World Academy of Science, Engineering and Technology
International Journal of Mechanical and Mechatronics Engineering
Vol:12, No:10, 2018

Combustion Improvements by C_4/C_5 Bio-Alcohol Isomer Blended Fuels Combined with Supercharging and EGR in a Diesel Engine

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***Abstract*—**Next generation bio-alcohols produced from non-food based sources like cellulosic biomass are promising renewable energy sources. The present study investigates engine performance, combustion characteristics, and emissions of a small single cylinder direct injection diesel engine fueled by four kinds of next generation bio-alcohol isomer and diesel fuel blends with a constant blending ratio of 3:7 (mass). The tested bio-alcohol isomers here are n-butanol and iso-butanol (C_4 alcohol), and n-pentanol and iso-pentanol (C_5 alcohol). To obtain simultaneous reductions in NOx and smoke emissions, the experiments employed supercharging combined with EGR (Exhaust Gas Recirculation). The boost pressures were fixed at two conditions, 100 kPa (naturally aspirated operation) and 120 kPa (supercharged operation) provided with a roots blower type supercharger. The EGR rates were varied from 0 to 25% using a cooled EGR technique. The results showed that both with and without supercharging, all the bio-alcohol blended diesel fuels improved the trade-off relation between NOx and smoke emissions at all EGR rates while maintaining good engine performance, when compared with diesel fuel operation. It was also found that regardless of boost pressure and EGR rate, the ignition delays of the tested bio-alcohol isomer blends are in the order of iso-butanol > n-butanol > iso-pentanol > n-pentanol. Overall, it was concluded that, except for the changes in the ignition delays the influence of bio-alcohol isomer blends on the engine performance, combustion characteristics, and emissions are relatively small.

***Keywords*—**Alternative fuel, Butanol, Diesel engine, EGR, Next generation bio-alcohol isomer blended fuel, Pentanol, Supercharging

I. Introduction

To achieve reductions in carbon dioxide emissions and prevent petroleum fuel shortages, numerous diesel combustion studies with biofuels as diesel fuel substitutes have been carried out, as biofuels such as biodiesels [1]-[10] and bio-alcohols [11]-[19] are promising renewable energy sources. Recently, the Research and Development of next generation bio-alcohol production with high efficiency fermentation methods using engineered micro-organisms that improve the yield have been promoted with non-food based sources like cellulosic biomass [20], [21]. Such next generation bio-alcohol fuels contain larger volumes of butanol (C_4) and pentanol (C_5) than ethanol and higher alcohol fuels. Compared with bio-ethanol, the next generation bio-alcohol fuels have advantages such as high cetane numbers, good solubility characteristics in conventional diesel fuels and biodiesels, and low hygroscopic characteristics. Therefore, the C_4/C_5 bio-alcohols are superior to bio-ethanol as diesel fuel substitutes. It is known that the next generation bio-alcohol fuels also contain isomers, depending on the production processes.

A technique combining supercharging and EGR is an effective measure to achieve simultaneous reductions of NOx and PM emissions [7]. The concept is based on the consideration that to decrease NOx emissions both the oxygen concentration and flame temperature in local combustion regions is reduced by applying EGR, while supercharging decreases the PM emissions caused by combustion deterioration with the high EGR rate operation. The present study investigated the effects of combining supercharging and EGR with the C_4/C_5 next generation bio-alcohol isomer and diesel fuel blends.

In recent years, a number of studies using C_4/C_5 next generation bio-alcohol blended fuels have been carried out with diesel engines over a wide range of experimental conditions [22]-[40], and these studies may be classified as follows: by the kind of bio-alcohol tested there are studies with n-butanol [33], [36], [40] or n-pentanol [23]-[25], [30], [35], [38], [39]; comparative studies with n-butanol and iso-butanol [26], n-butanol and n-pentanol [28], [29], [31], [37], iso-butanol and n-pentanol [27], [32], [34]; and with all the n-butanol isomers [22]. The study with butanol isomers [22] showed that the ignition delays were in the order of iso-butanol>2-butanol> n-butanol>tert-butanol. The result is consistent with a previous report by the authors here [17] (the study of [17] did not include tert-butanol however).

For the kind of base fuel used, studies with diesel fuel [22], [24], [26], [27], [32]-[34], blended fuel with diesel fuel and biodiesel [23], [28]-[30], [36], [38], [39], neat biodiesel [35], [37], blended fuel with diesel fuel and neat vegetable oil [31], neat n-butanol [40], and neat n-pentanol [25] have been conducted. For studies of the blending ratio of bio-alcohol, blends with less than 20 vol. % [28]-[31], [36]-[39], 30 vol. % blends [23], [26], [32], [33], [35], and higher concentration blends of 40 vol. % [22], [27] or 45 vol. % [24], [34] have been reported. For injection systems, common rail types have been employed [22], [23], [25], [33], [40], while other studies used jerk type injection systems.

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TABLE I
PROPERTIES OF THE TESTED FUELS

Test fuel	Diesel fuel JIS No. 2	n-butanol	iso-butanol	n-pentanol	iso-pentanol
Density [15 °C](a) (kg/m^3)	836	815	807	820	813
Viscosity [30 °C] (mm^2/s)	3.89	2.22 (b)	2.63(c)	2.89 (b)	—
Cetane number	57.1 (d)	17 (b)	<15(c)	20 (b)	—
Lower heating value(a) (MJ/kg)	42.95	32.63	32.61	34.72	34.62
B. P. at 90 % distillation (°C)	336	118(e)	108(e)	138(e)	131(e)
Carbon (mass %)	86.1	64.8	64.8	68.1	68.1
Hydrogen (mass %)	13.8	13.6	13.6	13.7	13.7
Oxygen (mass %)	—	21.6	21.6	18.2	18.2
Stoichiometric air-fuel ratio	14.6	11.2	11.2	11.7	11.7

(a) measured, (b) from Reference [31] (at 40 °C), (c) from Reference [27] (at 40 °C), (d) cetane index, (e) boiling point

Further, studies with supercharging [23], [25], EGR [24], [26], [27], [34], and combining supercharging and EGR [22], [33], [40] have also been carried out. Here, Zheng et al. [22] reported an experimental study over 0-65% EGR rates, but simulating actual EGR recirculated gas by neat CO_2. Cheng et al. [33] reported a study under a constant moderate EGR rate (17.6% intake oxygen concentration) and a constant boost pressure, without reporting specifics of the boost pressure. Han et al. [40] investigated the combined effects of boost pressure and cooled EGR, up to 1.5-2 bar boost pressures and with 0-55% EGR rates. Further, to realize neat n-butanol operation an advanced split injection strategy was applied, and this study achieved high load operation comparable to conventional diesel fuel.

As shown in the above literature survey, the authors have identified only few reports of diesel combustion combining supercharging and EGR with next generation bio-alcohol blended fuels, specifically no reports of investigations of iso-pentanol blended fuels were located.

II. EXPERIMENTAL APPARATUS AND METHODS

A. Test Fuels

The study here used four kinds of next generation bio-alcohol isomer and JIS No. 2 diesel fuel blends. The tested bio-alcohol isomers here are n-butanol and iso-butanol (C_4 alcohol), and n-pentanol and iso-pentanol (C_5 alcohol). Table I shows the particulars of the tested fuels. A previous study [17] used three kinds of butanol isomer and diesel fuel blends at a constant blending ratio of 4:6 (mass), and the experiments there were conducted with a single cylinder DI diesel engine. Those results showed that all the tested butanol isomer blends were able to maintain stable operation. Considering that result and practical adoptability, the present study used C_4/C_5 bio-alcohol isomer and diesel fuel blends at a constant blending ratio of 3:7 (mass). As shown in Table I, it is clear that compared with standard JIS No. 2 diesel fuel, the cetane numbers of butanol and pentanol isomers are very low, but the improvements in evaporation characteristics of the bio-alcohol isomer and diesel fuel blends could be expected because of the low boiling points of the bio-alcohol isomers. Also, the tested C_4/C_5 bio-alcohol isomers are oxygenated fuels with oxygen contents of 21.6 and 18.2%, respectively.

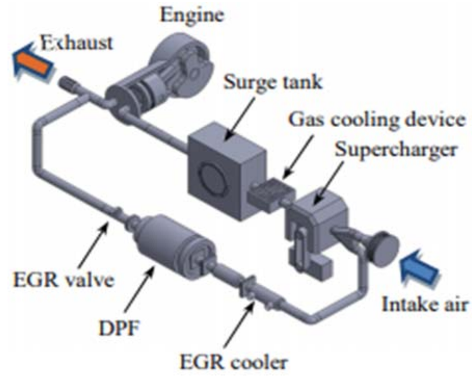

Fig. 1 Experimental setup

TABLE II
ENGINE SPECIFICATIONS

Engine model	4 stroke, Horizontal, Water cooled
Stroke volume	411 cc (Single cylinder)
Compression ratio	18
Combustion chamber	DI (Toroidal type)
Rated output	5.1 kW/2400 rpm (BMEP=0.62 MPa)
Injection pump	Bosch PFR (Plunger 7 mm)
Injection nozzle	DLLA 150 (4- □0.2)
Opening pressure	21.7 MPa
Injection timing	Fixed (19 °CA.BTDC)

B. Engine Setup

Fig. 1 shows an outline of the experimental apparatus, consisting of the test engine, with supercharging, and attachments for cooled EGR. The tested engine is a four stroke, water-cooled single cylinder direct injection diesel engine equipped with a toroidal type combustion chamber and the principal specifications of the engine and its fuel injection particulars are shown in Table II. The fuel injection system is a jerk type set to standard diesel fuel specifications. The study employed a Roots blower supercharger driven by an inverter controlled motor, and the boost pressures were set to two conditions, 100 kPa (naturally aspirated operation) and 120 kPa (with supercharging) independent of other engine operation variables. A previous study [41], where the boost pressures were varied from 100 to 140 kPa, suggested that the improvements in diesel combustion were small when the boost pressure was above 120 kPa. During the experiments, the engine was operated at a constant engine speed of 1900 rpm which corresponds to the maximum brake torque conditions. The engine load was set at a constant high load condition (BMEP=0.67 MPa) where the trade-off relation between NOx

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and smoke emissions assumes critical values. In the experiments, the intake gas temperatures were controlled at 30-33 °C.

C. Measuring Apparatus and Procedures

The combustion pressure was measured with a strain gauge type pressure pick-up and the crank angle was detected by a rotary encoder. The needle lift of the nozzle was monitored by a Hall-effect element. These three signals were recorded digitally, and the rate of heat release and the degree of constant volume of combustion η_{glh} were determined from the average pressure of 50 cycles. Assuming energy equilibrium of the gas in the cylinder as in (1), the degree of constant volume of combustion, η_{glh}, is determined from (2):

$$dQ = dQ_E - dQ_C = \frac{1}{\kappa - 1}(\kappa PdV + VdP) \tag{1}$$

$$\eta_{glh} = \frac{1}{Q}\int \frac{1 - \frac{1}{\varepsilon_\theta^{\kappa-1}}}{1 - \frac{1}{\varepsilon^{\kappa-1}}} \frac{dQ}{d\theta} d\theta \tag{2}$$

The ignition delay was determined from the crank angle interval between the start of the needle lift and the pressure rise due to the combustion. The EGR rate was determined from (3), and the intake air quantity was measured by a laminar flow meter attached upstream of the supercharger.

$$EGR\% = \frac{(CO_2)_{int\,ake}}{(CO_2)_{exhaust}} \times 100 \tag{3}$$

The NOx emissions were measured using a CLD analyzer, the HC was measured as ppm methane using an FID analyzer, the CO and CO_2 were measured using an NDIR analyzer, and the smoke density was measured with an opacity-meter.

III. Experimental Results and Discussion

A. Effects of Combining Supercharging and EGR on Engine Performance and Emission Characteristics with C_4 /C_5 Bio-Alcohol Isomer Blended Diesel Fuels

Fig. 2 shows the changes in brake thermal efficiency, η_e, the brake specific fuel consumption, *BSFC*, and the exhaust gas temperature as a function of the EGR rate with the respective tested fuels at the two boost pressures, 100 kPa and 120 kPa, with the Roots blower supercharger operating, and Fig. 3 plots the emission characteristics in these cases. The boost pressure of 100 kPa corresponds to the naturally aspirated condition with the present engine setup, and the engine operation at the boost pressure of 100 kPa is noted as “without supercharging” in the following. There were four kinds of tested bio-alcohol isomer blended diesel fuels, n-butanol and iso-butanol (left panels in Figs. 2 and 3), and n-pentanol and iso-pentanol (right panels in Figs. 2 and 3). The engine tests also used gas oil, the JIS No. 2 diesel fuel, as a reference fuel. As shown in the top panels in Fig. 2, the brake thermal efficiencies η_e with supercharging improved remarkably at all EGR rates compared to the naturally aspirated operation. The relation among the brake thermal efficiency, η_e, the theoretical thermal efficiency, η_{th}, the degree of constant volume of combustion, η_{glh}, the combustion efficiency, η_u, the cooling loss, ϕ_w, and the mechanical efficiency, η_m, is expressed by:

$$\eta_e = \eta_{th} \cdot \eta_{glh} \cdot \eta_u (1 - \phi_w)\eta_m \tag{4}$$

As shown in Fig. 3, there were substantial reductions in smoke and CO emissions with the supercharged operation also when the EGR rates increased. With the supercharged operation, insufficient quantities of oxygen in the combustion regions would diminish due to the increasing in-cylinder air density leading to a decrease in the smoke and CO emissions, resulting in the improvements in the combustion efficiency η_u, suggested by (4). This may be a reason for the increases in the brake thermal efficiencies η_e with supercharging. With the supercharged operation, the pumping loss is improved and it may be considered that the increasing mechanical efficiency η_m also resulted in the increased brake thermal efficiency. As shown in the bottom panels of Fig. 2, all the tested fuels showed substantial reductions in exhaust gas temperatures with the supercharging. The reason for this is considered to be that the heat capacity of the in-cylinder gas increases due to the increasing air density caused by the supercharging, resulting in a decrease in the mean gas temperature during combustion.

The influence of the fuel kind when combining operation with supercharging and EGR will be discussed next. The smoke emissions with ordinary diesel fuel without supercharging increased to extremely high values when the EGR rates increased to around 10% (the top panels in Fig. 3), and such conditions are not acceptable in practical operation. With the supercharged operation, however, with the tested bio-alcohol isomer blended fuels, it was possible to increase the EGR rates to 25% because of the low smoke emission characteristics and as the η_e (the top panels in Fig. 2) maintained relatively high values over the tested EGR region. As shown above, the effect of supercharging on the smoke emission improvements are very large when EGR is employed. Both with and without supercharging, the η_e with the butanol isomer blends and pentanol isomer here were similar to ordinary diesel fuel operation. The brake specific fuel consumption, *BSFC* with the bio-alcohol isomer blended fuels is higher than that with ordinary diesel fuel operation (the mid panels in Fig. 2). The reason is that the heating values of the tested bio-alcohols are lower than that of ordinary diesel fuel by 19～24% and a larger injected fuel quantity is necessary to maintain the same output.

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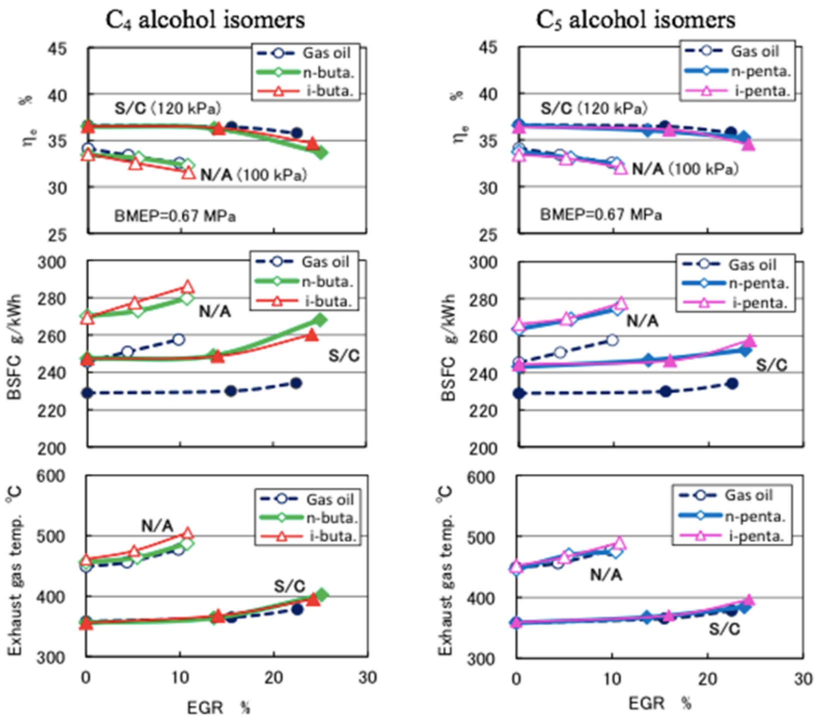

Fig. 2 Engine performance with the tested C_4/C_5 bio-alcohol isomer blended diesel fuels with and without supercharging at different EGR rates (BMEP=0.67 MPa)

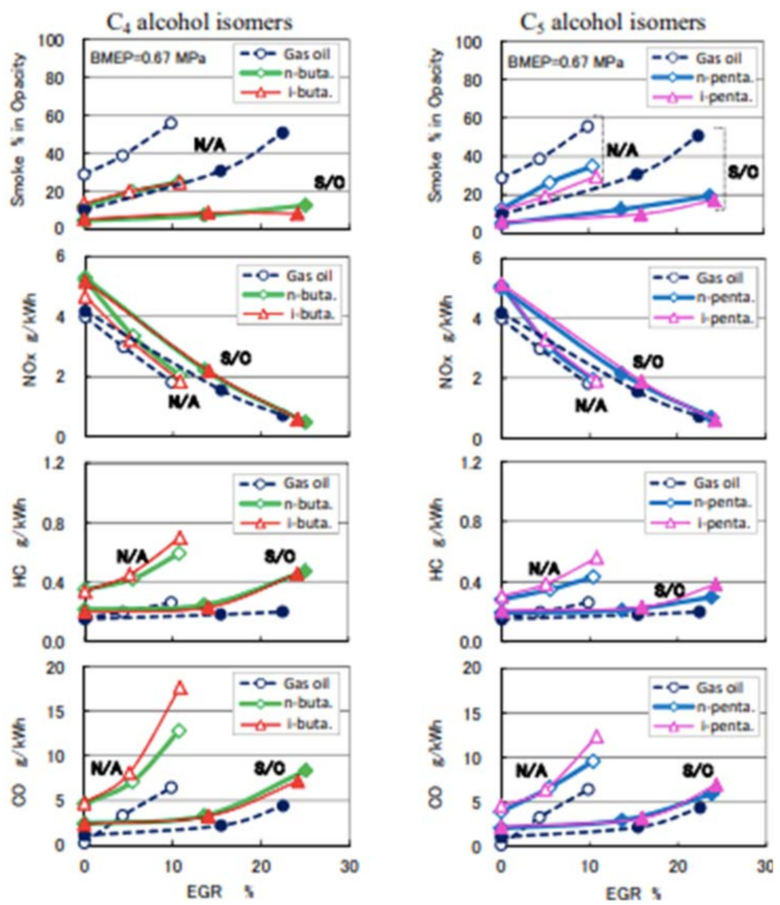

Fig. 3 Emission characteristics with the tested C_4/C_5 bio-alcohol isomer blended diesel fuels with and without supercharging at different EGR rates (BMEP=0.67 MPa)

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Compared with ordinary diesel fuel operation, the bio-alcohol isomer blended fuels showed substantial reductions in smoke emissions at all conditions (the top panels in Fig. 3). The C_4/C_5 bio-alcohol isomers are so called 'oxygenated fuels' with oxygen contents of 21.6% and 18.2% in the molecular structures, and it is considered that the oxygen contained in the fuel compensates for the oxygen shortage in the local combustion regions caused by EGR. The butanol isomer blended fuels showed lower smoke densities than those of pentanol isomer blended fuels. The reason is that the oxygen content of butanol is about 3 percentage points higher than pentanol. Another reason is considered to be that as described in the next section, the ignition delays with the butanol isomers are prolonged more than with the pentanol isomers because of the low cetane numbers, and the heat release in the premixed combustion phase promotes reductions in smoke emissions. Here, the smoke emissions with the n-butanol blend are similar to those with the iso-butanol blend while the iso-pentanol blend without supercharging shows slighter reductions in smoke emissions than those of the n-pentanol blend.

As shown in the second row panels in Fig. 3, both with and without supercharging, the NOx emissions decreased significantly with increasing EGR rates. The NOx emissions without EGR for all the tested bio-alcohol isomer blended diesel fuels increased above that of the ordinary diesel fuel operation. The reason would be considered to be that the ignition delay with bio-alcohol isomer blends is prolonged, and so the local gas temperatures in the combustion region increase due to promotion of the premixed combustion phase. Here, the NOx emissions with all the tested fuels under supercharged operation combined with EGR increase compared with the naturally aspirated condition. The reason is considered to be that the effect of the reduction of the local oxygen concentration in the combustion region becomes weaker because of the oxygen concentration increases in the recirculated exhaust gas, together with the increased air density due to the supercharging. It is well known that the NO formation rate is controlled by the local in-cylinder gas temperature, local oxygen concentration, and residence time in the high in-cylinder gas temperature. A number of studies attempted to establish the NOx reduction mechanisms in diesel engines with EGR. Shiozaki et al. [42] reported that the contribution of the NOx reduction with EGR works both to reduce the oxygen concentration and to decrease flame temperatures. The reduced oxygen concentration in the intake gas caused by EGR operation results in decreased flame temperatures, suggesting that both effects would influence the NOx emissions in the present study too.

As shown in the bottom panels in Fig. 3, the HC and CO emissions with iso-butanol and iso-pentanol blended diesel fuels without supercharging increased with increasing EGR rates to reach above those of the corresponding n-butanol and n-pentanol blends. This reason is considered to be that (as will be described in the next section) the ignition delays with iso-butanol and iso-pentanol blended fuels increase more than the corresponding n-butanol and n-pentanol blends, and that this causes an excessively lean mixture formation resulting in an expansion of the incomplete combustion regions. The reason for the considerable increases in the CO emissions with ordinary diesel fuel operation without supercharging is considered to be oxygen shortage in the local combustion regions. Regardless of the kinds of fuel, however, substantial reductions in the CO and HC emissions were obtained with the supercharged operation.

B. Effects of Combining Supercharging and EGR on Combustion Characteristics with C_4/C_5 Bio-Alcohol Isomer Blended Diesel Fuels

Figs. 4 (a)-(d) show plots of indicator diagrams and heat release rate profiles. The upper panels are for the butanol isomer blended diesel fuels and the lower panels for the pentanol isomer blends. Figs. 4 (a) and (b) show the influence with and without EGR at the naturally aspirated operation, while Figs. 4 (c) and (d) show the influence with and without EGR at the supercharged operation. Here, the EGR rates with the naturally aspirated operation were selected to be 10-11% (Fig. 4 (b)), and 23-25 % with supercharging (Fig. 4 (d)). Comparing Figs. 4 (a) and (b), for both of the C_4/C_5 bio-alcohol isomer blended fuels under EGR operation the ignition timings delay remarkably, and the peak values in the premixed combustion phase increase. Employing EGR, the oxygen concentration of the gas entrained in the spray flux decreases. This requires longer residence times for the mixture formation to enable ignition, so ignition timings would be delayed. Comparing Figs. 4 (a) and (c), it is clear that the ignition timings with the supercharged operation advance compared with the naturally aspirated condition. The reason is mainly the promotion of formation of combustible mixture, because the air quantity entrained into the spray flux increases with the increasing in-cylinder air density caused by the supercharging [7].

Fig. 5 shows the changes in combustion characteristics as a function of the EGR rate with the tested fuels. When the C_4/C_5 bio-alcohol isomer blended diesel fuels were used under the naturally aspirated condition, the ignition delays become significantly longer and the maximum heat release rates, $(dQ/d\theta)_{max}$ increase compared with ordinary diesel fuel operation. This trend is promoted with increased EGR rates, but the values decrease remarkably with the supercharged operation. Whether with or without supercharging, the ignition delays of the tested bio-alcohol isomer blends are in the order iso-butanol > n-butanol > iso-pentanol > n-pentanol. This corresponds to the order in the cetane number as shown in Table 1. Compared with ordinary diesel fuel operation, the ignition delays with the tested bio-alcohol isomer blended diesel fuels are very long even when supercharging was employed. However, the degree of constant volume of combustion, η_{glh} are similar up to a 20% EGR rate. This means that after the ignition, the C_4/C_5 bio-alcohol isomer blends show faster combustion than that of the ordinary diesel fuel operation. The reason may be that the evaporation characteristics of the C_4/C_5 bio-alcohol isomer blends have the lower boiling point of the tested bio-alcohols and that the atomization characteristics improve because of their low

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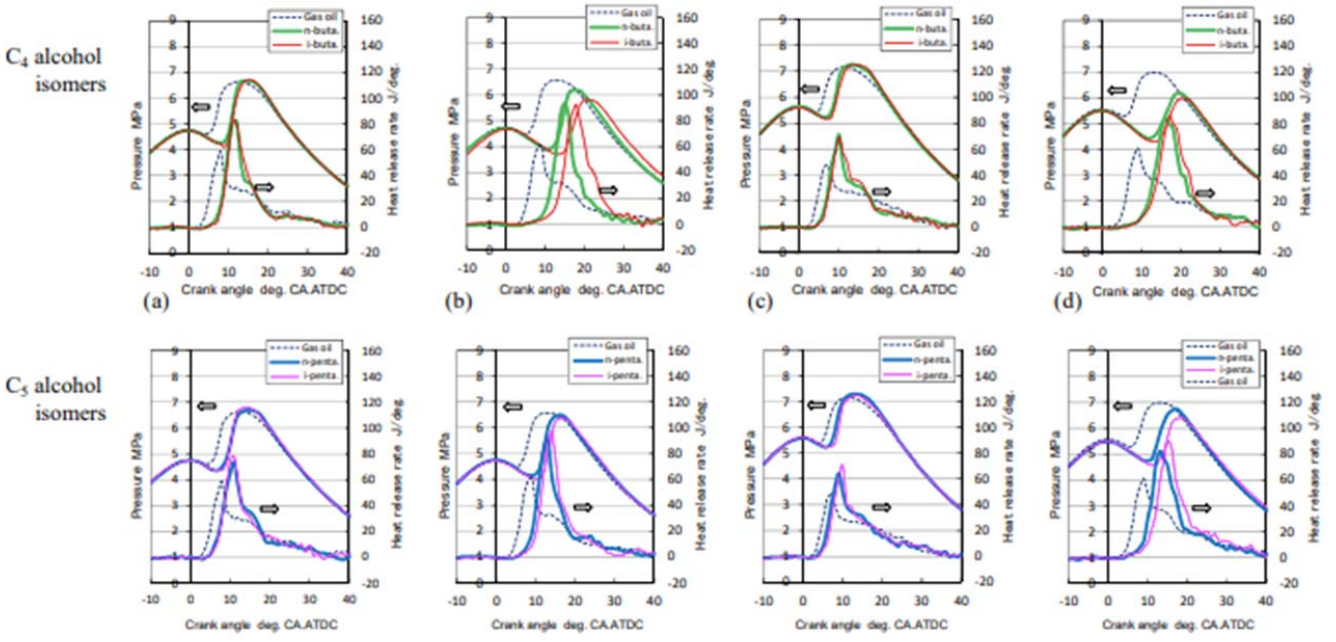
kinematic viscosity, together resulting in the promotion of mixture formation.



(a) w/o S/C, 0% EGR (b) w/o S/C, 10-11% EGR (c) with S/C, 0% EGR (d) with S/C, 23-25% EGR

Fig. 4 Indicator diagrams and heat release rates with the tested C_4/C_5 bio-alcohol isomer blended diesel fuels with and without supercharging at different EGR rates (BMEP=0.67 MPa)

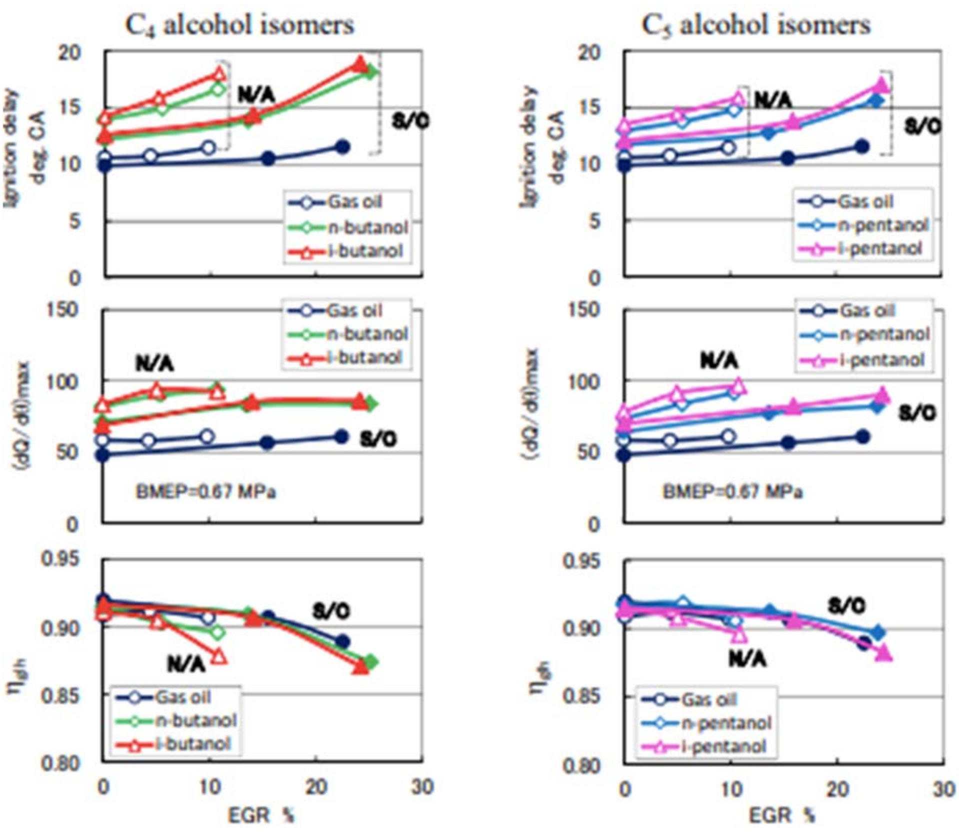


Fig. 5 Combustion characteristics with the tested C_4/C_5 bio-alcohol isomer blended diesel fuels with and without supercharging at different EGR rates (BMEP=0.67 MPa)

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C. Effects of the Trade-Off Improvements with C_4 /C_5 Bio-Alcohol Isomer Blended Diesel Fuels

Fig. 6 shows the trade-off relation between the NOx and brake thermal efficiency, η_e as well as between NOx and smoke emissions with the tested fuels as a function of the EGR rate, with and without supercharging. The NOx emissions with all the tested fuels decreased significantly when the cooled EGR was employed at the naturally aspirated condition (boost pressure: 100 kPa). But in this case, the EGR rates could not be increased above 10% because of the substantial increases in the smoke emissions, specifically for the ordinary diesel fuel operation. When the supercharging was employed (boost pressure: 120 kPa), the decreasing trend of the η_e is suppressed as well as the trade-off relation between the NOx and smoke emissions improved substantially. Comparing the fuel kind, the smoke emissions with all the bio-alcohol blended diesel fuels reduced much more than those of the ordinary diesel fuel operation. Also, the smoke reduction effects with the tested C_4 bio-alcohol isomer blended diesel fuels were stronger than those of the C_5 bio-alcohol isomer blends.

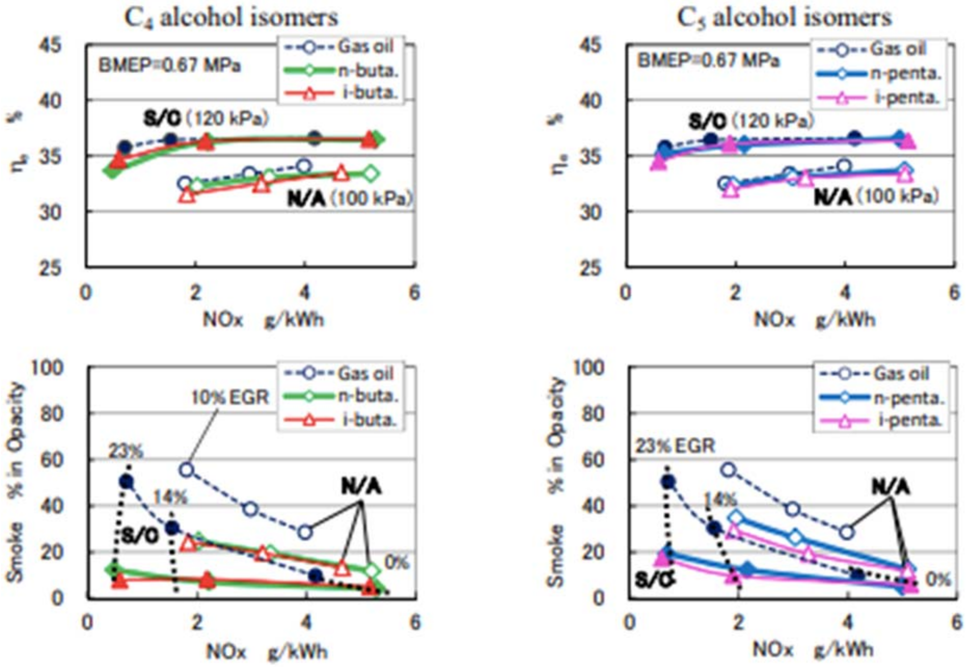

Fig. 6 Trade-off relation between NOx vs. brake thermal efficiency and NOx vs. smoke with the tested C_4/C_5 bio-alcohol isomer blended diesel fuels with and without supercharging at different EGR rates (BMEP=0.67 MPa)

IV. Conclusions

The influence of combining supercharging and cooled EGR on engine performance, combustion characteristics, and emissions were investigated with a small single cylinder direct injection diesel engine fueled by four kinds of next generation bio-alcohol isomer and diesel fuel blends with a constant blending ratio of 3:7 (mass). The tested bio-alcohol isomers here are n-butanol and iso-butanol (C_4), and n-pentanol and iso-pentanol (C_5). The boost pressures were fixed at two conditions, 100 kPa (naturally aspirated operation) and 120 kPa (supercharged operation) and the EGR rates were varied from 0 to 25%. The results of the present study may be summarized as follows:

(1) Regardless of boost pressure and EGR rate, all the tested bio-alcohol blended diesel fuels improved the trade-off relation between NOx and smoke emissions while maintaining good engine performance, when compared with ordinary diesel fuel operation.

(2) Regardless of boost pressure and EGR rate, the smoke emissions with the butanol isomer blended diesel fuels were lower than those of the pentanol isomer blends. The reason is considered to be that the oxygen content of the butanol is higher than that of pentanol, and the ignition delay increases because of the low cetane numbers of the butanol isomers.

(3) Regardless of boost pressure and EGR rate, the ignition delays of the tested bio-alcohol isomer blends are in the order of iso-butanol>n-butanol>iso-pentanol>n-pentanol.

(4) Except for the changes in the ignition delays, the influence of the bio-alcohol isomer blends on the engine performance, combustion characteristics, and emissions are relatively small.

Nomenclature

θ: crank angle
Q: heat release in cylinder
Q_E: lower heating value of fuel
Q_C: cooling heat to cylinder wall
V: gas volume in cylinder
P: gas pressure in cylinder
κ: ratio of specific heat
ε: compression ratio
ε_θ: compression ratio at crank angle θ

η_e : brake thermal efficiency
η_{glh} : degree of constant volume of combustion
BMEP: brake mean effective pressure
BSFC: brake specific fuel consumption
$(dQ/d\theta)_{max}$: maximum heat release rate
N/A: naturally aspirated operation
S/C: supercharged operation

Acknowledgment

The present study was supported by a grant-in-aid-for scientific research (17K07031) from the JSPS. The authors also wish to thank the students at the Heat Energy Laboratory, Niigata Institute of Technology, for their cooperation in the experiments.

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