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Comparative study of combustion and emissions of kerosene (RP-3), kerosene-pentanol blends and diesel in a compression ignition engine

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HIGHLIGHTS

- The suitability of RP-3 and its pentanol blends for aviation application were studied.
- Combustion and emissions performance were investigated and compared.
- Fuel consumption of RP-3, its pentanol blends and diesel were evaluated.

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ABSTRACT

Aviation Piston Engines for small general aviation aircrafts are currently facing a transition from being powered by AVGAS (aviation gasoline) to being powered by heavy fuels (diesel or kerosene). The present study compared the combustion and emission characteristics of diesel, aviation kerosene rocket propellant 3 (RP-3) and RP-3-pentanol blends in a single cylinder compression ignition (CI) engine. Heat release rate, indicated thermal efficiency, ignition delay, combustion duration, and coefficient of variation (COV) of indicated mean effective pressure were experimentally determined to reflect the engine combustion performance. The results demonstrated the feasibility of RP-3 and its mild pentanol blend (20% by volume) in modern CI engines whilst further optimisation of the injection strategy is needed if a higher ratio of pentanol (40% by volume) is used. The discrepancy in terms of combustion and emissions between diesel, RP-3 and its pentanol blends are appreciable, especially for ignition delay, combustion duration and soot emissions. Compared with diesel, RP-3 improved the indicated thermal efficiency by 1.4–12.4%, but pentanol addition decreased that by 1–6.5%. RP-3 and its pentanol blends reduced the soot emissions by nearly an order of magnitude at high engine loads compared with diesel without evident impact on nitrogen oxide (NO_x) emissions. Meanwhile, Carbon monoxide (CO) and total hydrocarbon (THC) emissions of RP-3 and its pentanol blends experienced a significant increase at low loads, but CO showed a slight decrease at high loads.

1. Introduction

Civil and military aircrafts are normally powered by gas turbine engines burning kerosene, whilst a large number of general aviation aircrafts (such as agriculture aircrafts, corporate aircrafts, civil helicopters) and military small aircrafts (military UAVs, military helicopters) are powered by Aviation Piston Engines (APEs) [1,2]. Generally, there are two combustion modes for APEs: Spark-ignition (SI) and Compression-ignition (CI). APEs have mainly relied on gasoline for decades. However, for the sake of safety, simplicity of logistics, costs and availability of gasoline, Heavy Fuel Aviation Piston Engines (HF-APEs), which run on light diesel or ker-

Abbreviations: APEs, aviation piston engines; CA ATDC, crank angle after top dead centre; CA BTDC, crank angle before top dead centre; CI, compression ignition; COV, coefficient of variation; ECU, electronic control unit; HF-APEs, heavy fuel aviation piston engines; HRR, heat release rate; IMEP, indicated mean effective pressure; ISFC, indicated specific fuel consumption; ITE, indicated thermal efficiency; LHV, latent heat of vaporization; LSA, light sport aircraft; MPRR, maximum pressure rise rate; RP-3, rocket propellant 3; SI, spark-ignition; SOI, start of injection; THC, total hydrocarbon; UAV, unmanned aerial vehicle.

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osene with high flash point, are desirable to replace the aviation gasoline engines in various applications [3,4]. In this regards, the NATO and US Army also adopted the policy of a 'Single Fuel Forward' using aviation kerosene JP-8 [5,6]. The demand for HF-APEs in non-military applications (e.g., agriculture aircraft, outboards) is increasing as well [7]. Therefore, the trend to adopt heavy fuel for Aviation Piston Engines is prevailing now for both military requirements and civil applications in the field of general aviation.

More attentions have been focused on two-stroke SI HF-APEs for the last decades [7–13] because CI engines with lower power/weight ratios were more difficult than SI engines to meet the design requirements of Unmanned Aerial Vehicle (UAV) and Light Sport Aircraft (LSA) manufacturers [10]. Falkowski et al. examined the feasibility of JP-5 using a two-stroke SI direct injection engine, and reported that the performance characteristics were similar to that with gasoline in terms of torque and power output at low engine speeds and low engine loads [12]. High performance SI HF-APEs burning heavy fuels (i.e., kerosene and diesel) have been widely applied for the ground fleet and UAV in the military [2,13]. Duddy et al. compared gasoline and JP-8 in an SI engine with the Sonex Combustion System, and found that comparable power outputs were achieved [13].

A small number of researchers and manufacturers have exploited the application of CI HF-APEs recently with the development of advanced CI engines, and they claimed that aviation kerosene fuels (such as Jet-A, JP-5 and JP-8 from the U.S.) could be used to satisfy the requirements of general aviation with respect to combustion performance and emissions [2,13–18]. From the previous researches, it was found that the use of JP-8 without modification of diesel engines did not show any critical problems in the engine operation [16,17]. Additionally, it was identified that jet A-1 has properties similar to winter diesel duel (DF-1), and the only difference between Jet A-1 and JP-8 lies in specific fuel additives [16,18].

The JP-8 is composed of approximately 60% of iso and n-paraffins, about 20% mono-, di-, and tri-cycloparaffins, and aromatics [14]. However, RP-3 aviation kerosene is widely used for civil aviation in China [19–21], yet almost no research is available on the feasibility and the performance of neat RP-3 aviation kerosene in CI engines. RP-3 kerosene consists of saturated hydrocarbons (92.1% volume) and aromatic hydrocarbons (7.9% volume), which is different with JP-8. These aviation fuels differ in their physical and chemical properties, which can result in significant changes to the combustion process. For example, the laminar combustion speeds of RP-3 kerosene measured were higher than Jet A-1 under similar conditions, which reflects the reactivity, diffusivity and exothermicity characteristics of aviation fuels [21]. Additionally, RP-3 has a relatively low viscosity compared to commercial diesel, which leads to better atomization, vaporization, and spray formation inside the combustion chamber of the turbine engine. Therefore, it is necessary to investigate the combustion performance and emission characteristics of RP-3 in a CI engine, which are rarely found in the existing literature.

Furthermore, the Committee on Aviation Environmental Protection (CAEP), a technical committee of the International Civil Aviation Organization (ICAO) Council proposed stricter aviation emission regulations in the 10th conference of Committee on Aviation Environmental Protection in 2016 [22]. Yet the literature on general aviation emission characteristics and their mitigation technologies are much scarcer compared with vehicular emissions [23–26]. It is conceivable that the emissions from general aviation engines will become a hot topic in the light of the upcoming general aviation emission regulations. The main gaseous pollutants from aero-engines are carbon monoxide (CO), nitrogen oxide (NO_x), soot and unburnt hydrocarbon [27–31]. It is well established that the improvements in the emissions can be achieved by adding oxygenated fuel (e.g. alcohols and biodiesel) into hydrocarbon fuels [32–35]. In recent years, pentanol with a 5-carbon structure as a renewable biofuel has been studied because of its positive thermodynamic properties [6,36] and technical breakthrough for mass production [37]. Higher alcohols such as pentanol become increasingly attractive due to the significantly reduced cost of biosynthetic pathways for large pentanol yields [37]. Compared with commonly studied alcohols with shorter carbon chains (e.g. methanol and ethanol), pentanol has the merits of higher energy density, lower hygroscopicity, lower volatility, higher cetane number, and better miscibility with hydrocarbon fuels [38–40]. Meanwhile, long chain alcohols can bring benefits in decreasing CO and soot emissions with little impact on NO_x emissions in CI engines [41]. However, the literature on the combustion and emission characteristics with the long chain alcohols is much scarcer compared with short chain alcohols.

Previous studies mainly concentrated on using Jet-A or JP-8 in CI engines, it is still necessary to investigate the performances of RP-3 in CI engines which is widely used in China and other regions due to the difference in terms of chemical and physical properties between different aviation kerosene fuels. In addition, it would be desirable to seek new generation biofuels to mitigate environmental pollutants in the light of the increasingly stringent regulations in the field of general aviation in the future. The objective of this study was to investigate the combustion and emission characteristics using RP-3 as the main constituent blended with pentanol for CI HF-APEs. The study could also provide relevant combustion and emission data for justifying the viability of HE-APEs in the field of general aviation and military aviation, especially under the auspices of the 'Single Fuel Forward' policy.

2. Experimental apparatus

2.1. Test engine and facility

A four-cylinder common-rail diesel engine was modified into a single-cylinder naturally-aspirated research engine for this work. Table 1 gives the test engine specifications. One Delphi seven-hole injector was installed on the test engine. An open electronic control unit (ECU) was retrofitted to enable the freely control over engine operational parameters, such as the injection pressure, and the injection timing.

Fig. 1 illustrates the layout of the research engine test rig. The AVL GH14P PR transducer was mounted to measure the in-cylinder pressure and the resolution of the encoder was 0.5° crank angle (CA). Combustion performance data were analysed based on the ensemble average values of the in-cylinder pressures for 250 successive cycles.

The AVL 439 opacimeter was utilised to evaluate the 'absorption coefficient' of the exhaust gas to reflect the smoke emission level. The 'absorption coefficient' is primarily affected by 'black

Table 1
Specifications of the test engine.

Engine parameters or parts	Value or type
Compression ratio	16.7
Displacement (L)	0.5
Bore (mm)	83.1
Number of valves	4
Stroke (mm)	92
Injection system	Common rail
Connecting rod length (mm)	145.8
Injector	7 holes, 0.136 mm diameter
Injection pressure	40–180 MPa
Swirl ratio	1.7