was based on the ensemble average of in-cylinder pressures of 250 consecutive cycles. The Heat Release Rate (HRR) was obtained according to the following equation:

$$dQ/d\theta = \frac{\gamma}{\gamma - 1} * p * dV/d\theta + \frac{1}{\gamma - 1} * V * dp/d\theta \quad (1)$$

where γ is the specific heat ratio; V is the instantaneous cylinder volume; p is the in-cylinder pressure. CA 10 was defined as the crank angles where 10% fuel quantity was used, while CA 90 were defined as the crank angles at which 90% fuel quantity was used. Ignition delay is defined as the interval of the crank angle between SOI (start of main injection) and CA 10, while the combustion duration is defined as the interval between CA 10 and CA 90. The Indicated Thermal Efficiency (ITE) was obtained based on the measured fuel flow quantity and the indicated work:

$$\eta_i = W_i/(m_f \times Hu_f) \quad (2)$$

where Wi is the indicated work; m_f is the fuel consumed per cycle; Hu_f is the fuel lower heating value.

2.2. Operating conditions and emission measurements

Three fuels have been tested, namely, baseline diesel, RP3 (kerosene) and FT (kerosene alternative fuel). The properties of the test fuels are listed in Table 1. The test engine was operated at four loads of 2, 4, 6, 8 bar indicated mean effective pressure (IMEP), with the engine speed maintained at 1600 rpm. The ratio between the main injection quantity and the pilot injection quantity was kept constant at 9:1. The injection pressure was set at 40, 60, 80 MPa. The engine loads under different injection pressures were controlled by adjusting fuel injection quantity. The details of the engine operation conditions are provided in Table S2.

The number concentrations of PM emissions were measured using a TSI Scanning Mobility Particle Sizer Spectrometer (SMPS) system, which was comprised of Electrostatic Classifier (EC) 3080, Condensation Particle Counter (CPC) 3775, Differential Mobility Analyzer (DMA) 3080 and Neutralizer 3087. Prior to entering SMPS system, the exhaust sample was diluted at 100 ± 5: 1 via heating lines to avoid water condensation. The soot emissions were measured by AVL 439 Opacimeter, which was located at the same sampling point as the SMPS for PM level validation. The specific absorption of the PM is calculated through light attenuation caused by the exhaust particles trapped between a light source and a receiver, which is based on the Beer-Lambert law. The error analysis was performed based on root mean square function as shown in Table S3.