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COMBUSTION AND EMISSION CHARACTERISTICS OF A SPARK-IGNITION AVIATION PISTON ENGINE FULED WITH ALCOHOL/KEROSENE BLENDS

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ABSTRACT

The fuel utilized in spark-ignition aviation piston engine is undergoing a transformation from gasoline to heavy fuels (kerosene and diesel) for security reasons. To overcome the problem that kerosene is difficult to be ignited by spark but easy to cause engine knocking, in this paper, short-chain alcohols were used to blend with kerosene to improve fuel physical and chemical properties. Specifically, three kind of alcohols namely ethanol, n-propanol and n-butanol were blended with kerosene by volume fraction of 30%, 50%, 70%, respectively. Results indicated that alcohol/kerosene blends could reach higher brake thermal efficiency (BTE) (alcohol ratio ≥ 50%) compared to gasoline. The low energy density of alcohols led to the increase in brake special fuel consumption (BSFC). Excessive ratio of ethanol and n-propanol (70%) led to higher maximum pressure rising rate (MPRR). For the main gaseous emissions aspects, CO and NO_x emissions of blend fuels decreased. However, the unburned hydrocarbons (UHC) and soot emissions were relatively higher. Notably, n-butanol/kerosene exhibited better emission characteristics, which have the lowest CO, UHC and soot emissions, compared with other blends. With the increase of alcohol proportion in blends, the downward trends of CO, UHC as well as soot emissions were more pronounced, while NO_x emissions increased first and then decreased for ethanol/kerosene and n-propanol/kerosene. N-butanol in 70% volume fraction led to extremely high NOx emissions.

Keywords: Alcohols; Kerosene; Spark-ignition aviation piston engine; Combustion and emission; Brake thermal efficiency

NOMENCLATURE

Abbreviations	
BSFC	Brake Specific Fuel Consumption
BTE	Brake Thermal Efficiency
COV_{IMEP}	Coefficient of Cycle Variation of IMEP
FDD	Flame Development Duration
HRR	Heat Release Rate
IMEP	Indicated Mean Effective Pressure
LHV	Low Heating Value
MHRR	Maximum Heat Release Rate
MPRR	Maximum Pressure Rising Rate
P_{peak}	Peak Pressure
RCD	Rapid Combustion Duration
RON	Research Octane Number
Tmax	Maximum Temperature
UHC	Unburned Hydrocarbons
Symbols	
K	Extinction Coefficient

1. INTRODUCTION

The applications of aviation kerosene on the spark-ignition aviation piston engine expressed more safety compared with gasoline due to the higher flash point and lower volatility of kerosene. Previous studies have shown that the poor spray and antiknock properties of kerosene resulted in the decrease of brake power and restricted operating load range of engine [1-3]. Therefore, it is particularly important to search the moderate solution to overcome those drawbacks.

Renewable alcohols, such as ethanol, propanol and butanol could significantly improve spray and spark ignition properties of most liquid fossil fuel due to their lower boiling point and higher research octane number [4]. Meanwhile, the high oxygen content of alcohols also help to promote the combustion of the charge which benefit the combustion efficiency [5]. But alcohols are not perfect in every respect. The low energy density of alcohols always led to the higher brake specific fuel consumption (BSFC) [6-12].

Although the boiling point of alcohol were low, their evaporation characteristics were much lower than that of gasoline. On the other hand, the flash points of short-chain alcohols were much higher than that of gasoline. Therefore, the safety of alcohols was higher than that of gasoline to some extent. Based on reasons above, in order to improve the safety of aircraft using aviation piston engine, alcohol/kerosene blends were used to replace gasoline in this paper. Three short-chain alcohols namely ethanol, n-propanol and n-butanol were blended with China kerosene RP-3. Meanwhile, in order to optimize the proportion of alcohols, the combustion and emission characteristics of alcohol/RP-3 blends with 30%, 50% and 70% volume fraction were studied. All results were compared with commercial gasoline.

2. EXPERIMENTAL RESULTS AND DISCUSSION

2.1 Material and methods

In this paper, a research platform of horizontal opposed 4-cylinder turbocharged aviation piston engine was established. The schematic of experimental engine setup is presented in Figure 1. Table 1 shows the detailed engine specifications. The main physical and chemical properties of fuels are shown in Table 2. At the same time, 95 # gasoline experiment was also carried out for comparison.

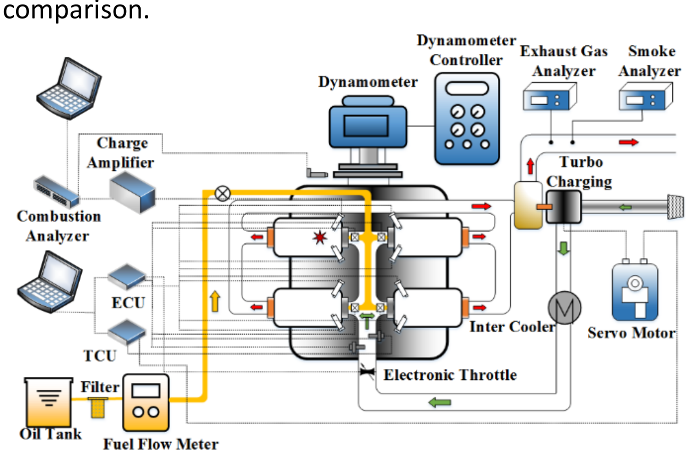


Figure 1 The schematic of experimental setup

Table 1 Engine specifications

Engine parameters	Values
Bore × Stroke (mm)	86×61
Displacement (L)	1.4
Compression ratio	9
Max power (kW/rpm)	84.5/5800
Max torque (Nm/rpm)	144/4900

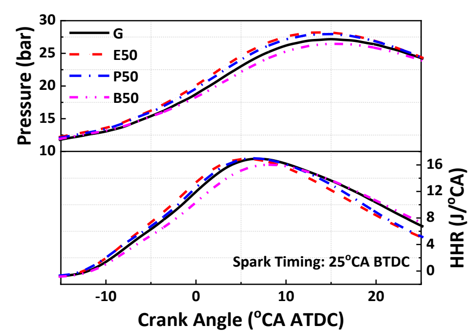
All the experiments were carried out under fixed operating load. The engine speed was kept at 3,500 rpm. The engine spark timing was fixed at 25 °CA before top dead center and fuel injection pressure was holding on 4 bar. The IMEP was maintained at around 5.2±0.1 bar by adjusting the fuel injection pulse-width and the throttle opening, while ensuring an excess air ratio of 0.95. During the operating process, the engine lubricating oil and coolant temperatures were maintained at 85±0.5 °C, and the intake air temperature was moderately controlled at 25 °C.

Table 2 Main properties of the RP-3, ethanol, n-Propanol and n-Butanol

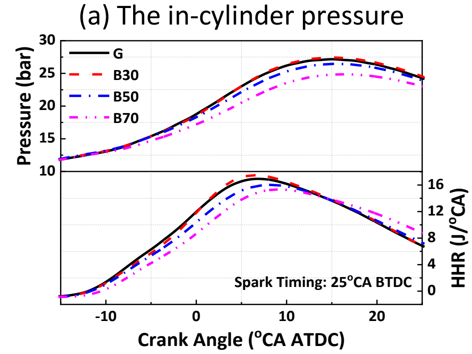
Fuel types	RP-3	Ethanol	n-Propanol	n-Butanol
Density (kg/m3@20°C)	775~830	789.3	805.3	809.8
Boiling point (°C)	-	78.29	97.2	117.6
Viscosity (mm^2/s@20°C)	1.837	1.361	2.801	3.643
RON	55.2	108.6	104	98
Flash point (°C)	35~ 51	8	15	35
Laminar flame speed (cm/s@403K, 1atm,ϕ=1,)	65	73	68	61.7
LHV (MJ/kg)	43.43	26.9	30.6	33.1
Latent heating (KJ/Kg@25°C)	-	919.6	792.1	707.9
Oxygen content (wt. %)	0	34.73	26.62	21.59

2.2 Results and discussion

2.2.1 Combustion properties



(a) The in-cylinder pressure

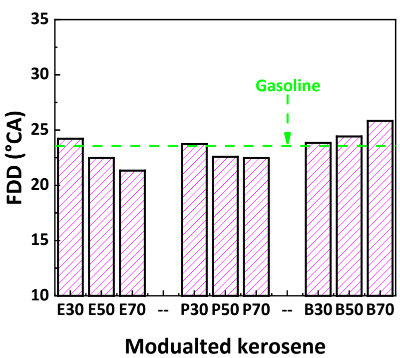


(b) The heat release rate (HRR)

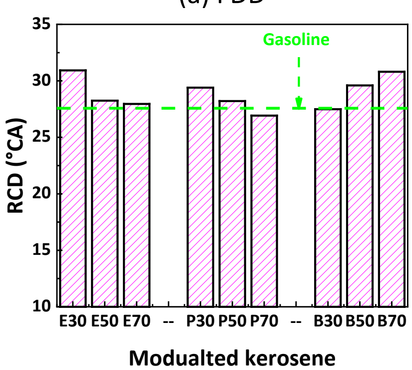
Figure 2 The in-cylinder pressure and HRR of gasoline and modulated kerosene

Figure 2 presents the in-cylinder pressure and heat release rate (HRR) for tested fuels. It can be found in Fig. 2 that the peak pressure (P_{peak}) and maximum heat release rate (MHRR) order was ethanol/RP-3 > n-propanol/RP-3 > gasoline > n-butanol/RP-3. The P_{peak} and MHRR were mainly determined by the combustion phase and the flame propagation rate. N-butanol/RP-3 had the lower laminar flame velocity, higher viscosity and boiling point relative to ethanol and propanol, which weakened the breakup and collapse of spray, resulting in poor time and spatial distribution of the mixture. Therefore, n-butanol/RP-3 blends showed the lowest P_{peak} and MHRR.

In Fig. 2(b), with the increase of n-butanol volume fraction, the P_{peak} and MHRR decreased gradually. As shown in Table 2, the laminar flame speed of n-butanol was the lowest which led to the decrease of combustion speed. The delayed combustion phase finally made the decrease of P_{peak} and MHRR. It is notable that the pressure and heat release of B30 were basically the same as those of gasoline.



(a) FDD



(b) RCD

Figure 3 Comparison of FDD and RCD between gasoline and modulated kerosene

The effects of blending short-chain alcohols on the flame development duration (FDD) and rapid combustion duration (RCD) are shown in Figure 3. In Fig. 3(a), for 30% blending ratio, the FDD of alcohol/RP-3 were always close to that of gasoline. As the ascending of alcohol volume fraction in blends, the lower boiling point of ethanol and n-propanol promoted fuel evaporative and mixing which led much lower of FDD. With respect to n-butanol, due to its relatively high boiling point, high viscosity and lower flame propagation rate, all these led to the higher FDD of n-butanol/RP-3.

In Fig. 3(b), the trend of RCD was basically consistent with FDD. For E30 and P30, the higher latent heat of ethanol and n-propanol may led to the decrease of combustion speed which led to higher RCD. With the increase of ethanol ratio, the high laminar flame speed of ethanol and n-propanol accelerated the combustion speed which led to the lower RCD and close to that of gasoline. For n-butanol/RP-3, the increase of FDD characterized the delay of CA10 which meant the combustion much far from top dead center. Then, the RCD would be increased due to the delayed combustion phase. Meanwhile, the high boiling point and viscosity made the difficult in air/fuel mixing which also made the combustion speed of n-butanol/RP-3 decreased. Among alcohol/RP-3 blends, the RCD of E50, E70, P50, P70 and B30 were basically the same as gasoline.

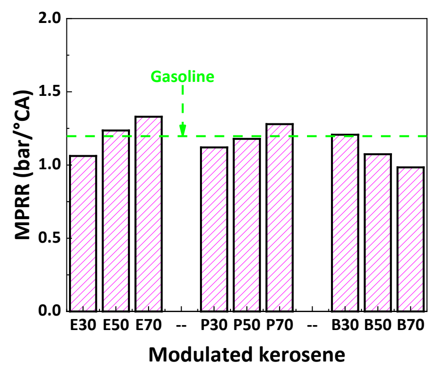


Figure 4 Comparison of the MPRR between gasoline and modulated kerosene

Figure 4 presents the effects of short-chain alcohols blended with RP-3 on the maximum pressure rising rate (MPRR). In spark ignition engine, the MPRR mainly determined by the combustion phase and flame speed. For ethanol/RP-3 and n-propanol/RP-3, with the increase of alcohol volume ratio, the MPRR increased gradually. But for n-butanol, the trend was opposite. Under fixed spark timing, when blending ethanol and n-propanol, the combustion speed gradually accelerated with the increase of alcohol volume fraction (as shown in Fig. 3) which led to the increase of MPRR. For n-butanol/RP-3, with the increase in n-butanol fraction, the FDD and RCD increased gradually. The lower combustion speed led to lower MPRR. When compared with gasoline, the MPRR of E70 and the P70 were higher than gasoline by 11% and 9%, respectively.

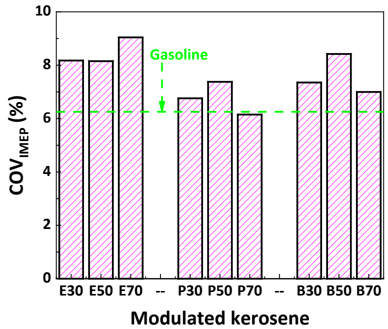


Figure 5 The CoV_{IMEP} of gasoline and modulated kerosene

Figure 5 shows the effects of alcohols blended with RP-3 on the coefficient of cycle variation of indicated mean effective pressure (CoV_{IMEP}). In Fig. 5, the CoV_{IMEP} of most alcohol/RP-3 were higher than gasoline which may be due to the difficult in mixing of RP-3. The insufficient mixing of fuel led to increased CoV_{IMEP}. N-propanol/RP-3 always had the lowest CoV_{IMEP} among the alcohol/RP-3 blends especially P70 even slightly lower than that of gasoline. As shown in Fig. 3(b), n-propanol/RP-3 had slightly lower RCD which indicated faster combustion speed. This made the CoV_{IMEP} of n-propanol/RP-3 slightly lower.

2.2.2 Emissions properties

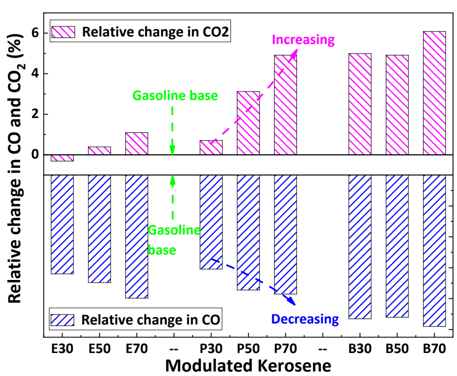


Figure 6 Relative change in CO and CO_2 compared with base gasoline for nine modulated kerosene

Figure 6 compared the CO and CO_2 emissions between gasoline and alcohol/RP-3 blends. CO emissions were mainly produced from the uncompleted combustion. As the alcohol proportion increased, the higher oxygen content causes a so-called "lean effect" (higher actual A/F ratio), resulting in an evident decrease in CO emissions of blends relative to neat gasoline. Especially, due to the CO re-oxidation occurring on afterburning, the CO emissions of B70 were the lowest due to the delay of combustion phase, which decreased by 49% compared with gasoline. CO_2 is the main greenhouse gas and the product of complete combustion from hydrocarbon fuels. With the increase of the alcohol ratios, due to the low energy density of alcohols, there would be an increase in fuel consumption which led to the CO_2 emissions of blends gradually increase and higher than neat gasoline.

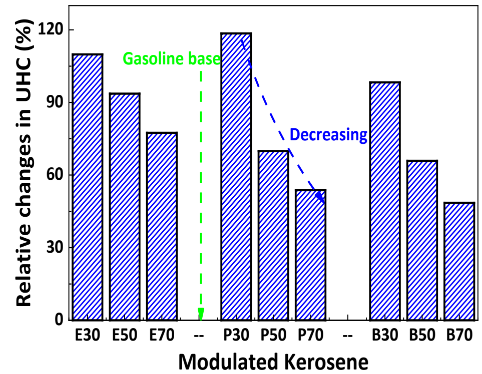
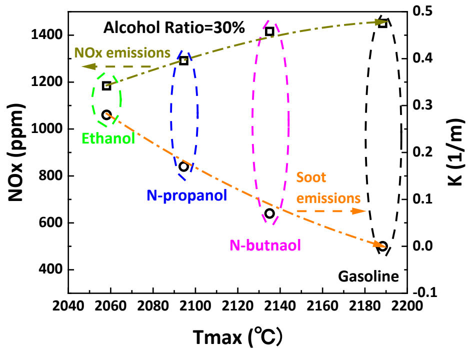


Figure 7 Relative change in UHC emissions compared with base gasoline for nine modulated kerosene

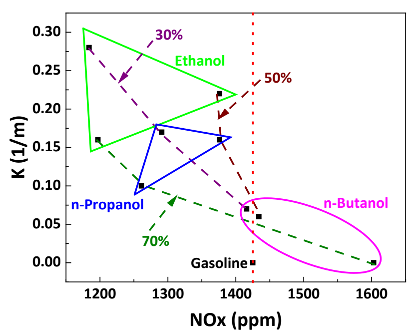
Figure 7 depicts the effects of alcohols blended with RP-3 on UHC emissions. The UHC emissions of alcohol/RP-3 blends were significantly higher than those of gasoline. UHC emissions mainly depended on fuel concentration in the boundary layer and combustion temperature. Compared to gasoline, kerosene was difficult to evaporate and atomize by port injection with injection pressure of 4bar. Poor mixing quality of combustible mixture may lead to higher UHC emissions. With the increase in alcohol proportion, UHC emissions showed a significant downward. The low boiling point of alcohols significantly improved the evaporation characteristics of kerosene which led to the decrease of UHC emissions. For n-butanol/RP-3, although the boiling point of n-butanol was higher, the delayed combustion phase of n-butanol/RP-3 benefited the oxidation of fuels released form boundary layer. Therefore, the n-butanol/RP-3 always had the lowest UHC emissions.

Figure 8 gives a detailed analysis of the effects of alcohol/kerosene blends on NO_x and soot emissions. In Fig. 8(a), the order of in-cylinder Tmax was ethanol/ kerosene < n-propanol/kerosene < n-butanol/kerosene < gasoline. It is well-known that high temperature can lead to higher NO_x emissions. Due to the high latent heat of the alcohol, the Tmax of the alcohol/kerosene blends were significantly lower than that of the gasoline, which was advantageous for suppressing the formation of NO_x.

The main reasons of soot production are high temperature and lack of oxygen. The poor spray characteristics of blended fuels generated more inhomogeneous mixtures, so the soot emissions were higher than those of gasoline. Among the three types of alcohol/kerosene blends, ethanol has the lowest NO_x emissions due to the maximum latent heat of vaporization and the shortest high temperature duration. Moreover, n-butanol had the lowest soot emissions probably because of the re-oxidation of soot in post-burning.



(a) 30% alcohol volume fraction



(b) The relationship between NO_x and K for all test fuels

Figure 8 Effects of short-chain alcohols blended with RP-3 on NO_x and soot emissions

Fig. 8 (b) shows that NO_x emissions and K (extinction coefficient) presented a negative trend, which was consistent with the contradiction of their generated reasons. The lower in-cylinder temperature of alcohol/kerosene blends inhibited the generation of NO_x emissions, resulting in an evident reduction compared with gasoline (except B50 and B70). The longer residence time in high temperature and higher oxygen concentration of B50 and B70 resulted in a significant increase in NO_x emissions. On the other hand, due to the poor spray characteristics of kerosene, the soot emissions of all blends were higher than those of gasoline. However, with the increase of the alcohol ratio, the soot emissions exhibited significant decrease trend.

2.2.3 Fuel economy properties

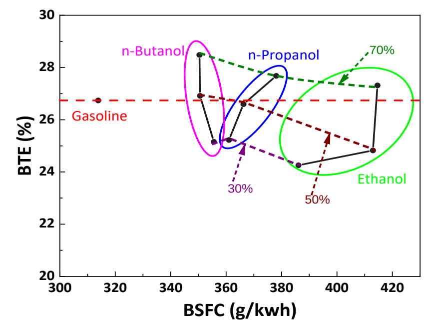


Figure 9 The relationship between BTE and BSFC for all test fuels

Figure 9 discussed the effects of short-chain alcohols blended with RP-3 on brake thermal efficiency (BTE) and brake specific fuel consumption (BSFC). In Fig. 9, there was an evident trend of BSFC that: ethanol/RP-3 > n-propanol/RP-3 > n-butanol/PR-3 > gasoline, which was exactly the opposite of their lower heating value (LHV). The lower the LHV was, the more fuel was required to achieve the same output power. Although blending alcohols led to higher BSFC, when the alcohol ratio reached 50%, the BTE of n-butanol/RP-3 was higher than gasoline. For all alcohol/RP-3 blends with 70% alcohol, the BTE was always higher than that of gasoline. Compared with ethanol/RP-3 and n-propanol/RP-3, n-butanol/RP-3 had the highest BTE and lowest BSFC. This was probably because n-butanol had the relatively higher LHV, the lower CO and UHC emissions.

2.3 Conclusions

In this paper, a strategy of short chain alcohol/kerosene blend fuel was proposed to replace gasoline for piston aviation engine in order to improve the safety of the corresponding aircraft. Specifically, three short-chain alcohols namely ethanol, n-propanol and n-butanol were blend with RP-3 by volume fraction of 30%, 50% and 70%, respectively. The combustion and emission characteristics of the above mentioned fuels were researched with a horizontally opposed 4-cylinder spark-ignition engine in detail. The main conclusions of this paper are as follows:

- Although blending alcohol led to higher BFSC, when alcohol ratio was 50%, the BTE of n-butanol/RP-3 was slightly higher than gasoline. For alcohol ratio of 70%, all blends get higher BTE than gasoline, among which n-butanol/RP-3 had the highest BTE.
- Except for E70 and P70, the MPRR of the remaining mixtures was constant or decrease compared with gasoline. However, the alcohol/RP-3 obviously increased the cycle variation of combustion. Only

P70 obtained approximately the same cyclic variation as gasoline.

- For all blends, CO emissions were lower compared with gasoline. The CO emissions of E70, P70 and B70 were reduced by 39.8%, 38.5% and 49.0%, respectively. The UHC emissions and soot emissions of blends were relatively higher.
- With the increase in alcohol ratio, the CO, UHC and soot emissions gradually descended, while NO_x emissions increased first and then decreased when fueled with ethanol/RP-3 and n-propanol/RP-3. N-butanol/RP-3 blends had the lowest CO, UHC and soot emissions, while its NO_x emissions were obviously higher than other blends.

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