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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.

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.

Key words

31 Heavy Fuel Aviation Piston Engines, Aviation kerosene, Pentanol, Compression ignition, Combustion analysis,
32 Emissions.

33 **Abbreviations**

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

34 **1. Introduction**

35 Civil and military aircrafts are normally powered by gas turbine engines burning kerosene, whilst a large number
36 of general aviation aircrafts (such as agriculture aircrafts, corporate aircrafts, civil helicopters) and military small
37 aircrafts (military UAVs, military helicopters) are powered by Aviation Piston Engines (APEs) [1, 2]. Generally, there
38 are two combustion modes for APEs: Spark-ignition (SI) and Compression-ignition (CI). APEs have mainly relied on
39 gasoline for decades. However, for the sake of safety, simplicity of logistics, costs and availability of gasoline, Heavy
40 Fuel Aviation Piston Engines (HF-APEs), which run on light diesel or kerosene with high flash point, are desirable to
41 replace the aviation gasoline engines in various applications [3, 4]. In this regards, the NATO and US Army also
42 adopted the policy of a ‘Single Fuel Forward’ using aviation kerosene JP-8 [5, 6]. The demand for HF-APEs in non-
43 military applications (e.g., agriculture aircraft, outboards) is increasing as well [7]. Therefore, the trend to adopt heavy
44 fuel for Aviation Piston Engines is prevailing now for both military requirements and civil applications in the field of
45 general aviation.

46 More attentions have been focused on two-stroke SI HF-APEs for the last decades [7-13] because CI engines
47 with lower power/weight ratios were more difficult than SI engines to meet the design requirements of Unmanned
48 Aerial Vehicle (UAV) and Light Sport Aircraft (LSA) manufacturers [10]. Falkowski *et al.* examined the feasibility of
49 JP-5 using a two-stroke SI direct injection engine, and reported that the performance characteristics were similar to
50 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 [13, 14]. 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 [13-19]. 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 [17, 18]. Additionally, it was identified that jet A-1 has properties similar to winter diesel fuel (DF-1), and the only difference between Jet A-1 and JP-8 lies in specific fuel additives [17, 19].

The JP-8 is composed of approximately 60% of isoand n-paraffins, about 20% mono-, di-, and tri-cycloparaffins, and aromatics [15]. However, RP-3 aviation kerosene is widely used for civil aviation in China [20-22], 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 [22]. 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 [23]. Yet the literature on general aviation emission characteristics and their mitigation technologies are much scarcer compared with vehicular emissions. 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) and unburnt hydrocarbon [24, 25]. 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 [26-29]. In recent years, pentanol with a 5-carbon structure as a renewable biofuel has been studied because of its positive thermodynamic properties [6, 30] and technical breakthrough for mass production [31]. Higher alcohols such as pentanol become increasingly attractive due to the significantly reduced cost of bio-synthetic pathways for large pentanol yields [31]. 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 [32-34]. Meanwhile, long chain alcohols can bring benefits in decreasing CO and soot emissions with little impact on NO_x emissions in CI engines [35]. 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.

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

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.

Fig. 1. Layout of the research engine test rig

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 soot’ according to the measurement principle. The effect of THC and NO_x on the ‘absorption coefficient’ evaluated by AVL opacimeter could be negligible [36]. The AVL CEB-II exhaust gas analyser was employed to evaluate gaseous emissions (NO_x, CO, CO₂ and THC). The dosage of fuel was measured through the FCM-D digital fuel meter.

2.2 Test fuel preparation

Table 2 lists the primary properties of diesel, RP-3, pentanol and the test blend fuels. The properties of Commercial 0# diesel and RP-3 kerosene were experimentally measured. The fuel blend properties can be calculated using equations found in the literature [27, 37]. These equations use basic properties of neat fuels along with the composition percentages to determine the blend properties. As mentioned previously, kerosene has less carbon atoms,

lower distillation temperature range, lower cetane number and lower viscosity than diesel. Meanwhile, kerosene has better atomisation compared with diesel due to its lower viscosity, surface tension and density. Pentanol was added to RP-3 to increase the viscosity and the oxygen content. Two different blended fuels, K80P20 (80% RP-3, 20% pentanol in volume) and K60P40 (60% RP-3, 40% pentanol in volume) were prepared.

Table 2.

Fuel properties of the baseline diesel, RP-3, Pentanol and blend fuels.

Fuel types	Diesel	RP-3	Pentanol	K80P20	K60P40
Chemical formula	C16-C23	C8-C12	C5H12O	--	--
A/F stoichiometric	14.3	14.9	11.76	14.27	13.64
Viscosity [mm ² /s]@20°C	4.13	1.28	2.89	1.602	1.924
Density [g/cc]@20°C	0.83	0.79	0.815	0.803	0.806
Cetane number	56.50	42.00	20-25	37.6-38.6 ^a	33.2-35.2 ^a
Lower heating value [MJ/kg]	42.68	43.43	35.06	41.731	40.0446
Oxygen content (% weight)	0.00	0.00	18.18	3.636	7.272
Latent heating @25°C [kJ/kg]	270	--	308	--	--
Surface tension @20°C (10 ⁻³ Nm ⁻¹)	27.50	23.60	24.7	23.82	24.04
Sulphur, wt%	0.50	0.30	0.00	0.24	0.18
Boiling point [°C]	T10=223 T50=266 T90=311	T10=172.8 T50=194.9 T90=224.4	138	-- -- --	-- -- --

^a Estimated by Ref. [27, 37].

2.3 Test procedure

The engine speed was fixed at 1600 rpm for all the engine tests. The engine Indicated Mean Effective Pressure (IMEP) was swept from 0.2 to 0.8 MPa. The lubricant oil and coolant temperatures were kept at $82 \pm 3^\circ\text{C}$ throughout the tests.

A split injection strategy (pilot and main injection) was employed. The pilot injection duration was fixed at 300 μs and the main injection duration was adjusted to achieve the same engine IMEP. The pilot ratio is the mass ratio of fuel injected during the pilot injection to the total injected fuel, and it was less than 10%. In addition, the interval between the two injection stages was kept constant at 16°CA. All the tests should have the Maximum Pressure Rise Rate (MPRR) under 1.0 MPa/deg and acceptable Coefficient of Variation (COV) of IMEP. For diesel, RP-3 and K80P20, the injection strategy from the original design of the test engine was adopted. For pilot injection, the fixed 300 μs pilot injection occurred at the 10 °CA Before Top Dead Centre (BTDC), and the main injection timing was 6 °CA After Top Dead Centre (ATDC). For K60P40, there existed very unstable combustion with large oscillation of heat release rate and in-cylinder pressure or even misfire occasionally when the same injection strategy was adopted. To achieve stable combustion, the pilot injection for K60P40 was advanced at the 20°CA BTDC, and the main

injection timing was advanced at 4°CA BTDC correspondingly. However, the NO_x emissions could be extremely high at this injection timing. Therefore, the original injection strategy with relatively late injection timing was adopted for the other three fuels to achieve low NO_x emissions within the Euro 4 limit. The engine operational parameters are summarised as shown in Table 3. According to the injection strategy, the injection pressure increases as the IMEP rises.

Table 3.

The operational parameters of the test engine

Operational parameters	Value or type			
Fuel	Diesel/ RP-3/ K80P20/ K60P40			
Injecting strategy	Main plus pilot injection			
Pilot ratio	Less than 10%			
Speed (rpm)	1600			
Indicated Mean Effective Pressure (IMEP) (MPa)	0.2	0.4	0.6	0.8
Injecting pressure (MPa)	40	45	60	65

2.4 Data analysis

Because the test fuels have different lower heat values (LHV), the fuel consumption for kerosene and oxygenate fuel blends was corrected for the comparison based on the following equations:

$$m'_{Kerosene} = m_{Kerosene} \times LHV_{Kerosene} / LHV_{diesel} \quad (1)$$

Where $m'_{Kerosene}$ is the corrected fuel consumption to reflect the same total energy with diesel; $m_{Kerosene}$ is the actual fuel consumption; $LHV_{Kerosene}$ and LHV_{diesel} are the LHV of kerosene and diesel fuel, respectively.

$$m'_{new} = m_{measure} \times (V_{Kerosene} \times \rho_{Kerosene} \times LHV_{Kerosene} + V_{pentanol} \times \rho_{pentanol} \times LHV_{pentanol}) / (V_{Kerosene} \times \rho_{Kerosene} + V_{pentanol} \times \rho_{pentanol}) / LHV_{diesel} \quad (2)$$

Where m'_{new} is the corrected fuel usage; $m_{measure}$ is the measured fuel usage; $V_{Kerosene}$ and $V_{pentanol}$ are the volume percentages of kerosene and pentanol; $\rho_{Kerosene}$ and $\rho_{pentanol}$ are the densities of kerosene and pentanol; $LHV_{Kerosene}$ and $LHV_{pentanol}$ are the LHVs of kerosene and pentanol. All the indicated specific fuel consumptions (ISFC) of the fuel blends were corrected correspondingly.

The following equation is used to calculate the heat release rate (HRR):

$$\frac{dQ}{d\theta} = \frac{\gamma}{\gamma-1} p \frac{dV}{d\theta} + \frac{1}{\gamma-1} V \frac{dp}{d\theta} \quad (3)$$

Where, γ is the heat ratio; V is the instantaneous in-cylinder volume, and p is the in-cylinder pressure.

The indicated thermal efficiency (ITE) was calculated according to the indicated work and the measured fuel flow rate:

$$\eta_i = W_i / (m_f \times Hu_f) \quad (4)$$

Where W_i is the indicated work; Hu_f is the fuel LHV and m_f is the fuel consumed per cycle.

An error analysis for engine measurements and analysis, such as load, IMEP, ISFC was performed using the root mean square function (5):

$$U_R = \left[\left(\frac{\partial R}{\partial x_1} U_{x_1} \right)^2 + \left(\frac{\partial R}{\partial x_2} U_{x_2} \right)^2 + \dots + \left(\frac{\partial R}{\partial x_n} U_{x_n} \right)^2 \right]^{\frac{1}{2}} \quad (5)$$

Where U_R is the uncertainty of the calculated quantity R ; x_n is the measured uncertainties of the N^{th} independent variable, and U_{x1} , U_{x2} , U_{xn} are error bars of the parameters to be investigated. The uncertainty of the instruments and their uncertainties are given in Table 4.

Table 4.

Uncertainties of calculated parameters and measurements.

Parameters	Resolution	Uncertainty (%)
Engine speed	1 rpm	0.5
Engine load	0.001 MPa	0.5
Crank angle	0.01 CAD	0.1
Intake pressure	1 kpa	0.1
Intake temperature	0.1 K	1.0
Fuel flow meter	0.01 kg/h	1.0
Gaseous analyser	1 ppm	0.5
Soot opacity	0.001/m	1.0
Air flow meter	0.1 m ³ /h	1.0
In-cylinder pressure	--	0.5
IMEP	--	0.6
ISFC	--	1.0
Combustion efficiency	--	<0.2

3. Results and Discussion

3.1 Combustion performance

In this section, the in-cylinder pressure, heat release rate, ignition delay, maximum heat release rate, combustion duration, coefficient of variation (COV) and maximum pressure rise rate over difference loads are analysed to unveil the difference in terms of combustion characteristics among the test fuels.

3.1.1 In-cylinder pressure and heat release rate

Diffusion combustion is the typical combustion mode in CI engines and is primarily influenced by the fuel physiochemical properties. Fig. 2 illustrates the heat release rate (HRR) and the in-cylinder pressure of all the test fuels under different engine loads. The injection timings are also shown in Fig. 2. It is worth noting that the pilot and main injection timings for K60P40 were 10° CA advanced than those for other fuels in order to achieve stable combustion as mentioned in Section 2.3.

For diesel, RP-3 and K80P20, the heat release of main combustion and in-cylinder pressure were similar at the loads of 0.2 MPa, 0.4 MPa, 0.6 MPa IMEP, whilst a slight difference could be observed at 0.8 MPa IMEP. In addition, the main combustion phase occurred earlier due to the earlier pilot and main injection of K60P40 than those of the other three fuels. Close-up inspection of the HRR curves demonstrated that there was no pilot peak of HRR for K60P40, which implies that there was very slight pilot combustion for K60P40. This was primarily attributed to the relatively poor ignitability of K60P40 among all the test fuels.

Fig. 2. Heat release rate, in-cylinder pressure, pilot injection timing and main injection timing at (a) 0.2 MPa (b) 0.4 MPa (c) 0.6 MPa (d) 0.8 MPa IMEP for neat diesel, neat RP-3, K80P20 (80% RP-3+20% pentanol) and K60P40 (60% RP-3+40% pentanol).

3.1.2 Maximum heat release rate

Fig. 3 compares the maximum heat release rate (MHRR) at pilot and main combustion phases respectively for all the test fuels under four engine loads. It is evident that diesel exhibited the highest first-stage MHRR, while K60P40 exhibited the lowest first-stage MHRR for all the test loads. The phenomena were relevant with the ignitability of the test fuel, which is normally reflected by the cetane number. The relatively lower cetane number of RP-3 in contrast to diesel resulted in the lower first-stage MHRR compared with diesel. The cetane number of RP-3 can be further decreased by blending with pentanol. Therefore, the RP-3-pentanol blends exhibit even lower MHRR in the pilot combustion process compared with diesel and RP-3.

Fig. 3 demonstrated that the four test fuels presented similar second-stage MHRR at 0.2 MPa, 0.4 MPa, 0.6 MPa IMEP. However, at 0.8 MPa IMEP, the second-stage MHRR of diesel was lower compared to RP-3 and its pentanol blends. This could be attributed to the smaller fraction of premixed combustion for diesel due to its shorter ignition delay. Besides, the RP-3, K80P20 and K60P40 fuels had better atomisation due to their lower viscosity and surface tension, which could further enhance the pre-mixing and led to higher second-stage MHRR.

In general, the pilot combustion was significantly affected by the cetane number of the fuels. The higher the cetane number, the higher first-stage MHRR it will have. However, the difference of HRR between the test fuels diminished for the main combustion, which was presumably because the atomisation characteristics might offset the influence of cetane number for the main combustion phase. For instance, diesel has the highest cetane number, yet it also has the highest viscosity which inhibits the breakup and collapse of fuel spray.

Fig. 3. Comparison of first-stage (pilot) and second-stage (main) maximum heat release rate (MHRR) for four fuels at different engine loads.

3.1.3 Ignition delay and combustion duration

The ignition delay of the main combustion process is illustrated in Fig. 4. CA10 and CA90 represent the crank angles at which 10% and 90% of the fuel mass were consumed. Ignition delay is defined as the crank angle difference between CA10 and the start of injection (SOI). It can be seen in Fig. 4 that the K80P20 presented the longest ignition delay for most of the test loads, while diesel exhibited the shortest delay due to its high cetane number at 0.6 and 0.8 MPa IMEP. At high temperatures (high loads), all the fuels evaporate rapidly and then the oxidation reaction rate (reflected by the cetane number) would dominate the ignition delay over the fuel physical properties. The higher in-cylinder temperature and pressure upon ignition for K60P40 due to earlier injection strategy will promote the formation of more active species, and hence K60P40 has a relatively shorter ignition delay even though its cetane number is the lowest among all the test fuels.

Fig. 4. Comparison of the ignition delay of main combustion process for the four fuels under different loads.

Combustion duration is another key combustion parameter which is defined by the CA interval between CA10 and CA90. Combustion duration can also be expressed as time interval of 10-90% mass fraction burned (MFB), and both metrics (time or crank angle) are linearly correlated at constant engine speed. Fig. 5 indicates that the combustion duration of kerosene was shorter compared to diesel and that was further shortened as the mild pentanol was mixed with kerosene (K80P20) owing to the improved volatility of blended fuels. It might not justified to compare K60P40 with other test fuels in terms of combustion duration because of the different injecting times.

Fig. 5. Comparison of the duration of combustion for all the test fuels under different loads

Fig. 6 illustrates that the combustion mode was in ‘mainly pre-mixed zone’ for 0.2 to 0.4 MPa IMEP with relatively lean air fuel mixture, in which combustion duration increased with the increase of ignition delay [38]. In contrast, the combustion mode was ‘mainly diffusion mode’ in which combustion duration decreased with the rise of

ignition delay for relatively high engine loads (from 0.4 to 0.8 MPa IMEP). There was a typical ‘transition zone’ between the two combustion modes [38]. It is evident in Fig. 6 that the combustion process occurred in ‘mainly diffusion zone’ for all the test fuels and loads, except for loads from 0.2 to 0.4 MPa IMEP. Higher cetane number favoured the diffusion combustion mode, therefore the diffusion degree of diesel was the strongest among all the test fuels under the same loads. The diffusion degree of K80P20 was less than that of kerosene due to the smaller cetane number value. The higher load was able to enhance the diffusion degree due to the fuel/air equivalence ratio of all test fuels increased gradually from around 0.3 to about 1 from 0.2 to 0.8 MPa IMEP. Therefore, in ‘mainly diffusion zone’ the combustion duration decreased with the rise of ignition delay as the load increased from 0.4 to 0.8 MPa IMEP. The results of K60P40 were absent in Fig. 6 due to its different injection strategy with other fuels.

Fig. 6. Schematic diagram for the dependence of combustion duration with ignition delay under different loads (The lowest point was 0.2 MPa IMEP whilst the highest point was 0.8 MPa)

3.1.5 Coefficient of variation and maximum pressure rise rate

Fig. 7 demonstrates that the Coefficient of Variation (COV) of IMEP was low at high loads (0.6 and 0.8 MPa IMEP), while the COV of IMEP was relatively higher at low loads (0.2 and 0.4 MPa IMEP) due to large air fuel ratios and low in-cylinder temperature. Moreover, the kerosene and its pentanol blends possessed relatively higher volatility and longer ignition delay compared with diesel, which may have led to almost perfectly homogeneous mixture. In other words, the local air fuel ratio was almost equal to the global one, and thereby the lack of local fuel rich zones may have caused the larger COV of IMEP of kerosene and its pentanol blends at 0.2 and 0.4 MPa IMEP compared with diesel. In addition, the upper boundary of MPRR was required to keep MPRR under 1.0 MPa/deg. The MPRRs of all the fuels were lower than the limit. The MPRR of K60P40 was higher than other test fuels due to earlier injection strategy and high volatility.

Fig. 7. Comparison of coefficient of variation (COV) of IMEP and maximum pressure rise rate (MPRR) for the test fuels under different loads.

3.2 Emission characteristics

In this section, regular emissions including soot, NO_x , THC and CO were presented as shown in Fig. 8-11 for all the test fuels under varying engine loads.

3.2.1 NO_x emissions

Fig. 8 shows that as the engine test load increased the NO_x emissions increased for all the test fuels. In general, there is no appreciable difference in NO_x emissions between kerosene and diesel. It is well established that the higher NO_x emissions were caused by the higher temperature of in-cylinder as the engine load increases, and mildly oxygen-rich and high temperature are the two key enablers for NO_x formation [39]. Both diesel and kerosene has little oxygen content and similar air/fuel ratio, and the second-stage MHRP shown in Fig. 3 are indistinguishable (except for 0.8 MPa IMEP). Therefore, it is not surprising to observe similar levels of NO_x emissions for kerosene and diesel.

NO_x emissions of K80P20 were observed to be moderately higher than those of kerosene for all the engine loads. Firstly, pentanol enhanced the proportion of the premixed combustion because of its longer ignition delay (see Fig. 4), thus contributing to NO_x formation. Secondly, the oxygen content of pentanol leads to smaller local equivalence ratio, which might promote the formation of NO_x as well. As mentioned in section 2.3, the NO_x emissions of K60P40 were found to be significantly higher than those of the other three fuels under all the test loads due to the early injection timing and the resultant higher combustion temperature.

Fig. 8. Comparison of indicated specific NO_x emissions characteristics for the four fuels under different engine loads.

3.2.2 Soot emissions

The soot emissions are presented in Fig. 9. It is evident that the soot emissions only slightly changed as IMEP increased from 0.2 to 0.6 MPa, but drastically increased at 0.8 MPa IMEP, especially for diesel. As the engine load increased from 0.6 to 0.8 MPa IMEP, the diffusion degree increased significantly and combustion entered ‘mainly diffusion zone’ due to the higher engine load, higher temperature and shorter ignition delay. Furthermore, the soot emissions are expected to be higher due to the presence of incomplete evaporation and more fuel rich zones in the cylinder under high engine loads.

Compared with diesel-derived soot emissions, kerosene and its pentanol blends could dramatically reduce the soot emissions especially at 0.8 MPa IMEP. It can be seen from Fig. 6 that the diffusion degree of kerosene was weaker than that of diesel at 0.8 MPa IMEP, while it was stronger than that of its pentanol blends. Compared with diesel, kerosene has higher volatility and hence more premixed combustion reduced the soot emissions [40]. When pentanol was added with kerosene, the further decrease of soot emissions was observed which could be explained by the following reasons: firstly, pentanol blends have even higher volatility and hence feature more premixed combustion, which is favourable for reducing the soot formation; secondly, the lower aromatic and sulphur content inhibits soot nuclei formation; thirdly, the oxygen atoms facilitate the soot oxidation process and hence reduce the overall soot emissions. Similar results on alcohols and diesel blends were presented elsewhere in the literatures [41, 42]. The K60P40 showed the least soot emissions and the reasons might be twofold: K60P40 has the highest oxygen content, and the early injection timing promoted the post-oxidation.

Fig. 9. Comparison of 'light absorption coefficient' for the four fuels under different engine loads.

3.2.3 THC emissions

The THC (total hydrocarbons) emissions are shown in Fig. 10. A declining trend can be observed with the rising engine loads for all the test fuels. It is attributed to the increased in-cylinder temperature, and more efficient combustion when the engine loads increased. At the engine loads of 0.2 and 0.4 MPa IMEP, kerosene produced more THC emissions than the diesel by 49.6% and 10.5% respectively, and it could be attributed to the longer ignition delay of kerosene and incomplete combustion caused by over-mixing [38]. However, the THC emissions of kerosene were nearly the same with that of diesel at 0.6 and 0.8 MPa IMEP. The reasons might be twofold: the lean combustion zone began to shrink with the increasing load; secondly, the higher second-stage MHRR of kerosene compared with diesel at 0.6 and 0.8 MPa IMEP might have led to more THC post-oxidation.

Similar results were also observed for the kerosene/pentanol blends. At the test loads of 0.2 and 0.4 MPa IMEP, the average increase in THC emissions for K80P20 were 63.8% and 46.4% respectively compared to kerosene, while the THC emissions of K80P20 were approximately the same with those of kerosene at 0.6 and 0.8 MPa IMEP. At low loads, the increase of THC emissions from K80P20 compared to kerosene might be attributed to leaner mixture and incomplete combustion [43]. Another reason was that the higher latent heat of pentanol led to lower cylinder temperature, thus increasing THC emissions. For the K60P40, the THC emissions cannot be readily compared with other fuels due to the different injection timing.

Fig. 10. Comparisons of indicated specific THC emissions characteristics for the four fuels at different engine loads.

3.2.4 CO emissions

Similar to gaseous hydrocarbon emissions, the CO emissions were primarily governed by the air fuel ratio, which determined the completeness of combustion. Fig. 11 presents the effects of using kerosene and pentanol on CO emissions at different loads. For loads from 0.2-0.6 MPa IMEP, CO concentrations declined with the increase in the engine load for all the test fuels, presumably due to low in-cylinder temperature under moderate engine loads [22]. The combustion temperature gradually rose with the increase of engine load, which decreased the CO emissions from 0.2 to 0.6 MPa IMEP. However, oxygen was not plentiful at 0.8 MPa IMEP, and the CO emissions were generated in the lean-oxygen regions of the diffusion combustion. Similar results could be found elsewhere in the literature [22].

The CO emissions of kerosene were 12.5% and 24.6% higher than those of diesel fuel at 0.2 and 0.4 MPa IMEP. The lower cetane number of kerosene and its longer ignition delay enlarged the low temperature zones and thus promoted CO emissions at low loads. On the other hand, the CO emissions of kerosene were 10.2% and 22.7% lower than those of diesel at 0.6 and 0.8 MPa IMEP. The high volatility of kerosene promoted the combustion and increased the second MHRRs, decreasing the CO emissions in the diffusion combustion.

Owing to the longer ignition delay and higher latent heat of K80P20, combustion occurred in a relatively cold environment, which was the main reason for the increase of CO emissions of K80P20 compared with kerosene under low loads. Whilst at high load of 0.8 MPa IMEP, the CO emissions of K80P20 were found to be 21.9% lower than that of kerosene. The higher volatility is favourable to decrease CO, and the pentanol with oxygen presence could make a vital contribution to the decline of CO emissions as well.

Fig. 11. Comparison of indicated specific CO emissions characteristics for the four fuels under different engine loads.

3.3 Fuel economy

Fig. 12 illuminates the indicated thermal efficiency (ITE) and corrected indicated specific fuel consumption (ISFC) data for all the test fuels. The ITE firstly increased from 0.2 to 0.6 MPa IMEP, then decreased from 0.6 to 0.8 MPa IMEP. With the combustion temperature increased, the ITE started to increase due to the higher combustion efficiency. However, from 0.6 to 0.8 MPa, the ITEs for all test fuels decreased which is because the higher equivalence ratio and longer combustion duration (see Fig. 5). In addition, the higher combustion temperature could decrease the ITE because it led to higher energy dissipation via heat transfer to the cylinder wall. Fig. 12b exhibits the curves of ISFC at different engine loads that showed a reverse tendency compared with Fig. 12a.

The kerosene showed higher IFE than diesel by 1.4%-12.4%. The primary reason might be that the combustion efficiency of kerosene is higher than that of diesel due to its shorter combustion duration and resultant higher isovolumetric degree. Similar experimental results were reported that engine thermal efficiency increased with the kerosene addition [44]. Furthermore, the K80P20 presented lower ITE and higher ISFC than kerosene by 1%-6.5%, which was due to less complete combustion of K80P20 caused by its lower combustion efficiency. Fig 3 shows that there was only small amount of effective work during the pilot-injection combustion stage which could explain the worse ITE for pentanol blends. This can be reflected by higher CO and THC emissions observed for K80P20 compared with kerosene. The K60P40 had the highest ITE and the lowest ISFC among all the test fuels, which implies that the advantage of advanced injection timing prevail over the effect of pentanol addition. As shown in Fig. 2, the main combustion and second-stage MHRR occurred just after the top dead centre and the negative work caused by the pilot injection was barely detected, therefore, higher thermal efficiency was achieved for K60P40.

(a) Indicated thermal efficiency

(b) Indicated specific fuel consumption

Fig. 12. Comparison of fuel economy for the four fuels under different engine loads.

4. Conclusion

Diesel, RP-3, RP-3/pentanol blends with 20% pentanol and 40% pentanol by volume were tested in a single-cylinder CI engine. The combustion performance, the emission characteristics and the fuel economy of all the test fuels were evaluated under different engine loads. Main findings are as follows:

1. RP-3 and K80P20 could be readily used instead of diesel without modification in the test single-cylinder CI engine for all the test loads (0.2-0.8 MPa IMEP) based on the analysis of combustion characteristics, which indicates that RP-3 could be applied widely in CI engines, especially for the Aviation Piston Engines under the auspices of the 'Single Fuel Forward' policy. High percentage of pentanol (K60P40) significantly increased the COV of IMEP (in other words, deteriorated the stability of combustion) and thus the injection time had to be altered from the original injection timing to maintain stable combustion.

2. Compared with diesel, RP-3 presented higher second-stage MHRR at high load (0.8 MPa IMEP) and similar second-stage MHRR for the rest engine loads. RP-3 protracted ignition delay for all the test loads (0.2-0.8 MPa IMEP) because of its low cetane number, while shortened the combustion duration and increased the second-stage MHRR due to its high volatility. There was negligible discrepancy in terms of COV of IMEP and MPRR between RP-3 and diesel.

3. RP-3 generated less soot emissions than diesel at high engine loads by an order of magnitude approximately. However, little difference of NO_x emissions was observed between RP-3 and diesel. The CO and THC emissions from RP-3 experienced an increase of about 12.5%-24.6% and 10.5%-49.6% respectively at low loads, but a slight decrease

at high loads.

4. Pentanol addition protracted ignition delay, whilst shortened the combustion duration and had little impact on the second-stage MHRR for all the test engine loads. Compared with RP-3, the soot and CO emissions of RP-3/pentanol blends could be reduced at high loads with little difference in terms of NO_x and THC emissions. Pentanol addition increased the CO and THC emissions by about 23%-24% and 46%-63.8% respectively at low loads.

5. In general, RP-3 improved the indicated thermal efficiency by 1.4%-12.4% and reduced fuel consumption compared with diesel. However, adding pentanol into RP-3 decreased the thermal efficiency by 1%-6.5% due to the lower energy density of pentanol compared with the hydrocarbon fuels, thereby requiring more fuel to achieve the same power output.

Although the combustion-related parameters such as cetane number, viscosity, surface tension of RP-3 make it fit in CI engines. It is worth noting that RP-3 has low lubricity compared to diesel which might cause wear, therefore, long-term durability of CI engines run on RP-3 or its oxygenate blends should be carried out for justifying its application in CI engines further.

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