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Combustion, performance and emissions characteristics of a spark-ignition engine fueled with isopropanol-*n*-butanol-ethanol and gasoline blends

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HIGHLIGHTS

- IBE-gasoline blends with various IBE content were tested.
- Combustion, performance and emissions characteristics were investigated.
- IBE-gasoline blends showed an advanced combustion phasing compared to G100.
- IBE30 performed well in BTE and emissions among IBE-gasoline blends.
- IBE30 showed higher BTE and lower emissions compared to G100.

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ABSTRACT

Among primary alcohols, bio-*n*-butanol is considered as a promising alternative fuel candidate. However, relatively low production efficiency and high cost of component recovery from the acetone-*n*-butanol-ethanol (ABE) or isopropanol-*n*-butanol-ethanol (IBE) fermentation processes hinders industrial-scale production of bio-*n*-butanol. Hence it is of interest to study the intermediate fermentation product, i.e. ABE and IBE as a potential alternative fuels. However, for fuel applications, the IBE mixture appears to be more attractive than ABE due to more favorable properties of isopropanol over acetone, such as being less corrosive to engine part, higher energy density and octane number. In this study, an experimental investigation on the performance, combustion and emission characteristics of a port fuel-injection SI engine fueled with IBE-gasoline blends was carried out. By comparisons between IBE-gasoline blends with various IBE content (0–60 vol.% referred to as G100-IBE60) and more commonly used alternative alcohol fuels (ethanol, *n*-butanol and ABE)-gasoline blends, it was found that IBE30 performed well with respect to engine performance and emissions, including brake thermal efficiency (BTE), brake specific fuel consumption (BSFC), carbon monoxide (CO), unburned hydrocarbons (UHC) and nitrogen oxides (NO_x). Then, IBE30 was selected to be compared with G100 under various equivalence ratio ($\Phi = 0.83–1$) and engine load (300 and 500 kPa BMEP). Overall, higher BTE (0.04–4.3%) and lower CO (4%), UHC (15.1–20.3%) and NO_x (3.3–18.6%) emissions were produced by IBE30 compared to G100. Therefore, IBE could be a good alternative fuel to gasoline due to the environmentally benign fermentation process (from non-edible biomass feedstock and without recovery process) and the potential to improve energy efficiency and reduce pollutant emissions.

1. Introduction

Depleting fuel resources and increasing environmental problems have driven the development of biofuels all over the world. Among various biofuels, alcohols have been extensively investi-

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gated as alternative engine fuels because of their great potential for improving engine performance and reducing pollutant emissions [1–6].

n-Butanol is considered as a more promising alcohol compared to methanol and ethanol because of its numerous advantages over short-chain alcohols including higher energy density, higher viscosity and better blending ability [7]. Also, *n*-butanol is much less hygroscopic and corrosive, therefore it is known as a "drop-in" fuel that would be compatible with the current fuel distribution infrastructure [8]. n-Butanol is a second-generation biofuel and can be produced from non-edible biomass. A well-to-wheels analysis of corn-based *n*-butanol as a transportation fuel showed that, on a life-cycle basis, the use of corn-based *n*-butanol could result in fossil energy saving of 39–56% over gasoline while reducing greenhouse gas emissions by up to 48% [9]. Motivated by the potential of *n*-butanol being a viable alternative fuel, Zheng et al. experimentally compared combustion and emission characteristics of a two-stage injection engine fueled with pure diesel, diesel/gasoline, diesel/*n*-butanol and diesel/gasoline/*n*-butanol, respectively [10]. It was found that blending gasoline and/or *n*-butanol in diesel improved smoke emissions while induced an increase in maximum pressure rise rate. They also investigated the effects of four butanol isomers, including *iso*-butanol, *sec*-butanol, *n*-butanol and *tert*-butanol, on conventional and low temperature combustion in a single-cylinder diesel engine [11]. The results indicated that the addition of butanol isomers retarded combustion phasing, improved thermal efficiency, and reduced soot emissions compared with diesel. Liu et al. observed the spray and flame natural luminosity of various oxygenated biofuels in a constant volume chamber using laser diagnostics [12,13]. Compared to biodiesel, the soot concentration of *n*-butanol was lower and restricted within the downstream of the spray jet. By comparing five different fuels, including *n*-heptane, *iso*-octane, *n*-butanol, 2-butanol and methyl octynoate, it was concluded that oxygenated structures have little effect on nitrogen oxides (NO_x), carbon monoxide (CO), unburned hydrocarbons (UHC) emissions and gross indicated thermal efficiency [14]. Ref. [15] reported *n*-butanol/biodiesel dual-fuel injection in a diesel engine. *n*-Butanol was injected into the intake port, while soybean biodiesel was directly injected into the cylinder.

However, *n*-butanol is currently less competitive with ethanol and gasoline in term of costs, mainly because of the relatively low production efficiency and high recovery costs in the acetone-*n*-butanol-ethanol (ABE) or isopropanol-*n*-butanol-ethanol (IBE) fermentation processes, which are current bio-*n*-butanol production methods [16]. If the ABE or IBE mixtures could be directly used for clean combustion, the costs of recovery and dehydration processes would be eliminated. In this respect, ABE has been tested in several studies as a green fuel. By the investigation of diesel engine generator and diesel engine dynamometer fueled with water-containing ABE and diesel blends, it was found that the addition of 20 vol.% ABE and 0.5 vol.% water enhanced the brake thermal efficiency (BTE) and reduced the emissions of particulate matter (PM), NO_x, polycyclic aromatic hydrocarbons (PAHs) and the toxicity equivalency of PAHs (BaP_{eq}) [17]. The spray and combustion characteristics of ABE-diesel blends were studied in a constant volume chamber [18,19]. ABE-diesel blends showed a high potential to increase thermal efficiency and decrease soot emission based on its shorter combustion duration and lower natural flame luminosity. In addition, the combustion, performance and emissions characteristics of ABE-gasoline blends were also investigated [20,21].

However, for fuel application, the IBE mixture appears to be more attractive than ABE [22,23]. An important reason for this is that the acetone in ABE is potentially corrosive to the engine parts composed of rubber or plastic [24–26]. Meanwhile, isopropanol shows a higher energy density than acetone (23.9 MJ/L vs 22.6 MJ/L). It also has been reported that isopropanol can be used as a fuel additive for the preparation of high-octane gasoline [27]. Therefore, the objective of this study is to evaluate the use of IBE-gasoline blends in a port fuel-injected SI engine based on the investigation on performance, combustion and emissions characteristics.

2. Experimental methods

2.1. Fuel preparation

In this study, pure commercial summer gasoline with research octane number (RON) of 92 was selected as the baseline fuel. Analytical grade acetone (99.5%), *n*-butanol (99.5%), isopropanol (99.5%) and ethanol (99.8%) were first mixed using a temperature-controlled magnetic stirrer to provide ABE and IBE mixtures with a volume ratio of 3:6:1 (A:B:E or I:B:E). This ratio was used to simulate the composition of the ABE and IBE fermentation product. The properties of individual fuels and fuel blends are listed in Table 1 [8,28–34]. The properties of the fuel blends were calculated using simple mixing rules [35]. The stability of fuel blends was tested using a gravitational test. The prepared fuels were deposited in test tubes at 25 °C and 1 atm for 14 days. The fuels displayed a clear single phase throughout the stability test.

2.2. Test engine

The engine used in this study was a single cylinder SI engine with identical cylinder geometry to a 2000 Ford Mustang Cobra V8. The general specifications of the test engine are given in Table 2. The engine was connected to a GE type TCL-15 class 4-35-1700 dynamometer controlled by a DYN-LOC IV controller. A DyneSystems DTC-1 controller was used to control throttle position. A Megasquirt V3.0 electronic control unit system was used to control air-fuel ratio (AFR) and spark timing. In-cylinder pressure was measured by a Kistler type 6125B pressure transducer and recorded by a LabVIEW acquisition system. The crank angle position was acquired with a BEI XH25D shaft encoder. The measurements of AFR and NO_x emission were conducted using a Horiba MEXA-720 analyzer. A Horiba MEXA-554JU analyzer was used to measure UHC and CO emissions. Water vapor in the exhaust gas was condensed out before emissions measurements. The measuring range, accuracy and resolution of the experimental apparatus are listed in Table 4. The picture and schematic diagram of the engine setup are shown in Fig. 1.

2.3. Test conditions and parameters

In this study, the engine speed was fixed at 1200 rpm. The throttle plate was fully opened and the intake manifold pressure was fixed at 60 kPa and 90 kPa by regulating the compressed air, which corresponded to engine loads of 300 kPa BMEP (Brake Mean Effective Pressure) and 500 kPa BMEP. The engine was running at the spark timing corresponding to gasoline's MBT at stoichiometric condition. Equivalence ratio varied over a range of lean and stoichiometric conditions, i.e. Φ varying from 0.83 to 1. Measurements of engine torque, equivalence ratio and NO_x emission were averaged in a 60-s period, while UHC and CO emissions were recorded directly from the emissions analyzer. The tests of each fuel were performed 3 times on a single day, and the datasets for each fuel were then averaged. The experiments were performed on several consecutive days in a temperature and humidity-controlled laboratory. The test conditions mentioned above are summarized in Table 3. In each test, the investigated parameters for combustion,