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Improved SI engine efficiency using Acetone–Butanol–Ethanol (ABE)

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HIGHLIGHTS

- Acetone–Butanol–Ethanol (ABE) (6:3:1, 3:6:1 and 5:14:1 vol.% ratio) blends were combusted in an SI engine.
- ABE(6:3:1) showed combustion phasing closest to gasoline, accompanied by an improved brake thermal efficiency.
- Increasing n-butanol content increased HC emissions and CO emissions, due to incomplete combustion. On the other hand, ABE(6:3:1) showed reduced HC emissions.
- Under the tested conditions, fermentation products with higher acetone content, such as ABE(6:3:1) would be much better suited as alternative fuels for SI engines.

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ABSTRACT

Alcohols, especially n-butanol, have received a lot of attention as potential fuels and have shown to be a possible alternative to pure gasoline. The main issue preventing butanol's use in modern engines is its relatively high cost of production. ABE, the intermediate product in the ABE fermentation process for producing bio-butanol, is being studied as an alternative fuel because it not only preserves the advantages of oxygenated fuels, but also lowers the cost of fuel recovery for individual component during fermentation. With the development of advanced ABE fermentation technology, the volumetric percentage of acetone, butanol and ethanol in the bio-solvents can be precisely controlled. In this respect, it is desirable to estimate the performance of different ABE blends to determine the best blend and optimize the production process accordingly. In this paper, pure ABE fuels with different component volumetric ratio, (A:B:E of 3:6:1, 6:3:1 and 5:14:1), were combusted in a naturally aspirated, port-fuel injected spark ignited engine. The performance of these blends was evaluated through measurements of in-cylinder pressure, and various exhaust emissions. In addition, pure gasoline and neat n-butanol were also tested as baselines for comparison of ABE fuels. The tests were conducted at an engine speed of 1200 RPM and loads of 3 and 5 bar brake mean effective pressure (BMEP) under different equivalence ratios. On the basis of the experimental data, the combustion characteristics and emission behavior of these fuels have been presented and discussed. It was found that in terms of thermal efficiency, ABE(6:3:1) might be much better suited for use as an alternative fuel, relative to ABE(3:6:1) or n-butanol.

1. Introduction

In recent years, growing public concern over the economic and environmental viability of gasoline, diesel and other fossil fuels, has prompted the investigation into oxygenates as fuel additives [1]. Oxygenated compounds previously considered include butanol, ethanol, methanol, and methyl or ethyl esters or ethers [2]. Many research studies into n-butanol have been conducted due to its properties that closely resemble those of gasoline [2–4]. These properties include ease of transportation through pipelines due to its hydrophobic nature thereby resulting in a lower tendency to separate from the base fuel (i.e. diesel or gasoline) when mixed with water; an air fuel ratio that closely resembles that of

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gasoline allowing for greater percentages of butanol to be mixed with gasoline; and an energy content that is 30% more than ethanol [5,6]. Furthermore, n-butanol, when used as a transportation fuel, can save 39–56% fossil energy while reducing greenhouse gas emissions by up to 48% on a lifecycle basis [6]. The main issue that prevents butanol's use in modern engines however is its relatively high cost of production, which has been the subject of many other research studies [5–16].

Acetone–Butanol–Ethanol (ABE) fermentation primarily involves bacterial fermentation of biomass feedstock to produce acetone, n-butanol and ethanol at volume percentages of approximately 22–33%, 62–74%, and 1–6% respectively (roughly a 3:6:1 ratio [16,17]). Due to the depletion of fossil fuels, and subsequent rise in oil prices, interest in ABE production by fermentation as a viable alternative to the petroleum process has been renewed. Bio-butanol usually uses a strain of bacteria from the Clostridia Class (Clostridium Family). Clostridium acetobutylicum is the most well-known strain, although Clostridium beijerinckii has also been used for this process with good results. Clostridial species show promise for ABE fermentation using lignocellulosic (e.g., bagasse, barley straw, wheat straw, corn stover, switchgrass, etc.) and non-cellulosic (e.g., glucose, corn, sago, and sugarcane) feedstocks. The United States produces the largest amount (approximately 280 million tons per year) of corn in the world, whereas China comes in second with approximately 131 million tons per year. From the availability point of view, the lignocellulosic materials have been marked as a cheaper and more abundant feedstock for biofuels [3]. If the intermediate product of fermentation, the ABE mixture, could be used for clean combustion, the separation costs would be mitigated. This would save an enormous amount of time and money in the production chain of bio-butanol [8]. It should be noted that the actual fermentation product contains a relatively small amount of water (<0.5% by weight) [11], which has not been included in this study. This study of water-containing ABE is being carried out and will be discussed in a future paper. However, this level of purity is sufficient for full miscibility with gasoline. ABE fuel properties can be adjusted to suit internal combustion engine requirements, by changing the ratio of the ABE components through fermentation. As mentioned earlier, the typical ratio of acetone, butanol and ethanol is 3:6:1 during the formation process, but this is adjustable. Modification of bacterial strains at the genetic level is the common method for researchers to optimize production components. At the same time, fermentation products and the ratio of their formation also vary with the fermentation conditions (pH, temperature, nutrients) [17]. The goal of this study is to investigate the combustion characteristics of ABE in a spark-ignited engine estimate the performance of different ABE blends to determine the best blend and optimize the production process accordingly. In the future, ABE mixture could be used directly, with the components ratios controlled during the ABE fermentation process [18,19].

Butanol has been widely investigated as an alternative fuel for both gasoline and diesel engines. Zheng et al. investigated the effects of n-butanol and its isomers on combustion and emissions of a diesel engine, and found that the alcohol blends showed a retarded combustion phasing, higher combustion efficiency and lower soot emissions. However, gaseous emissions were not affected obviously [20]. They also studied combustion and emission of blends of diesel, gasoline and n-butanol, and found that the ITE was slightly increased with the blended fuels [21]. Liu et al. studied the combustion of neat n-butanol and soybean biodiesel in a constant volume chamber and found that n-butanol was more effective in soot suppression relative to biodiesel [22]. They also studied n-butanol and biodiesel dual-fuel combustion in a diesel engine. A slightly higher ITE and significantly reduced NOx, soot emissions were observed [23]. Liu et al. also investigated the effect of adding various oxygenated fuels (20% by volume) to diesel fuel and found that among n-heptane, iso-octane, n-butanol and methyl octynoate, n-butanol showed the largest soot reduction, however, they found that fuel properties and oxygenated structures had minor effects on gaseous emissions and ITE [24]. As for SI engines, Masum et al. [25] studied the combustion and emissions of methanol, ethanol, butanol and pentanol blended with 80 vol.% gasoline. They found that all alcohol blends displayed better engine torque and lowered emissions relative to gasoline. Costagliola et al. [26] studied performance and emissions of various gasoline/alcohol blends. They found an increase in global efficiency and a reduction in emissions using the blends. Williams et al. [27] investigated a series of conventional and alcohol fuels and concluded that thermal efficiency, combustion, and emissions were not adversely affected as a result of adding any butanol to gasoline. Dernotte et al. [28] evaluated the combustion and emissions characteristics of butanol–gasoline blends in a port fuel injection (PFI) SI engine. The results demonstrated that a 40% butanol/60% gasoline blend by volume minimized HC emissions and no significant change in NO_x emissions were observed with the exception of the 80% butanol/20% gasoline blend. The addition of butanol improved combustion stability and reduced ignition delay (0–10% MFB). The change of specific fuel consumption of B40 blend was within 10% of that of pure gasoline for stoichiometric mixture. Wigg et al. [29] showed that blends containing below 40% volume of butanol offered similar unburned hydrocarbon (UHC) emissions to gasoline, but higher hydrocarbons (HC) levels than pure gasoline at higher butanol concentrations. The results also indicated a slight increase in brake specific fuel consumption (BSFC) with the butanol addition. Venugopal and Ramesh [30] studied engine performance with simultaneous injection of butanol and gasoline, as well as blended fuels. On the whole, at all operating conditions, simultaneous injection results in reduced HC levels and improved or similar performance as compared with B50 (injection of fixed blend). Gu et al. [31] studied combustion in a spark-ignition engine fueled with gasoline–n-butanol blends. It was found that, HC, carbon monoxide (CO) and NO_x emissions fueled with gasoline and n-butanol blends are lower than those of gasoline. Pure n-butanol increased the HC and CO while decreased the NO_x; these tendencies were similar to [28]. Yacoub et al. [32] performed several studies on application of straight-chain alcohols C1–C5 (methanol to pentanol) as fuels blended with gasoline. The study showed that all alcohol–gasoline blends showed reduction in CO emissions, and total hydrocarbons (THC) emissions were also reduced at optimized operating conditions. However, all blends had a higher unburned alcohol emission than gasoline, with the highest emissions coming from those with the highest alcohol content. Aldehyde emissions were higher for all blends with formaldehyde as the main constituent and the NO_x emissions may increase or decrease depending on different operating conditions. Szwaja and Naber [33] investigated the combustion characteristics of n-butanol in a single cylinder engine and results indicated that the highest peak pressure advanced with the increase of n-butanol ratio due to a faster combustion and the crank angle degree (CAD) of 50% mass fraction burn (MFB) for n-butanol was approximately 2° earlier when compared to gasoline. Wallner et al. [34] investigated the combustion, performance, and emissions of pure gasoline, 10% ethanol (E10) and 10% butanol (Bu10) blends in a direct-injection (DI) four-cylinder SI engine. Results showed that the burning velocity of the Bu10 was higher than those of both E10 and gasoline. Their further study [35] demonstrated that addition of alcohol to the fuel blend results in a consistent reduction in NO_x emissions regardless of operating point. Both formaldehyde and acetaldehyde emissions increased with the addition of butanol, whereas formaldehyde did not increase significantly with addition of