Combined Effects of a Biobutanol/Ethanol–Gasoline (E10) Blend and Exhaust Gas Recirculation on Performance and Pollutant Emissions

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ABSTRACT: Butanol is attracting more attention as an alternative fuel. The performance and emissions of butanol/ethanol–gasoline (E10) was investigated in a spark ignition engine. Exhaust gas recirculation (EGR) was employed to improve the engine performance and emissions in this reported test. The experimental results showed that high brake thermal efficiency (BTE) was observed with a high proportion of blended fuels in comparison to E10. During EGR operation, the introduction of butanol changed the combustion behavior, including prolonged ignition delay, shortened rapid burning duration, a reduced knock number, and knock intensity. The brake-specific fuel consumption (BSFC) increased with butanol addition, and when EGR was introduced, it decreased similarly to E10. The butanol–E10 blends exhibited lower exhaust gas temperature in comparison to E10 at various EGR rates. Hydrocarbon emissions from the blends increased slightly with the increased EGR rate, whereas CO emissions decreased. EGR exhibited high inhibition of NOx emissions for both blended fuels and E10, which were reduced by more than 80%. The NOx emissions from the blended fuels were 20–30% less than that of E10 with or without EGR conditions. Finally, EGR contributed to a reduction in BSFC and improvement in BTE for the butanol–E10 engine. The butanol–E10 blends exhibited a similar power performance, slightly reduced combustion stability, and acceptable emissions with respect to the baseline conditions.

1. INTRODUCTION

Fossil fuel is an important source of energy as well as a chemical raw material, serving a variety of anthropogenic activities. Transportation consumes more than 25% of the world’s petroleum resources and produces a large amount of carbon dioxide emissions and pollutant emissions.1,2 One feasible short-to-midterm solution to the overdependence on fossil fuels is to replace them with renewable bioalcohol fuels.3,4 Biofuels can be made from plants, sugars, grains, plant fibers, and other natural materials. Bioethanol is already utilized in Brazil, the United States, China, and other nations.5,6 Anhydrous bioethanol–gasoline (ethanol 10% by volume), containing bioethanol mainly produced by corn, is available on the Chinese market. There are indeed millions of cars running on ethanol–gasoline (E10) in several provinces of China today. Arguably, there will be tens of millions of vehicles fueled with ethanol–gasoline in the future as regulations grow ever stricter regarding petroleum consumption and dependence. Bioalcohols are carbon-containing, so they are intermediate products of the carbon cycle. Carbon-containing biofuels are known to significantly reduce carbon emissions.7,8

Bioethanol has been accepted and widely used as an additive source of transportation fuel.9 Ethanol–gasoline can reduce engine-out emissions such as CO, hydrocarbon (HC), and particles.10,11 Ethanol’s octane number is higher than that of gasoline, which reduces the knock tendency. Ethanol’s heat of vaporization (HOV) is also about three to four times higher relative to gasoline, which enhances the volumetric efficiency owing to the cooling effect on intake charge. However, its higher HOV negatively influences fuel evaporation and atomization.12 The ethanol has a higher laminar flow speed (LFS) relative to gasoline, which is beneficial to extract useful work in the expansion stroke owing to an improvement in concentrated heat release.13 However, there is a penalty of fuel economy owing to ethanol’s low energy content. The three-way catalytic under ethanol–gasoline conditions, however, has conversion efficiency as high as that under gasoline conditions.14

Biofuel addition to gasoline has been gradually accepted by the global market.15,16 In addition to bioethanol, biobutanol is a promising biofuel.17 There are four isomers for butanol: n-butanol, isobutane, sec-butanol, tert-butanol, and saturated alcohols with four carbon atoms in butanol.18,19 1-Butanol is acknowledged as a type of n-butanol wherein there is a unbranched composition with –OH on the end carbon.20 Biobutanol is considered to be the next generation of renewable fuel; it has
similar combustion properties to gasoline, is less corrosive than ethanol, and has lower vapor pressure, making it markedly safer.21,22 The physical and chemical properties (e.g., high octane number, oxygen content) of butanol make it very suitable as an alternative fuel. It has been shown to optimize ignition timing to significantly improve engine efficiency over other biofuels.23 Butanol addition also reduces engine-out pollutant emissions, such as unburnt HC and carbon monoxide (CO) and has low coefficient of variation (COV) of indicated mean effective pressure (IMEP).24–26 Its high HOV and low adiabatic flame temperature also help to minimize NOx emissions. However, butanol exerts some negative effects on the engine including cold start issues. Although the low heating value (LHV) of n-butanol is high relative to ethanol or methanol, it is still lower than that of gasoline, resulting in a fuel consumption penalty in high-proportion butanol–gasoline blends.27

Exhaust gas recirculation (EGR) technology is applied to spark ignition (SI) engines to minimize NOx emissions by reducing combustion temperatures.28,29 EGR technology also improves the engine thermal efficiency because of a decrease in throttle loss and heat transfer losses to the chamber surfaces under partial loads.30,31 The specific heat of the working fluid increases because of the introduced EGR and contains large amounts of triatomic gas, which contributes to useful work extraction in the working stroke.32 Moreover, EGR is beneficial to reduce the engine knock tendency and optimize ignition timing to improve engine thermal efficiency. However, the inactive gas in EGR slows down the combustion process and leads to reduced combustion stability; this is why it is impossible to further increase the EGR rate.33,34

The purpose of this paper is to appraise and further understand the effect of biobutanol addition on an ethanol–gasoline (E10) engine. In terms of performance improvement and exhaust emissions reduction, the potential benefits of EGR technology is evaluated in conjunction with a butanol/ethanol–gasoline blend in an SI engine.

2. EXPERIMENT SETUP

2.1. Engine and Instrumentation. This study was carried out in a single-cylinder, naturally aspirated, SI engine. The schematic of the experimental system is illustrated in Figure 1. The engine specifications are illustrated in Table 1. The engine crankshaft coupled with an ergometer (Mai-kai CW50) controlled the engine speed and torque. An externally cooled EGR unit was employed to allow tail-pipe gas to flow into the intake manifold, employing a manual EGR valve to control the flow rate. Engine exhaust emissions were measured through five-gas emissions analyzer (AVL Digi 4000) and these included CO, NOx, and UHC. Engine intake flow was measured using an air mass flow sensor (BOSCH HFMS) and an intake pressure sensor (Kistler 601CBA). Fuel flow was measured through a fuel meter (SHNRJ FCM-D). The cylinder pressure was measured through a piezoelectric sensor (Kistler 6124A) fixed on the engine cylinder head, and cylinder pressure signal was collected and calculated using a combustion analyzer (Kistler KiBox). An optimal encoder with 0.6° resolution was used to measure the crankshaft speed. A general engine electronic control unit (ECU) was employed to manipulate the throttle position, fuel injection, and spark timing of the engine.

2.2. Experimental Procedures. In the reported research, the engine speed was fixed at 2300 rpm/min and the manifold absolute pressure (MAP) was kept at 78 kPa. The EGR dilution was performed by controlling the EGR gas flow rate using an EGR valve. During EGR operation, the fuel–air mixture was maintained at a set stoichiometric ratio and was controlled in a closed loop by the ECU and an oxygen sensor (BOSCH LSU4.9) attached to the tail pipe. The EGR gas was cooled using a cooling unit so that the temperature of the EGR gas was not higher than 320 K. After the engine was started, it was warmed up for approx. 30 min until the cooling water warmed up. During the experiment, the temperature of the engine cooling water was controlled between 80 and 90 °C. High-purity 99.5% n-Butanol was used in the experiments. The additive was added to the ethanol–gasoline in a volume ratio of 15 and 30%. The properties of the fuel are illustrated in Table 2. Butanol’s energy density is about 23% lower than gasoline, so it was necessary to improve the pulse width of fuel injection to achieve stable engine power output.
The burning characteristics of the engine were determined as per the collected in-cylinder pressures. A consecutive 200 cycles were collected to assess burning behaviors and combustion stability.

The cylinder pressure data for 200 cycles were collected and analyzed, and these data were used to calculate the COV of IMEP. The formula for calculating the COV is as follows

$$\text{COV}_{\text{IMEP}} = \frac{\sigma_{\text{IMEP}}}{P_{\text{IMEP}}} \times 100$$

where $P_{\text{IMEP}}$ is the IMEP value and $\sigma_{\text{IMEP}}$ is the standard deviation.

The EGR rate was calculated according to the CO 2 concentration in the intake and the CO 2 concentration in the exhaust gas. The calculation formula for the EGR is as follows

$$R_{\text{EGR}} = \frac{(\text{CO}_2)_{\text{in}}}{(\text{CO}_2)_{\text{ex}}} \times 100$$

where $(\text{CO}_2)_{\text{in}}$ is the CO 2 concentration of intake air, $(\text{CO}_2)_{\text{ex}}$ is the CO 2 concentration of exhaust gas.

### 3. RESULTS AND DISCUSSION

The cylinder pressures in the chamber when using blended fuels are shown in Figure 2. As shown, the engine speed was 2300 rpm/min and the MAP was 78 kPa. The engine cylinder pressure developed with the blended fuels exhibited a small decrease and retardation in comparison to E10. The energy density of butanol is lower relative to E10 because the LHV of n-butanol is about 23% lower compared with gasoline (n-butanol 33.1 MJ/kg, ethanol–gasoline 41.3 MJ/kg). This meant that when butanol was present, more fuel needed to be sprayed into the engine to maintain the engine power performance. The theoretical air–fuel ratio of blended fuels decreased because of the addition of butanol. In addition, n-butanol’s latent HOV is high (380–500 and 716 kJ/kg for gasoline and butanol, respectively), contributing to lower cylinder temperatures and retarded maximum pressure.

The EGR generally produces reduced combustion stability in SI engines. In this reported test, the combustion stability of the butanol–E10 blends was measured and evaluated. The COV of blended fuels is demonstrated in Figure 3. As can be observed in this figure, there was a small increase in the COV for blended fuels during EGR operation. The combustion stability of ethanol–gasoline was better than the butanol–gasoline blends with small EGR rates (less than 20%). At high EGR rates, the COV of the blended fuel was similar to that of ethanol–gasoline. Butanol has a much higher viscosity and higher HOV than gasoline, so the fuel injection and atomization of the blended fuels degraded with the addition of butanol, which produced a lower quality mixture with slightly worse combustion stability.

The peak cylinder pressure distribution under EGR conditions is shown in Figure 4. As shown, the cylinder pressure distribution was more concentrated in the low-proportion blends than in high-proportion blends without EGR conditions. During EGR operation, the cylinder pressure distribution for high proportion blends was more concentrated. The oxygen content of butanol contributed to the combustion, especially at the high EGR rate when the concentration of oxygen in the cylinder was lower. The laminar flame speed of butanol is higher relative to gasoline. At high EGR rates, the COV of the blends was similar to that of ethanol–gasoline, possibly owing to the higher oxygen content of blended fuels and their higher laminar flame speed in comparison with E10.

The combustion process of the butanol–E10 blends was evaluated and the results are shown in Figure 5 with ignition delay (CA0-10) and rapid burning duration (CA10-90). During the EGR operation, the ignition delays of blended fuels were significantly longer than those of E10. However, the rapid burning duration of blended fuels was slightly less than that of E10 at a high EGR rate. Butanol’s high HOV and viscosity caused a reduction in the equality of the mixture, and the mixture temperature in the chamber was reduced, which produced a slower combustion at the initial stage of combustion and an increase in CA0-10. In addition, the oxygen content of butanol and its higher laminar flame velocity increased the velocity of flame propagation during EGR operation, so the rapid burning duration of blended fuels was slightly shorter than ethanol–gasoline.

### Table 2. Fuel Properties

| fuel property | gasoline | n-butanol | ethanol–gasoline (E10) |
|---------------|----------|-----------|------------------------|
| chemical formula | C2–C12 | C4H9OH | |
| density [kg/m³] | 747 | 810 | 752 |
| stoichiometric air/fuel ratio [-] | 14.7 | 11.2 | 14.1 |
| mass share of O [%] | 0 | 21.5 | 3.67 |
| LHV [kJ/kg] | 43 | 33.3 | 41.3 |
| viscosity [mPa·s] | 0.4–0.8 | 2.57 | |
| Laminar flame speed (m/s) | 51 | 58.5 | 52.1 |
| latent HOV [kJ/kg] | 380–500 | 716 | |
| octane number (R/M) | 88–98/80–88 | 104/89 | |

![Figure 2. Effects of EGR and blends on in-cylinder pressure.](https://dx.doi.org/10.1021/acsomega.9b03303)

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Engine knock using the blended fuels was evaluated and the results are shown in Figures 6 and 7. As shown in this figure, when knock occurs during the combustion progress, the cylinder pressure curve is accompanied by pressure oscillation. The knock index decreased with the increased butanol ratio in the blended fuels, and the engine knock tendency of the high-proportion blends was smaller than that of the low-proportion blends. For both high and low proportions of blended fuels, the EGR exhibited significant suppression in the knock number and its intensity. As the octane number of butanol is slightly higher relative to gasoline, the knock of the high-proportion blends was reduced. The suppression of knock by the EGR contributed to optimization of the ignition timing and improvement in the engine thermal efficiency.  

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The brake-specific fuel consumption (BSFC) of blended fuels is demonstrated in Figure 8. When compared to ethanol–gasoline, the BSFC of the blended fuels was higher. As the content of butanol was increased, the BSFC continued to increase. The increase in BSFC was due to butanol’s lower energy density relative to gasoline. For the blended fuels, the EGR clearly reduced the BSFC because of a decrease in throttling loss and heat transfer loss.  

The brake thermal efficiency (BTE) of the engine is shown in Figure 9. The BTE of the engine with high-proportion blends was closer to E10. The BTE increased when high quantities of butanol were
present in the blended fuels. For blended fuels, the gas temperature in the chamber decreased, and this decrease in the temperature in the cylinder was reflected by the decrease of the exhaust temperature (Figure 10); the reduced heat transfer to the chamber surface contributed to improve BTE.

The exhaust gas temperature of the engine run on the blended fuels was measured and the results are shown in Figure 10. As shown, during the EGR operation, the exhaust gas temperature for the blended fuels was lower than that of E10. EGR caused the exhaust gas temperature to decrease significantly. The results were consistent with previous research about alcohol addition.26,27 When run on blended fuels, the engine’s exhaust temperature was lower than on E10 with or without EGR. With the increased blending ratio, the temperature of the engine exhaust gas further decreased. The reduced energy density of the blended fuels caused a reduction in combustion heat release although the reduced stoichiometric ratio required more fuel. The increased HOV also contributed to low temperature in the compression stroke. The lower exhaust temperature indicated a lower in-cylinder temperature, which resulted in less heat transfer losses to chamber surfaces and a higher engine thermal efficiency.

The engine gaseous emissions were measured. The unburnt HC emissions are shown in Figure 11. Unburnt HC emissions increased slightly when the EGR was used. At high EGR rates, HC emissions using the blended fuels increased significantly over those when E10 was used. During EGR operation, the temperature in the cylinder decreased, which contributed to a reduction of the wall temperature, and an increased quenching effect of the cylinder wall produced more HC emissions.36 In addition, the reduced in-cylinder temperature with blended fuels also produced increased HC emissions.

The CO emissions from blended fuels are shown in Figure 12. The CO emissions from blended fuels were slightly lower in comparison to E10. The addition of butanol increased the oxygen content of the blended fuels, which in turn increased the oxidation of CO in the late burning stage.37 At the same time, the reduced in-cylinder temperature with blended fuels also produced increased CO emissions.
time, the engine adopted a closed-loop control strategy through the oxygen sensor (fixed in the tail-pipe), and the fuel injection pulse width was determined from the oxygen concentration in the exhaust gas. This resulted in a small change in the concentration of CO emissions.

The NO\textsubscript{x} emissions from the exhaust tailpipe are shown in Figures 13 and 14. As shown, the NO\textsubscript{x} emissions for blended fuels was reduced during EGR operation. The butanol−E10 blends had lower NO\textsubscript{x} emissions than E10. Under EGR condition, the burning temperature and oxygen content in the cylinder were both decreased, which produced a significant reduction in NO\textsubscript{x} emissions. A high cylinder temperature and an oxygen-enriched environment are the key factors in the formation of NO\textsubscript{x}.\textsuperscript{28,31} EGR operation reduces both the burning temperature and oxygen concentration in the chamber, leading to a significant reduction in NO\textsubscript{x} formation. Compared to E10, the combustion temperature of the blended fuel was lower, which also contributed to the reduction of NO\textsubscript{x}. EGR operation can reduce NO\textsubscript{x} emissions by more than 80% and use of blended fuels reduced NO\textsubscript{x} emissions by 20−30% compared to E10.

The torque, BSFC, and BTE of the engine under different loads were measured and the results are shown in Figure 12. The throttle opening was increased from 20 to 60%. The data showed that the butanol/ethanol−gasoline yielded a torque output that was comparable to E10. At high loads, the engine BSFC decreased and higher thermal efficiency was achieved. The BSFC of the high proportion blends was closer to E10 under various loads. For the blended fuels, the heat transfer losses from the engine decreased, which improved the thermal efficiency. In addition, the duration of the combustion of the blended fuels was shortened, because the combustion heat release was more concentrated, which also improved the thermal efficiency of the engine.

4. CONCLUSIONS

In this reported research, the combustion and pollutants in an SI engine with butanol/ethanol−gasoline were investigated. EGR was employed to enhance the fuel economy of the butanol−E10 engine. The basic conclusions of this study are as follows:

Butanol/ethanol−gasoline exhibited an extended ignition delay and shorter CA10-90 than E10 during EGR operation. Butanol−E10 blends showed a slightly lower combustion stability. The addition of butanol reduced the engine knock tendency, and the intensity and frequency of the knock for the high-proportion blends was reduced clearly.

The butanol−E10 blends exhibited a power performance that was similar to that of E10. The BSFC of blended fuels was higher relative to E10 because of its lower energy density. The BTE of high-proportion blended fuels was higher than low-proportion blends and was closer to that of E10.

The NO\textsubscript{x} emissions of butanol/ethanol−gasoline blends were greatly reduced. At the high EGR rate, the NO\textsubscript{x} emissions were reduced by more than 80%. The butanol−E10 mixture emitted 20−30% less NO\textsubscript{x} than E10. The HC emissions from the butanol blends increased slightly with increased EGR rate, and was slightly higher than E10. CO emissions were slightly less for the blended fuels than for E10. EGR had little effect on CO emissions for blended fuels.

In summary, the butanol−E10 engine had an output power that was comparable to that of the E10 engine. Use of EGR technology can improve the fuel economy of the butanol−E10 engine and can provide an acceptable BTE. Overall, there appeared to be reduced exhaust emissions from engines with blended fuels.

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