Combined Effects of Cooled EGR and Air Dilution on Butanol–Gasoline TGDI Engine Operation, Efficiency, Gaseous, and PM Emissions

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ABSTRACT: Biobutanol is a promising alternative fuel for spark-ignition engines. Exhaust gas recirculation (EGR) and air dilution were evaluated on a TGDI engine fueled with butanol–gasoline (B20) in view of engine operation, efficiency, gaseous emissions, and PM emissions. For the B20 engine, EGR affected combustion more strongly than excess air dilution; the brake thermal efficiency (BTE) under excess air dilution was much higher than that with EGR. The oxygen concentration in the cylinder was also markedly reduced with EGR relative to air dilution, as the partial fresh charge was substituted with nonreactive gas. A reduced oxygen concentration contributed to differences in combustion between excess air dilution and EGR. Higher BTE was observed during combined EGR and excess air dilution operation, though it was slightly lower than that under excess air dilution alone. NOx was also markedly reduced by the combination of EGR and excess air dilution, but was slightly higher than that with EGR alone. Under combined dilution conditions, the particle number (PN) emissions from the B20 engine were reduced significantly, particle sizes decreased, and the nucleate PN significantly decreased.

1. INTRODUCTION

The emission and fuel consumption of GDI vehicles have garnered a great deal of research attention as they have grown increasingly ubiquitous. GDI technology may significantly improve engine efficiency and reduce harmful exhaust emissions.1 However, GDI vehicles fall under increasingly stringent vehicle emission regulations as they emit more particulate matter (PM) than PFI engines.2,3 Lower carbon emissions than fossil fuels can be achieved with biofuels, as biofuels are an intermediary in the carbon cycle.4 In addition, the addition of alcohol is generally beneficial to reduce engine-out regular and PM emissions.5 Butanol is a 4-carbon atomic alcohol and a promising renewable alternative fuel.6 Butanol can be produced by biomass fermentation; its production technology is rapidly growing more sophisticated.7 Compared with ethanol or methanol, butanol’s combustion characteristics are closer to that of gasoline. The energy density of butanol is also higher than that of ethanol.8 The antiknock properties of butanol are similar to those of gasoline due to their close octane numbers.9 Butanol has been regarded as the most promising potential alternative fuel for spark ignition (SI) engines. According to the US Department of the Energy’s Fuel and Engine Program, butanol is currently being prepared for mass production as a second-generation biofuel.10 Butanol is less corrosive to the fuel supply system, and engine modification is not required.11 Butanol is miscible with gasoline, does not absorb water vapor from the air, has low volatility, and is generally safe.12 According to the existing research, butanol additives can reduce engine emissions such as carbon monoxide (CO), nitrogen oxides (NOx), and carbon dioxide (CO2).13 However, the latent heat of vaporization of butanol is much higher than that of gasoline (although it is lower than that of ethanol).14 In addition, the viscosity of butanol is much higher than that of gasoline, and its saturated vapor pressure is much lower.15 All of the above have a negative impact on the evaporation and atomization of fuel. The hydrogen carbon (HC) emissions also markedly increase when the proportion of butanol blended with gasoline exceeds 30%.16 Although butanol has a high low calorific value compared to ethanol or methanol, it is still 23% lower than gasoline resulting in a penalty of fuel consumption in the butanol or butanol-gasoline engine. The fuel consumption penalty is one of the obstacles most hindering the application of
butanol-gasoline. It is crucial to improve the thermal efficiency of butanol-gasoline engines before they can be considered practically applicable.

Charge dilution is an effective pathway to improve engine thermal efficiency. Lean burn (air dilution) technology has been shown to enhance the efficiency of gasoline engines; the essence of lean burn is excessive air dilution. The lean burn reduces particle emissions, improves the fuel economy, and enhances the engine performance. Lean burn also creates an increase in NOx emissions due to a reduction in three-way catalyst efficiency resulting in a lower combustion stability at high air/fuel ratios. The effect of lean burn on engine efficiency was investigated on a 1.4 L GDI engine using the downsizing and turbocharging technology; the results showed that the lean mixture improved engine fuel consumption. Irimescu et al. studied cycle-by-cycle variations under lean operation conditions and reported the effects of operation parameters on the coefficient of variation (COV) and fuel conversion efficiency in lean mixtures.

There have been many other valuable contributions to the literature. Park et al. explored engine-operating parameters and engine emissions under lean burn conditions as per the effect of the excess air ratio on the PM concentration and particle size distribution. A significant increase in PM emissions upon an excess air ratio of 1.5 was attributed to the transfer from premixed flames to stratified mixture flames. At an excess air coefficient of 2.0, PM and particulate number (PN) emissions again increased significantly. Zhou et al. studied the effects of lean burn and intake tumble on the engine-operating process. The results showed that the intake tumble extended the lean burn and allowed for an acceptable combustion stability. In an optical GDI engine, a lean mixture increases flame distortion, center movement, and incomplete combustion during flame front propagation compared to a stoichiometric mixture. Charge stratification leads to impingement on the chamber surface and reduces the engine stability. However, the efficiency of the three-way catalytic converter in terms of nitrogen oxidation decreases as the mixture deviates from stoichiometry.

Exhaust gas recirculation (EGR) is a charge dilution technique commonly used in diesel engines and gradually more often applied in gasoline engines which can reduce fuel consumption, reduce NOx emissions, and suppress knock. Previous studies have shown that EGR can also reduce PM emissions. EGR technology can reduce fuel consumption by introducing engine exhaust gas into the intake air to form a diluted mixture. The dilution of the intake charge reduces pumping loss and heat-transfer loss while the heat capacity of the mixture increases. Xie et al. studied the effects of EGR addition on the combustion and emissions of GDI gasoline engines and compared the effects of hot EGR with cold EGR. They found that EGR could effectively improve engine brake specific fuel consumption, reduce NOx emissions, and reduce PM emissions. The effects of EGR on NOx emissions under stoichiometric mixture were investigated in another study to find that EGR had a significant effect on NOx emissions at up to a 50% reduction. EGR also inhibits abnormal combustion at high intake pressure and reduces engine fuel consumption by about 7%. Again, EGR technology not only reduces NOx emissions and improves engine efficiency but also suppresses knock. Fontana and Galloni found that EGR affected the ignition advance angle; the demand for the fuel octane number under EGR conditions was relatively low, which suggested that EGR could optimize the ignition advance angle and yield better engine efficiency. In a previous study, we explored the effects of EGR on the performance and particle emissions of GDI engines. We found that EGR could indeed effectively reduce particle emissions. The effect of cold EGR on engine thermal efficiency is equivalent to an increase in the engine compression ratio from 9.3 to 10.9.

Combining EGR and lean burn work may enhance the engine efficiency while reducing NOx emissions, but further research is needed to confirm this. Previous studies have compared EGR with lean burn to investigate the combustion, performance, and emissions of the engine in both modes. Vancollie et al. investigated the lean-burn and EGR in methanol engines, the relative efficiency improvements up to 20% were achieved at part load. Park et al., for example, studied a combination of EGR and lean burn in a hybrid engine based on H2 and natural gas. The effects of EGR under stoichiometric mixture and lean mixture conditions were investigated alongside the effects of dilution rates (DRs) on engine performance and emissions. The results showed that engine thermal efficiency under EGR was lower than that under the lean burn mode that hydrocarbon emissions under the lean burn mode were lower than those under a stoichiometric mixture and that NOx decreased slightly with increasing dilution under lean burn conditions.

The effects of EGR compositions on combustion and NOx emissions were studied in SI CNG engines and found that CO2 had a more significant effect on combustion and NOx emissions than N2. Lee et al. studied the dilution effects of EGR/lean burn in low caloric gas engines in terms of their comparative effects on engine combustion and emissions. The dilution range with EGR was found to be narrower than that with the lean burn. Under similar operation conditions, more heat release and a higher peak under lean burn conditions were obtained as well. The effect of EGR on O2 concentration is more significant than that of specific heat; lean burn has a more significant effect on the fuel economy than EGR, and EGR is more effective in reducing NOx emissions as HC emissions increase. When the DR is increased to the dilution limit, lean burn and EGR nearly meet legal emission regulations though efficiency is slightly reduced. Although the individual effect of EGR and lean burn on combustion and emissions are well-documented, there has been little research on the effects of combining them. This information is valuable to researchers, especially in terms of the combined effects on particle emissions.

Although a few researches have been carried out in the butanol-gasoline engine under EGR or lean burn conditions, however, the combination and interactions of EGR and air dilution on the B20 engine is rarely reported, especially for PM emissions while two dilution modes operate together. The contribution of this investigation was to explore combined EGR and air dilution to improve the fuel economy and emissions of B20 engines. In this study, we evaluate the combined effects of EGR and lean burn on B20 engine efficiency and emissions. The PM emissions of B20 engine were investigated and compared under EGR, air dilution and EGR–air dilution conditions.

2. EXPERIMENTAL SETUP AND METHODOLOGY

2.1. Experimental Setup. The EGR/lean burn experiment was conducted on a four-cylinder GDI engine fueled with B20. The engine characteristics are listed in Table 1. As shown in Figure 1, the test bench was composed of an engine, dynamometer, emission test system, combustion test system, and engine electric controller. The engine was directly connected to a dynamometer which controlled the engine
speed and load. Coolant temperature, intake air flow, and other engine operating parameters were collected on an integrated data acquisition system. The gas emissions were detected by a gas analyzer (ALV Digi 4000) (Table 2), and the air–fuel ratio was detected by a lambda meter (ETAS La4) and an oxygen sensor (Bosch LSU 4.9) mounted in the exhaust pipe. The crankshaft position information was measured by an angle gauge, and the cylinder pressure was measured by a cylinder pressure sensor (Kistler 6114B) mounted on the spark plug. The crankshaft angle signal and cylinder pressure signal were recorded on a combustion analyzer (DS-0928, Ono). The particulate emissions were measured with a particulate emission meter (TSI 3090). The engine exhaust gas was diluted by a two-stage dilution system and then pumped into the particulate emission meter via the pumping system. The measurement range of the particulate emission meter was 5.6–560 nm. The measurement frequency was 10 Hz.

2.2. Experimental Methods. The engine was operated in a speed of 2500 rpm and a load of 25%, which was the typical working condition in the WLTC cycle. The engine introduced external cooling EGR to dilute the intake air. The EGR flow rate was adjusted throughout the test as necessary by a manual valve; the EGR temperature was not more than 35 °C while the intake temperature was 21 °C. Base gasoline was purchased from Beijing Petroleum Company (95#). The addition volume rate of 20% iso-butanol to 80% gasoline was expressed here as “B20”. Butanol has a lower low heating value than gasoline. The fuel injection pulse was increased after butanol addition to maintain the engine power performance.

![Schematic diagram of experimental setup.](https://dx.doi.org/10.1021/acs.omega.9b04279)
where \( m_{\text{charge dilution}}, m_{\text{a, st}}, m_{\text{f}} \) represent the intake mass flow, the mass flow of air for the stoichiometric mixture, and the mass flow of fuel, respectively. For EGR dilution, \( m_{\text{charge dilution}} \) represents EGR mass flow. In the case of a lean mixture, \( m_{\text{charge dilution}} \) represents the mass flow of excess air. The DR is the ratio of the mass flow of excess air to the total inlet flow, which was written as follows\(^3\)

\[
\text{Dilution rate} = \frac{m_{\text{a, actual}} - m_{\text{a, st}}}{m_{\text{a, actual}} + m_{\text{f}}} \times 100\%
\]

where \( m_{\text{a, actual}} \) represent the mass flow rate of actual inlet air.

Cylinder pressure data over 250 cycles were collected continuously on a cylinder pressure sensor, then filtered, and averaged as the basic data for calculating the cylinder pressure, heat release rate, and other information. The COV was calculated as follows\(^3\)

\[
\text{COV}_{\text{IMEP}} = \frac{\sigma_{\text{IMEP}}}{P_{\text{IMEP}}} \times 100\%
\]

where \( \sigma_{\text{IMEP}} \) is the standard deviation of the peak cylinder pressure, and \( P_{\text{IMEP}} \) is the average cylinder pressure for 200 consecutive cycles.

The brake thermal efficiency (BTE) of the engine was calculated as

\[
\text{Thermal efficiency} = \frac{P_{\text{brake}}}{m_{\text{f}} \times \text{LHV}_{\text{fuel}}} \times 100\%
\]

where \( P_{\text{brake}} \) is the engine brake power, \( m_{\text{f}} \) is the fuel consumption rate, and \( \text{LHV}_{\text{fuel}} \) is the lower heating value of the fuel.

The particle concentration and particle size were in this experiment on a Model 3090 (TSI EEPS System) in the sample exhaust gas per unit volume. The surface area of the (spherical) particle per unit volume of the exhaust gas was calculated accordingly. Equation 6 was used to calculate the particulate concentration, and eq 7 was used to calculate the total particulate concentration. Equation 8 was used to calculate the particulate surface area concentration, eq 9 to calculate the mean particle size, and eq 10 to calculate the median particle size.

\[
n = \frac{c \times \Omega}{tQ \gamma}
\]

\[
N = \sum n
\]

\[
s = \pi D_{l}^{2} n
\]

\[
N = \frac{\sum n_{i} D_{i}^{2}}{N}
\]

\[
N = D_{l}(N/2)
\]

where \( c \) represents particle counts per channel, \( t \) is the sample time, \( Q \) is the sample flow rate, \( \Omega \) is the sample dilution factor, \( \gamma \) is sample efficiency, \( D_{i} \) is the particle diameter (channel midpoint), \( u \) is the upper channel boundary, and \( l \) is the lower channel boundary.

### 3. RESULTS AND DISCUSSION

In this test, a comparative evaluation of EGR and air dilution was conducted in an SI engine fueled with 20% vol butanol blends.

The combined effects of EGR and air dilution on combustion, gaseous emissions, performance, and PM emissions were assessed and shown in the results.

#### 3.1. Effects of EGR Versus Lean Burn on Combustion.

The oxygen concentrations after dilution were calculated as shown in Figure 2 to determine the influence of EGR and lean burn modes. Under lean burn conditions, the air dilution did not change the oxygen concentration in the cylinder. When EGR was added, the oxygen concentration in the cylinder decreased rapidly from 21 to 16.4% at a DR of 23.7%. The oxygen concentration with EGR dilution was significantly lower than that under lean burn, which can raise the misfire limit due to excess air dilution.\(^4\)

Under an engine speed of 2500 rpm, a brake mean effective pressure (BMEP) of 4.5 bar, and a ignition time of 20°CA BTDC, the effects of excess air dilution on the cylinder pressure of the B20 engine are as shown in Figure 3. The effect of EGR dilution on the cylinder pressure of the B20 engine is shown in Figure 4. The combustion speed under both dilution operations...
decelerated, the phase of the peak cylinder pressure was progressively retarded, and the peak cylinder pressure decreased gradually as the DR increased. At a similar DR, EGR dilution caused a more considerable decrease in the cylinder pressure over air dilution. This was attributable to the addition of nonreactive gas into the in-cylinder mixture after EGR introduction resulting in a decrease in burning velocity.43 When the EGR DR was high, the peak cylinder pressure and the heat release rate decreased significantly; the combustion phase was markedly delayed and the combustion deteriorated. The maximum heat release rates of the B20 mixture under the dilution of EGR and excess air were compared as shown in Figure 5. At low DRs (EGR DR 6%, excess air DR 7%), the peak heat release rate under lean burn was higher than that under EGR dilution conditions. The phase corresponding to the peak heat release rate was unchanged. Under high dilution (17%) for excess air, the peak value and phase of heat release rate decreased only slightly. However, under EGR dilution (15%), the peak heat release rate value decreased substantially and the phase of the heat release rate was significantly delayed, although fuel oxygenation drove a strong burn. When EGR was used, the oxygen concentration in the cylinder decreased. EGR increased the concentration of CO2 and H2O in the cylinder, so the specific heat ratios of the fresh charge increased and the combustion temperature decreased; the addition of nonactive gas slowed down the combustion heat release process at this time as well.44

As shown in Figure 6, the COV value increased gradually with increased DR indicating that the combustion stability of the B20 engine deteriorated. The COV value under EGR dilution increased faster than that under excess air dilution. The COV value at EGR 21% was nearly 3%. EGR dilution resulted in fuel, and O2 being interrupted because of the increase in the burnt product as CO2 and water vapor markedly increased.43 Excessive air led to an increase in the specific heat capacity of the intake charge and a decrease in the flame temperature. A relatively constant oxygen concentration had little effect on combustion activation.45

As shown in Figure 7, the ignition delay duration (CA0-10) and rapid burning duration (CA10-90) of B20 increased with increased DR, while the ignition delay duration and rapid burning duration did not significantly change under excess air dilution. When EGR was added, CA0-10 and CA0-90 increased rapidly. EGR appeared to have increased the specific heat capacity of the intake charge, inhibited the combustion of the mixture, slowed the combustion chemical reaction process, and reduced the burning velocity of the mixture in this test. Figure 7 shows that EGR had a more pronounced effect on flame propagation than the lean burn; the CA0-10 duration with 15% DR of EGR was almost equal to that with 25% DR of excess air. The rapid burn duration was more affected by EGR than by excess air because the oxygen content under excess air dilution was higher than that under EGR dilution. A previous study on natural gas and hydrogen showed that the effect of EGR on combustion was mainly attributable to a lower oxygen fraction.46

For SI engines, the intake air need be throttled to control the load, which caused a negative intake manifold pressure in suction strokes, resulting in high pumping losses at light loads.47 The pumping losses of the test engine were calculated through the pressure curves during intake and exhaust strokes. The pumping losses are shown in Figure 8 during EGR and air dilution operation. The pumping losses decreased with increasing dilution ratio. The decrease in pumping losses under EGR dilution was more pronounced relative to that under air dilution. The contribution of pumping losses was assessed as
PMEP (0.12 bar)/BMEP (4.5 bar) = 2.6%. During air dilution operation, the pumping loss decreased about 0.1 bar while the BTE showed an improvement from 20.6 to 26%, which was an increase of 5.4%. The results showed pumping loss reduction partly contributed to the BTE improvement during air dilution. The throttling loss was somewhat smaller for EGR dilution due to smaller throttling at the same dilution ratio. The reduced pumping losses contributed to an increased engine efficiency during dilution operation.

The combustion efficiency of this test engine is shown in Figure 9. There were increased combustion efficiencies during EGR and air dilution. The increase in combustion efficiency was more pronounced for air dilution than that under EGR conditions. The combustion efficiency began to decrease at a high dilution ratio because of degraded burning such as longer burning duration and reduced burning stability. The oxygen content under air dilution promoted the oxidation of CO to CO₂. Adding excess oxygen was helpful to more complete burning and improved the engine theory efficiency (higher ratio of specific heat).²⁸

3.2. Effects of EGR Versus Lean Burn on Engine Performance and Emissions. The BTE trends of B20 at a engine speed of 2500 rpm, BMEP of 4.5 bar, and ignition of 20°CA BTDC are shown in Figure 10. The BTE (BTE) of the B20 engine increased from 21 to 27% during excess air dilution operation. Under the action of EGR, the engine efficiency did not significantly change; it increased by 1–2% under moderate EGR dilution. As the DR increased, in order to maintain the engine power output, the throttle opening was increased to boost the fresh charge into the cylinder thereby reducing the pumping loss and increasing the engine efficiency.⁴³ The reduction in heat-transfer losses to the chamber walls can be attributed to the reduction in combustion temperature owing to EGR and air dilution. At a higher EGR DR, increased CO₂ and water vapor inhibited the combustion reaction.²⁸ The combustion was delayed in this case resulting in low combustion efficiency and combustion stability leading to a decline in overall engine efficiency.

The effects of EGR and excess air dilution on B20 engine emissions are shown in Figure 11. The NOₓ emissions from the stoichiometric mixture with EGR were compared to those under the lean-burning mode. NOₓ emissions were almost linearly suppressed as the EGR DR increased. The addition of EGR caused an increase in triatomic gas, which increased the intake charge specific heat and decreased the oxygen concentration, driving down the combustion temperature. High temperature and enriched oxygen were important predictors of NOₓ production.⁴⁹ As expected, the NOₓ emissions decreased slightly as the excess air rate increased due to a decrease in combustion temperature under lean burn conditions.

As shown in Figure 11, HC emissions from the B20 engine gradually decreased as the air DR increased, and the effect of the lean mixture on the reduction of emitted HC grew more obvious. The increased oxygen content was beneficial for the oxidation of hydrocarbons.⁴⁵ At a low EGR rate, HC emissions increased slightly. At a high EGR rate, HC emissions increased by up to about 20% due to the lower combustion temperature at high EGR resulting in poor evaporation of the wall fuel film.

3.3. Combined Effects of EGR and Lean Burn on Combustion, Performance, and Emissions. The combustion and performance of the B20 engine at a speed of 2500 rpm and a BMEP of 4.5 bar are shown in Figure 12 under EGR dilution, excess air dilution, and a combination of EGR and excess air conditions, where the EGR rate was 20%, excess air rate was 1.3, and combined dilution was EGR 15%/excess air 1.2. The DRs under all three operation conditions were almost equivalent. Among them, EGR showed the most significant effect on COV while excess air had the lowest COV value. The COV value under combined dilution was similar to that under solely excess air. The combustion stability under combined dilution was better than that under EGR dilution.

Under EGR dilution conditions, the combustion parameters CA0-10 and CA10-90 had the longest durations. Under the combined dilution of EGR and excess air, the combustion parameters CA0-10 and CA10-90 were similar to those under excess air dilution alone. The effect of combined dilution on the
combustion speed was higher than that under EGR alone. Under all three operation conditions, the differences in the combustion behavior were also reflected in the fuel consumption rate. As shown in Figure 12, the fuel consumption rate under EGR dilution was the highest—which represented a benchmark for fuel savings—and the fuel consumption under excess air dilution was the lowest at up to 24.2%. Under combined dilution conditions, the fuel economy significantly increased to about 21.6% compared to that under EGR dilution conditions.

As shown in Figure 13, EGR markedly reduced NOx emissions. There was a more significant reduction in NOx emissions with combined dilution than under air dilution alone. Under the combined dilution, the excess air rate and exhaust gas flow were reduced because of the excess air dilution so that the NOx emissions concentration and exhaust gas decreased. HC and CO emissions were lower under lean burn and combined dilution conditions compared to those under EGR alone. EGR drove down the combustion temperature, worsens the evaporation of the fuel film on the wall, and increased the cycle variation; in our experiment, as expected; this caused an increase in HC emissions. Conversely, the oxygen in the cylinder was sufficient under lean burn conditions. This benefited the conversion of CO to CO2 resulting in a significant reduction of CO emissions.

3.4. Combined Effects of EGR and Lean Burn on PM Emissions. We next measured PN values to evaluate the effects of combined dilution on PM emissions from the B20 engine. The results are shown in Figures 14 and 15. There was lower PN in the nuclear mode (<20 nm) under combined dilution conditions than that under air dilution alone. The PN in the agglomerated mode (>20 nm) under combined dilution was lower than that under sole EGR dilution. For premixed combustion, H-abstraction occurs at a high burn temperature, and particulates are formed. A lean burn inhibited the H-abstraction reaction due to the lower combustion temperature. Sufficient air and longer flame development together improved the mixture and reduced local rich phenomena.

The effect of EGR on particulate emissions was obvious in this experiment. When rgw EGR rate was 23%, the PN decreased...
considerably as did the concentration of nuclear particulates, while the concentration of agglomerated particulates slightly increased. When EGR and excess air dilution were combined, the PN was lower than that under excess air dilution alone but higher than that under EGR alone. The peak values of the particle surface area (PSA) concentration under combined dilution were similar to those under EGR and lean burn, respectively, but the particle size corresponding to the PSA concentration under combined dilution was smaller than that under EGR alone and larger than that under excess air dilution alone. EGR reduced the oxygen concentration in the cylinder resulting in a higher specific heat capacity in the intake charge and a decrease in the combustion temperature. A low combustion temperature inhibited primary carbonaceous particulates because of the reduced thermal pyrolysis and the H-abstraction reaction resulting in a significant decrease in the PN concentration.

As shown in Figure 16, the median particle size under EGR dilution was 26.8 nm, the median particle size under the combined dilution was 20.2 nm, and the median particle size under lean burn was 13.6 nm (the smallest of the three dilution modes). The distribution of nuclear and agglomerated particulates is shown in Figure 17. With EGR addition, the concentration of nuclear and agglomerated particulates significantly decreased. Under combined dilution, the concentration of agglomerated PM increased, but the concentration of nuclear particulates was the lowest among all the modes we tested.

4. CONCLUSIONS

The combustion, regulated emissions, and particle emissions of a B20 engine were investigated in this study. The charge dilutions of air dilution, EGR dilution and a combination of both dilution modes were investigated in the B20 SI engine. The results can be summarized as follows.

1. The effect of EGR addition on the combustion behavior was more significant than that under excess air dilution. The burning duration increased significantly, and the COV increased to 3% limit at the EGR DR of 21% while the COV limit (3%) was exceeded at excess air DR of 28%. Air dilution improved BTE up to 26.7% at a DR of 20%. EGR showed less influence on the thermal efficiency compared to excess air dilution. A decrease in efficiency was observed as the EGR DR exceeded 20%.

2. Under a combination of EGR and air dilution, the combustion behaviors and thermal efficiencies were similar to those under excess air dilution alone; higher thermal efficiency was observed and the combustion stability was better than that under EGR alone. Under combined dilution conditions, the NOx emissions were significantly reduced—to a similar extent as under EGR alone.

3. When EGR and excess air worked together in this test, the PN emissions from B20 were as low as those under solely air dilution. The PSA concentration was similar to that of EGR alone, that is, lower than that under air dilution alone. The particle sizes decreased significantly and the concentration of nucleate particles were markedly reduced under combined dilution conditions.

Future work will investigate the performance of B20 engines at cold start and idle conditions. The HC and PM emissions from the cold start stage need to be studied in SI engines. The irregular emissions will be investigated with B20 to assess the potential harmful emissions.

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Notes
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NOMENCLATURE

| Abbreviation | Description |
|--------------|-------------|
| TGD | turbo-charged gasoline direct injection |
| PFI | port fuel injection |
| B20 | butanol–gasoline (20% vol butanol) |
| BTE | brake thermal efficiency |
| SI | spark ignition |
| EGR | exhaust gas recirculation |
| BMEP | brake mean effective pressure |
| CA | crank angle |
| BTDC | before top dead center |
| ID | ignition delay |
| PME | pumping mean effective pressure |
| PM | particulate matter |
| PN | particle number |
| PSA | particle surface area |
| DR | dilution ratio |
| COV | coefficient of variation |
| HC | hydrogen carbon |
| CO | carbon monoxide |
| CO₂ | carbon dioxide |
| NOₓ | nitrogen oxides |

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