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Experimental evaluation of water-containing isopropanol-n-butanol-ethanol and gasoline blend as a fuel candidate in spark-ignition engine

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HIGHLIGHTS

- Water containing isopropanol-n-butanol-ethanol (IBE) is used as an alternative fuel of SI engine.
- Water containing IBE-gasoline blends with various IBE and water concentration are tested.
- Combustion, performance and emissions characteristics are investigated.
- Water containing IBE has a potential to improve energy efficiency and reduce pollutant emissions.

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ABSTRACT

Bio-n-butanol has attracted great attention as a potential alternative fuel in internal combustion engines (ICEs) due to its favorable physicochemical properties. However, the main issue impeding the use of bio-butanol in ICEs is its relatively high cost and energy consumption of dehydration and recovery processes in acetone-n-butanol-ethanol (ABE) or isopropanol-n-butanol-ethanol (IBE) fermentation technologies. Some researchers have proposed to use intermediate fermentation product, i.e. water-containing ABE or IBE, for clean combustion. Therefore, an experimental evaluation of spark-ignition (SI) engine fueled with water-containing IBE-gasoline blends was carried out in this study. Effects of IBE and water addition on combustion, performance, and emissions characteristics were first investigated at stoichiometric condition. Then, a “drop-in” fuel test was performed, i.e. IBE9W1 (9 vol.% IBE, 1 vol.% water and 90 vol.% gasoline) was compared with pure gasoline under various engine loads (3 and 5 bar BMEP) and equivalence ratios (Φ = 0.83–1.25). It was found that IBE9W1 showed a higher brake thermal efficiency, and a lower CO, NO_x and BTX (benzene, toluene and xylene) emissions. The results indicate that water-containing IBE could be used as a fuel candidate in SI engine due to its eco-friendly production method and potential to improve energy efficiency and reduce emission pollutants.

1. Introduction

In recent years, the increasing concern of energy crisis and environmental protection is driving the development of clean and sustainable energy sources all over the world [1–5]. Bio-fuels, derived from biomass and thus being renewable, biodegradable and oxygenated, are receiving increasing public and scientific attention [6]. Bio-alcohols are widely used biofuel because of the great potential for reduction of emissions [7–9].

Among the bio-alcohols, bio-n-butanol has attracted more attention due to its advantages over bio-ethanol, including higher energy content, less corrosive, lower vapor pressure, higher tolerance to water contamination and so on [10,11]. Motivated by the potential of bio-n-butanol being a viable alternative fuel, Rakopoulos et al. investigated the emissions from a turbocharged diesel engine fueled with neat diesel fuel and two blends of diesel fuel with either 30 vol.% bio-diesel or 25 vol.% n-butanol. It was found that n-butanol blend significantly decreased exhaust gas opacity but notably increased nitric oxide emission [12]. By comparing five different fuels, including n-heptane, isooctane, n-butanol, 2-butanol and methyl octynoate, Liu et al. concluded that fuel properties had little effect on gaseous emissions and indicated thermal efficiency compared to EGR rates [13]. An experimental study was conducted in a port fuel-injection, spark-ignition engine fuelled with blends of gasoline and n-butanol at different spark timings and EGR rates. The effects of spark timing, blend ratio and EGR rate on the emission characteristics were analyzed [14]. Mack et al.

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Nomenclature

ABE	acetone-n-butanol-ethanol
IBE	isopropanol-n-butanol-ethanol
ICE	internal combustion engine
SI	spark ignition
ATDC	after top dead center
BMEP	Brake Mean Effective Pressure
Φ	fuel-air equivalence ratio
RON	Research Octane Number
BSFC	Brake Specific Fuel Consumption
BTE	Brake Thermal Efficiency
ECU	engine control unit
EGT	exhaust gas temperature
LHV	lower heating value
MFB	mass fraction burned
UHC	unburned hydrocarbons
CO	carbon monoxide
NO_x	nitrogen oxides
BTX	benzene, toluene and xylene

performed an experimental study of butanol isomer combustion in homogeneous charge compression ignition (HCCI) engine. The results indicated that butanol was suitable for HCCI engines, either in neat form or in blend with gasoline [15]. Jin et al. discussed the application researches of n-butanol from three aspects, including fundamental combustion experiments, a substitute for gasoline in spark-ignition engine, and a substitute for diesel in compression-ignition engine [16].

Acetone-n-butanol-ethanol (ABE) and isopropanol-n-butanol-ethanol (IBE) fermentation are typical technologies used to produce bio-n-butanol [17,18]. However, high cost and energy consumption of recovery and dehydration process have impeded the use of bio-n-butanol in modern engines. Some researchers have turned their attention to the feasibility of using intermediate mixtures in the ABE and IBE fermentation for clean combustion, which would eliminate the extra cost and energy consumption for separating bio-n-butanol. The economic assessment of ABE and IBE fermentation was investigated in Refs. [19–21]. The results showed that the price of ABE and IBE was projected to be US\$0.27 kg^{-1}, which was close to the price of gasoline, i.e. US\$0.22 kg^{-1}. Therefore, with the development of strains, substrates, and fermentation technologies for improving productivity, ABE and IBE could become economically feasible potential fuel. A series of water-containing ABE-diesel blends were investigated in diesel engine generator and diesel engine dynamometer [22]. Results showed when adding 20 vol.% ABE and 0.5 vol.% water into diesel, the brake thermal efficiencies was enhanced by 3.3–8.6%, and the emissions of particulate matter (PM), nitrogen oxides (NO_x), polycyclic aromatic hydrocarbons (PAHs) and the toxicity equivalency of PAHs (BaP_{eq}) were reduced by 5.8–61.6%, 3.7–16.4%, 0.7–31.1% and 2.6–40.2%, respectively. They also used water-containing ABE as a biodiesel-diesel blend additive to lower NO_x emissions [23]. It was found that the biodiesel-diesel solution containing 25 vol.% water-containing ABE simultaneously reduced NO_x and PM by 4.3–30.7% and 10.9–63.1%, respectively. Spray combustion of ABE-diesel blends was investigated in a constant volume chamber under ambient temperature (800–1200 K) and oxygen concentration (11–21%), respectively [24–27]. The ABE-diesel blends significantly reduced natural flame luminosity (an indicator of soot), and the diesel solution with 20 vol.% ABE gave a close-to-zero natural flame luminosity flame at an ambient temperature of 800 K and ambient oxygen concentration of 11%. The short combustion duration of ABE could potentially increase the thermal efficiency of compression-ignition engine. Ten-step phenomenological soot model for ABE-diesel blends was developed through modifying the fuel pyrolysis reaction in Tao's model based on detailed chemical mechanism [28,29].The combustion and emissions behavior of spark-ignition (SI) engine fueled with ABE-gasoline blends were evaluated in Refs. [30–32].

In comparison with acetone, isopropanol appears to be a more attractive fuel. Acetone is an incredibly powerful polar solvent, so it has a tendency to attack hoses and seals selected for gasoline resistance. Over time, this can cause leaks or damage injectors [21]. Isopropanol has a longer carbon chain than regular lighter alcohols, and thus belongs to heavy alcohols. Isopropanol has a higher energy density than acetone (23.9 MJ/L vs 22.6 MJ/L) [33]. Meanwhile, isopropanol is a major ingredient of gas-dryer and has been used as an additive for gasoline. It can solubilize the water in gasoline so that the water cannot pose the same risk as insoluble water as it will no longer accumulate in the supply lines and freeze [34]. Additionally, it has been reported that isopropanol was used to substitute methyl tert-butyl ether (MTBE) as isooctane index enhancer in gasoline composition [35]. However, the researches related to water-containing IBE in ICEs were rarely reported. Therefore, as a continual investigation step of our previous study [36,37], an experimental evaluation of spark-ignition engine fueled with water-containing IBE-gasoline blends was conducted in this study from the viewpoints of combustion, performance, and emissions characteristics.

2. Experimental methods

2.1. Fuel preparation

A commercial gasoline (Research Octane Number (RON) = 92) was used as the base fuel. In a typical IBE fermentation process, isopropanol, n-butanol and ethanol are produced at a ratio of 3:6:1, respectively. The products proportion of IBE fermentation is mainly affected by substrate, strain, and production process. With the development of IBE fermentation technology, such as developing new strains of bacteria developed by mutagenesis, evolutionary or metabolic engineering, using upstream processing of pretreatment, hydrolysis or detoxification, replacing batch and fed-batch fermentation processes by continuous fermentation processes, etc., the ratio of isopropanol, ethanol, butanol and by-products can be adjusted in a certain extent. In order to simulate typical intermediate mixtures in IBE fermentation process, analytical grade isopropanol (99.8%), butanol (99.5%) and ethanol (99.8%) supplied by Decon Laboratories Inc. were mixed at a volume ratio of I:B:E = 3:6:1 using a temperature-controlled magnetic stirrer. The samples of pure gasoline (G100) blended with IBE or water, including IBE10, IBE30, IBE9.5W0.5, and IBE9W1 (9 vol.% IBE, 1 vol.% water and 90 vol.% gasoline), were kept in tubes at 25 °C and 1 atm for14 days to test stability. All samples showed a clear single phase after the stability test. Properties of the test fuels are listed in Table 1.

2.2. Test engine

Fig. 1 and Table 2 shows the engine setup and the engine general specifications, respectively. Experiments were performed using a single-cylinder port-fuel injection (PFI) SI engine with a peak output of 30 kW and 52 N m. The engine was mounted on a GE TCL-15 4-35-1700 dynamometer controlled by a DyneSystems DYN-LOC IV controller. The dynamometer is able to absorb 26.1 kW and deliver 14.9 kW at a maximum speed of 4500 rpm. The position of the engine throttle was adjusted by a DyneSystems DTC-1 digital throttle controller. The engine was controlled by a Megasquirt V3.0 electronic control unit system which allows the adjustment of air-fuel ratio and spark timing. In-cylinder pressure was measured by a Kistler type 6125B pressure transducer coupled with an AVL 3057-AO1 charge amplifier, and its corresponding crankshaft position was obtained through a BEIXH25D shaft encoder. The intake air system provided compressed, filtered air from