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Combustion and Emissions with Bio-alcohol and Nonesterified Vegetable Oil Blend Fuels in a Small Diesel Engine

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ABSTRACT

Combustion and exhaust gas emissions of alcohol and vegetable oil blends including a 20% ethanol + 40% 1-butanol + 40% vegetable oil blend and a 50% 1-butanol + 50% vegetable oil blend were examined in a single cylinder, four-stroke cycle, 0.83L direct injection diesel engine, with a supercharger and a common rail fuel injection system. A 50% diesel oil + 50% vegetable oil blend and regular unblended diesel fuel were used as reference fuels. The boost pressure was kept constant at 160 kPa (absolute pressure), and the cooled low pressure loop EGR was realized by mixing with a part of the exhaust gas. Pilot injection is effective to suppress rapid combustion due to the lower ignitability of the alcohol and vegetable oil blends. The effects of reductions in the intake oxygen concentration with cooled EGR and changes in the fuel injection pressure were investigated for the blended fuels. Also, the operation with all the blended and reference fuels with optimized pilot quantities and suitable EGR rates was investigated over a wide range of IMEP 1.0 MPa. Silent, low NOx, and smokeless combustion is possible over a wide IMEP range with the alcohol and vegetable oil blended fuels here with optimized quantities of pilot injection and EGR rates. Premixed combustion with pilot injection occurs near TDC with the alcohol + vegetable oil blended fuels due to the poor ignitabilities, which make it possible to increase the quantity of pilot injection and reduce the after burning with the main injection, resulting in improvements in the indicated thermal efficiency due to the increase in the degree of constant volume heat release. Smokeless operation is possible with the alcohol and vegetable oil blends even at low injection pressure and large EGR rate conditions.

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INTRODUCTION

Vegetable oil has attracted attention as a diesel fuel substitute due to its sufficient ignitability, comparable with diesel fuel, as well as it is a carbon neutral, renewable fuel produced from biomass. As the viscosity of vegetable oil is very high, it is generally difficult to utilize nonesterified vegetable oils in small diesel engines. To overcome the difficulty, esterification [1], fuel heating [1, 2], and blending with low viscosity fuels [1] were proposed in the 1980s, and there are many reports for utilization of estirified vegetable oil (fatty acid methyl ester, FAME) as a bio-diesel fuel [3,4,5,6,7,8,9,10,11]. However, bio-diesel fuels are difficult to utilize due to the complicated, high cost esterification. The blending with low viscosity fuels is a simpler and more economical way, and it is reported that the fuel properties of nonesterified vegetable oils can be improved by blending with low viscosity fuels including ordinary diesel fuel [12, 13].

There are also reports of diesel combustion with microemulsion fuels of alcohol and vegetable oil from the 1980s [14, 15]. Lujaji, et al. reported the combustion and emissions with croton oil, diesel fuel, and butanol blends in a modern diesel engine and there were no difficulties when the croton oil content in the blended fuels was limited below 20%, where the blended fuel has sufficiently high ignitability

Table 1. Properties of the components in blended fuels

	Viscosity [mm^2/s]	Density [g/cm^3]	LHV [MJ/kg]
Diesel fuel	3.0 (@30°C)	0.827 (@15°C)	46.2
Vegetable oil	39.2 (@30°C)	0.922 (@15°C)	37.0
1-Butanol	3.6 (@20°C)	0.810 (@20°C)	33.1
Ethanol	1.2 (@40°C)	0.788 (@20°C)	26.8

and low viscosity due to the 80% diesel fuel content [16]. The ignitability of alcohols including butanol and ethanol are low, but blends of alcohols and vegetable oil have sufficiently high ignitability and low viscosity, as well as low soot formation characteristics due to the oxygen content. The solubility of butanol and vegetable oil is very high and a wide range of blends is possible, but ethanol is insoluble in vegetable oil. However, the solubility of ethanol and vegetable oils improves significantly when blending with butanol, and utilization of ternary blends of ethanol, butanol, and vegetable oils in diesel engines is possible. Ignitability decreases with increasing alcohol contents, but stable combustion can be realized with low ignitability fuel including emulsified blends of aqueous ethanol and diesel fuel with optimized pilot injection [17]. In this research, combustion and exhaust gas emissions of ethanol, 1-butanol, and vegetable oil blends were examined in a diesel engine with a supercharger and a common rail fuel injection.

EXPERIMENTAL APPARATUS AND PROCEDURES

Experiments were conducted on a single cylinder, four-stroke cycle, 0.83L direct injection experimental diesel engine converted from a commercial four cylinder engine, with a supercharger and a common rail fuel injection system. The specifications of the engine are a bore of 98 mm, a stroke of 110 mm, and a compression ratio of 18.5. The fuel injection nozzle has nine-holes of 0.18 mm diameter and a 152° spray angle. Figure 1 shows the schematic of the experimental set up. Supercharging is realized with a lysholm compressor driven by an electric motor and the exhaust manifold pressure was kept at the same pressure as the intake pressure with a throttle valve in the exhaust manifold. The engine operating conditions were set to an engine speed of 1200 rpm, a boosted pressure of 160 kPa (absolute pressure), and a coolant temperature of 80°C. The cooled low pressure loop EGR was realized by diverting a part of the exhaust gas via a DPF and an EGR cooler to the upstream of the supercharger. The intake gas temperature was kept below 30°C with the EGR cooler and an intercooler.

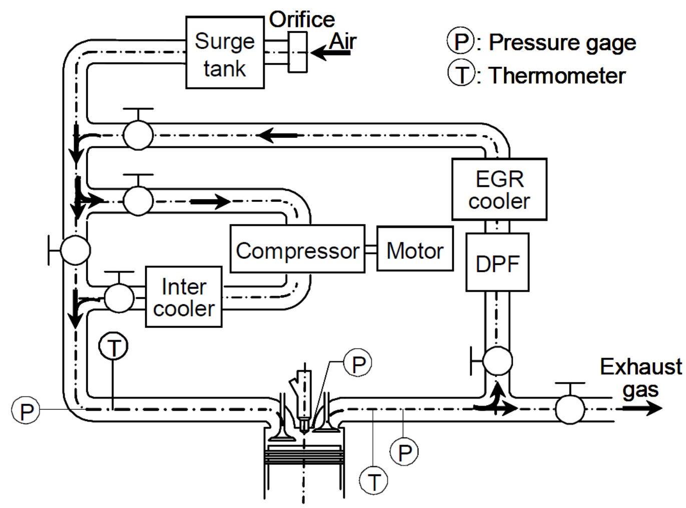


Fig. 1. Experimental set up

The oxygen concentrations in the intake gas were measured with a portable oxygen tester (POT-101: SHIMAZU) and the smoke emissions were measured with a Bosch-type smoke meter (DSM-20AN: ZEXEL). The exhaust gas was analyzed with an automotive exhaust gas analyzer (MEXA-8120: HORIBA) including NDIR (non-dispersive infrared absorption) for CO and CO_2, and CLD (chemical luminescence detector) for NOx.

Blends of equal volumes of 1-butanol and vegetable oil (commercial cooking oil, mixture of soybean oil and rapeseed oil) (B50V50) and 20% ethanol, 40% 1-butanol, and 40% vegetable oil (E20B40V40) were investigated. Further, blends of equal volumes of diesel fuel (JIS No.2) and nonesterified vegetable oils, volume ratio 50:50 (D50V50), and regular unblended diesel fuel were used as reference fuels. Table 1 shows the properties of the components in the blended fuels and Figure 2 shows the kinematic viscosities of the tested fuels and the vegetable oil in the blends at 30°C. The viscosities of the alcohol and vegetable oil blends (E20B40V40, B50V50) are comparable with that of diesel fuel. No problem including carbon deposition on the combustion chamber wall due to high distillation temperatures of these blended fuels were occurred in this experiment.

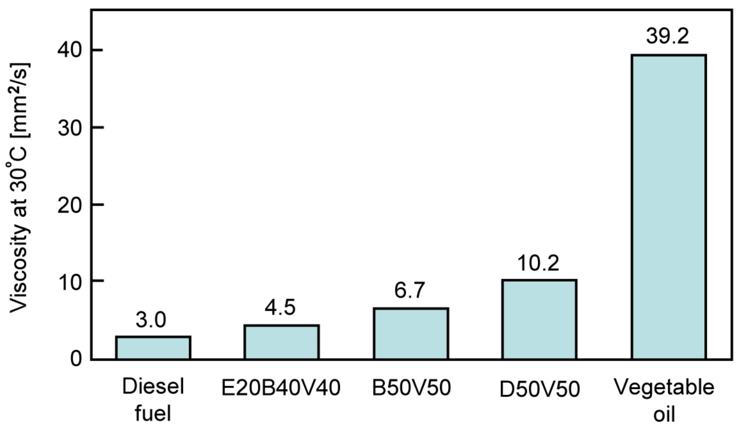


Fig. 2. Kinematic viscosities of the tested fuels and the vegetable oil in the blends at 30°C

Figure 3 shows the soluble mixing range for ethanol + 1-butanol + vegetable oil ternary blends (colored area), and the part of the mixing range that is suitable for high-speed diesel engines (blue). As suggested by the figure, 1-butanol and vegetable oil form stable solutions at most mixing ratios while ternary blends of ethanol + 1-butanol + vegetable oil are limited to the specified mixing ratio range. The suitable mixing range for small high speed diesel engines considering viscosity and ignitability is limited to a much smaller range.

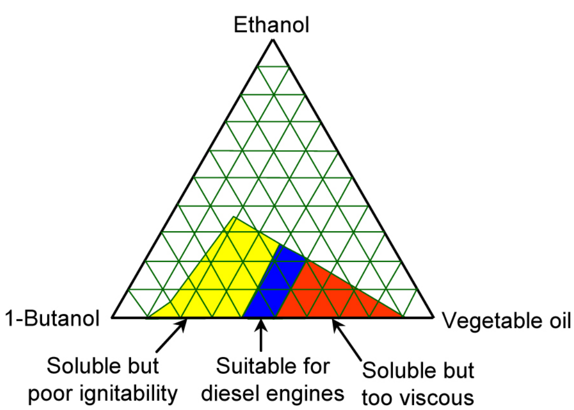


Fig. 3. Soluble and suitable ranges for high speed diesel engines of vegetable oil - 1-butanol - ethanol ternary blends

EXPERIMENTAL RESULTS AND DISCUSSION

Effect of Pilot Injection Quantity on Combustion and Emissions with Alcohol and Vegetable Oil Blended Fuels

A high ratio of alcohol in blended fuels causes an excessively rapid combustion due to poor ignitability, but employing a pilot injection can suppress the rapid combustion. Figure 4 shows the effects of the pilot fuel injection quantity on engine noise, the maximum rate of pressure rise ($dp/d\theta_{max}$), NOx, and smoke with two alcohol and vegetable oil blended fuels including an ethanol + 1-butanol + vegetable oil blend (E20B40V40) and a vegetable oil + 1-butanol blend (B50V50), and with a diesel fuel + vegetable oil blend (D50V50) as a reference. Here, the indicated mean effective pressure (IMEP) was set to 0.7 MPa, the pilot injection timing, θ_p was 23°CA BTDC, the main injection timing, θ_m, was at TDC, and the intake oxygen concentration, O_{2in}, was maintained at 15% with cooled EGR. The maximum rate of pressure rise without pilot injection is excessively large, however, the pilot injection suppresses the rapid combustion to acceptable levels for all the blended fuels here. There is an optimum pilot injection quantity that minimizes the maximum rate of pressure rise for each fuel, and the pilot injection quantities to achieve moderate (not over rapid) combustion with the alcohol blended fuels (E20B40V40 and B50V50) were larger than with diesel fuel blend (D50V50) as shown in Fig. 4. The optimum pilot quantities are 2 mm^3/cycle for D50V50, 6 mm^3/cycle for B50V50, and 8 mm^3/cycle for E20B40V40. The NOx with E20B40V40 and B50V50 are slightly lower than with D50V50 and are maintained at a low level for all fuels due to the low intake oxygen concentration with the cooled EGR. The smoke emissions with E20B40V40 and B50V50 are maintained at a zero level in Bosch units regardless of the pilot injection quantities while there are slight smoke emissions with the D50V50 blend.

Figure 5 shows the in-cylinder pressure and the rate of heat release (ROHR) for three pilot injection quantities with the 50% 1-butanol and 50% vegetable oil blend fuel (B50V50). With the small pilot injection quantities (Q_p = 2 mm^3/cycle) the maximum rate of pressure rise increases due to the rapid heat release with the main combustion, and with the large pilot injection quantity (Q_p = 10 mm^3/cycle) the maximum rate of pressure rise increases due to the rapid combustion with the pilot injection fuel. The pilot injection quantity of 6 mm^3/cycle results in a moderate (not over rapid) progress of combustion, intermediate between the high and low pilot injection quantities, for both the pilot and main injections, and the maximum rate of pressure rise, $dp/d\theta_{max}$, becomes smaller as shown in Fig. 4. A similar influence of the pilot injection quantity on the combustion is also obtained with the other blends and with the unblended diesel fuel (diagrams not shown).

Effect of EGR on Combustion and Emissions with the Alcohol and Vegetable Oil Blends

Figure 6 shows the effect of the intake oxygen concentration changed with cooled EGR on the NOx, smoke, and engine noise for the E20B40V40, B50V50, and D50V50 blends. Here, the overall fuel injection quantities to achieve

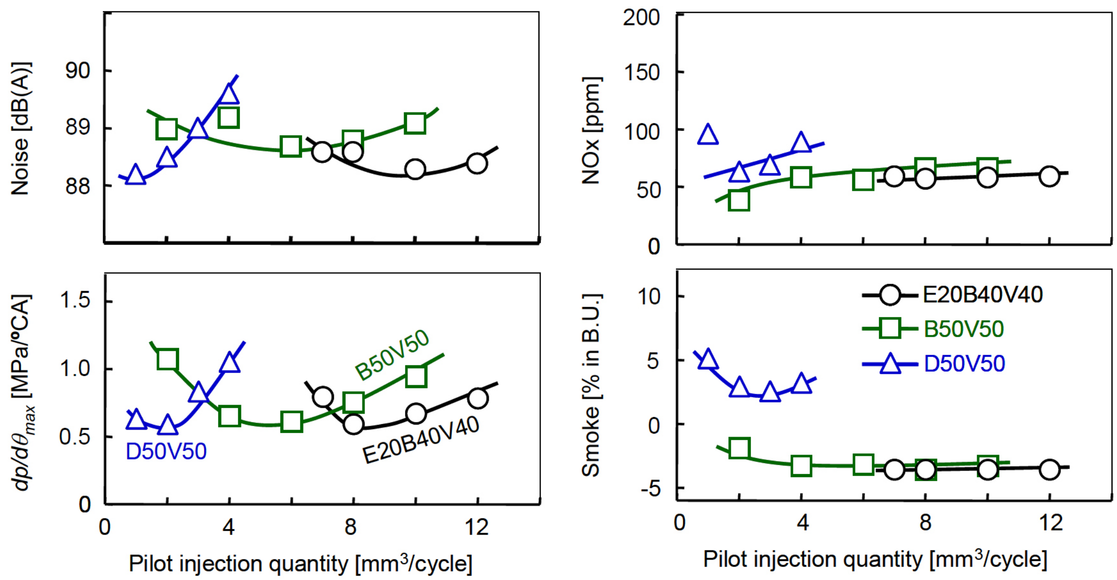


Fig. 4. Effects of the pilot fuel injection quantities on engine noise, the maximum rate of pressure rise ($dp/d\theta_{max}$), and exhaust gas emissions with the three vegetable oil blended fuels (IMEP: 0.7 MPa, O_{2in} = 15%, θ_p = 23°CA BTDC, θ_m = TDC)

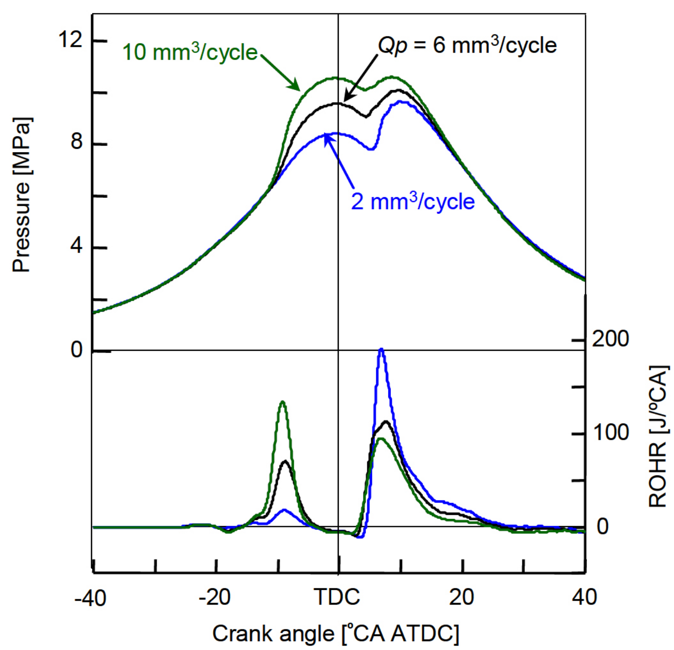


Fig. 5. In-cylinder pressure and the rate of heat release (ROHR) for three pilot injection quantities with a vegetable oil and 1-butanol blended fuel (B50V50) (IMEP: 0.7 MPa, O_{2in} = 15%, θ_p = 23°CA BTDC, θ_m = TDC)

1.0 MPa IMEP without EGR are maintained at all the intake oxygen concentrations tested. The pilot fuel injection quantities were set at the values that minimize the maximum rate of pressure rise for all the blended fuels. For all intake oxygen concentrations, the engine noise with E20B40V40 is larger due to its lower ignitability properties than the other blended fuels for all intake oxygen concentrations. However, engine noise decreases with an increase in the intake oxygen concentrations with larger EGR rates, and an acceptable engine noise level is established with E20B40V40 below 17% intake oxygen concentration. A 16% intake oxygen concentration with E20B40V40 establishes very low NOx and smokeless operation, and the NOx - smoke trade-off is improved with all the alcohol blended fuels at low intake oxygen concentrations.

Figure 7 shows the combustion characteristics with E20B40V40 under three intake oxygen concentrations. While the rate of heat release with pilot injection is retarded with

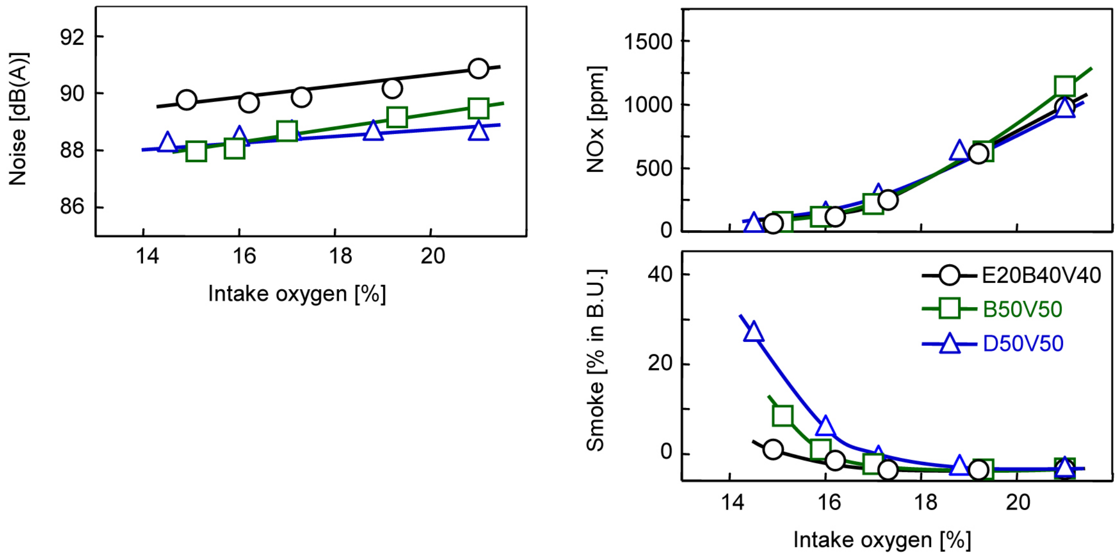


Fig. 6. Effects of the intake oxygen concentration on engine noise, NOx, and smoke emissions with the three vegetable oil blended fuels (IMEP: 1.0 MPa at O_{2in} =21%, θ_p = 23°CA BTDC, θ_m = TDC)

decreases in the intake oxygen concentrations, the combustion with the main injection does not significantly change with the intake oxygen concentration and the reduction in engine noise is mainly due to the suppression of the excessively rapid combustion with the pilot injection.

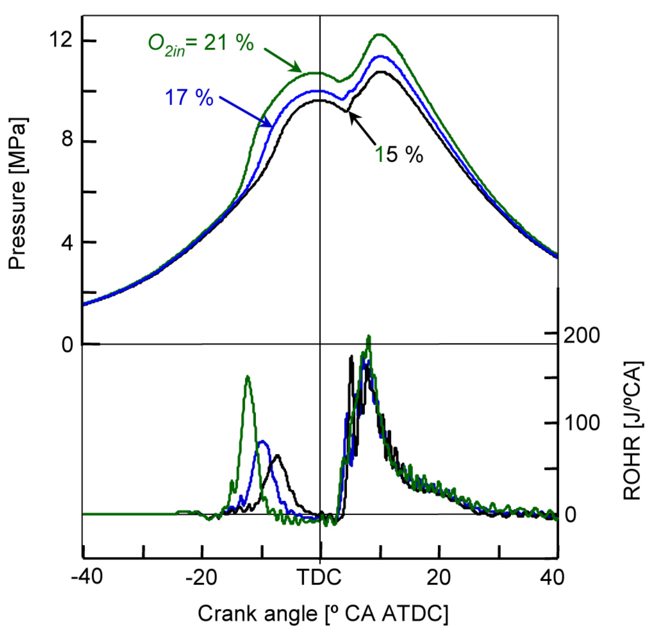


Fig. 7. Effect of intake oxygen concentration on combustion characteristics with an ethanol, 1-butanol, and vegetable oil blend (E20B40V40) (IMEP: 1.0 MP, θ_p= 23°CA BTDC, θ_m = TDC)

Figure 8 shows the in-cylinder pressure and the rate of heat release at a 15% intake oxygen concentration with the blended fuels. With E20B40V40 the rate of heat release with the pilot injection is retarded to near the TDC and the afterburning decreases, resulting in improvements in the degree of constant volume heat release.

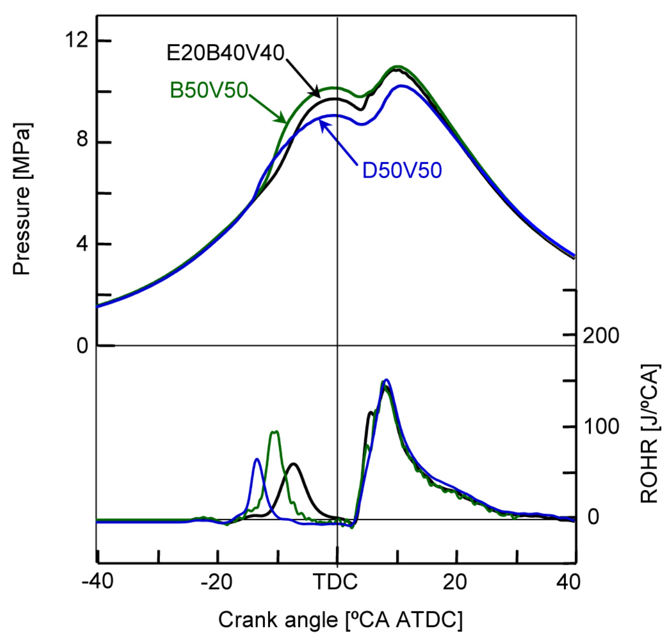


Fig. 8. Combustion characteristics at 15% intake oxygen concentration with the three vegetable oil blended fuels (IMEP: 1.0 MPa, θ_p = 23°CA BTDC, θ_m = TDC)

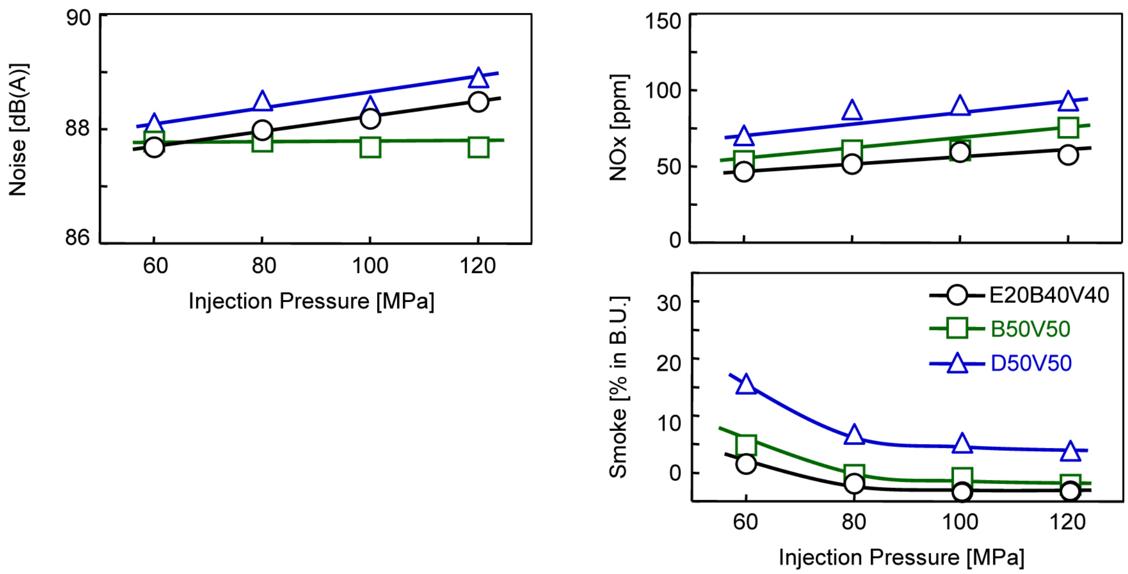


Fig. 9. Effects of the fuel injection pressure on smoke, NOx, and engine noise with the three vegetable oil blended fuels (IMEP: 0.75 MPa, O_{2in} = 15%, θ_p = 23°CA BTDC, θ_m = TDC)

Effect of Injection Pressure on Combustion and Emissions with Alcohol and Vegetable Oil Fuel Blends

Smokeless operation even with lowered injection pressures can be expected with blends of alcohol and vegetable oil due to the low soot formation properties. Figure 9 shows the effects of fuel injection pressure on engine noise, NOx, and smoke with the E20B40V40, B50V50, and D50V50 blends. Here, the pilot injection quantities are set at 8 mm^3/cycle for the E20B40V40, 6 mm^3/cycle for the B50V50, and 2 mm^3/cycle for the D50V50, where the maximum rate of pressure rise was found to be the minimum. The IMEP is set at 0.75 MPa and the intake oxygen concentration is maintained at 15% with cooled EGR. The smoke emissions increase with a decrease in injection pressure for all fuels, but smokeless operation is possible even at a low injection pressure (80 MPa) with the alcohol blended fuels (E20B40V40 and B50V50), due to the lower soot formation properties of the alcohol blend fuels, and the promotion of premixing with the larger pilot injection and smaller main injection. The NOx levels decrease with lowering injection pressure for all the blended fuels, and the levels with alcohol blends (E20B40V40 and B50V50) are lower than with the diesel fuel blend (D50V50). Here, as the EGR rate can be increased more with the alcohol blends due to the lower soot formation properties, realization of the lower NOx would be practical with larger EGR rates. Engine noise decreases slightly with decreases in injection pressures with E20B40V40 and D50V50 while there is little change with B50V50.

Figure 10 shows the effect of injection pressure on the combustion characteristic with E20B40V40 and D50V50. With E20B40V40 the rate of heat release with the pilot injection is almost unchanged irrespective of injection pressure. However, with D50V50 the heat release with the pilot injection decreases and retarded with a decrease in injection pressure, showing the deterioration in mixture formation. This may be due to the shorter ignition delay of D50V50, resulting in sensitivity to injection pressure. The combustion with the main injection at 60 MPa injection pressure is more moderate (not over rapid) than the 120 MPa injection for both fuels.

Combustion and Emissions with Alcohol and Vegetable Oil Blended Fuels Under Various IMEP

Figure 11 shows the exhaust gas emissions from three vegetable oil blended fuels and from regular unblended diesel fuel under various IMEP. Here, the intake oxygen concentration was maintained at 15%, and the pilot injection quantities were fixed at 8 mm^3/cycle for E20B20V40, 6 mm^3/cycle for B50V50, and 2 mm^3/cycle for D50V50 and diesel fuel. Smoke emissions with all fuels increase at higher loads, but are much lower with the alcohol blends (E20B40V40 and B50V50) than with the diesel fuel and D50V50. Especially E20B20V40 establishes smokeless operation even at around 0.9 MPa. This may be due to the oxygen content in the fuel. There is little difference in the NOx emissions for these fuels over a wide IMEP range, and the NOx emissions increase with increases in IMEP, but remain below 100 ppm for all the fuels here due to the high rate of cooled EGR. The CO emissions with the alcohol blends are higher at low and medium loads. This may be due to local low temperature combustion with the larger pilot injection quantities. The THC emissions with the alcohol

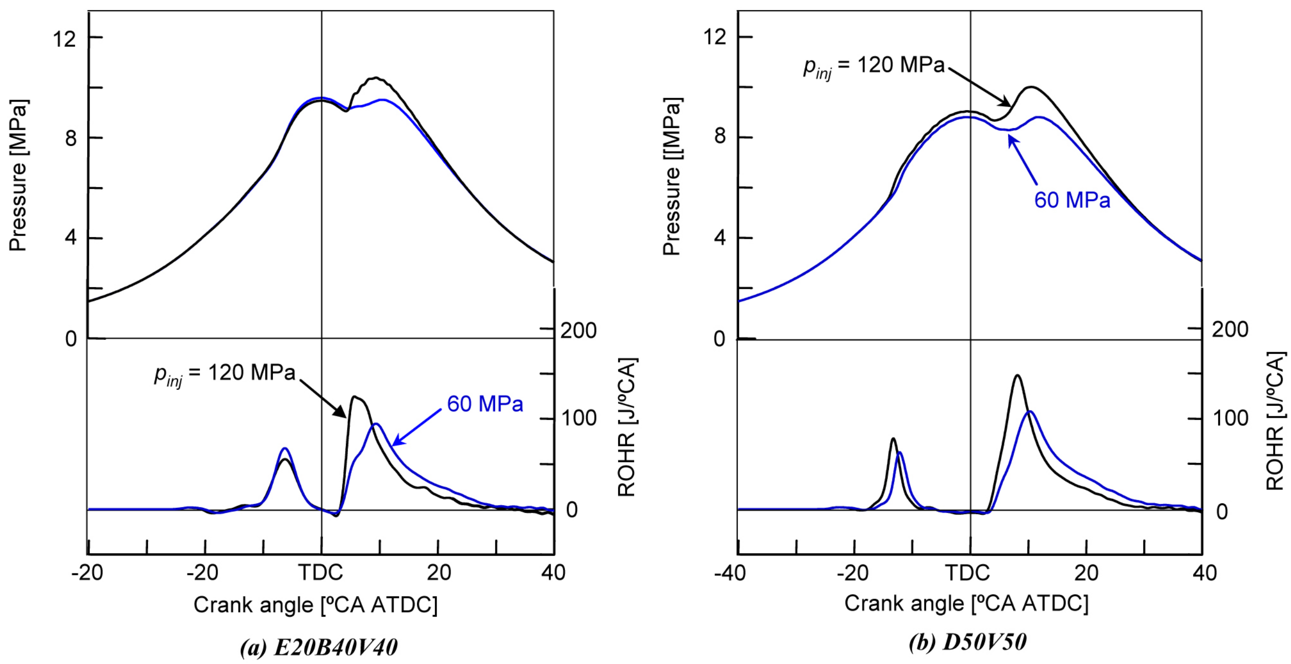


Fig. 10. Effect of injection pressure (p_{inj}) on combustion characteristics with E20B40V40 and D50V50 (IMEP: 0.75 MPa, O_{2in} =15%, θ_p = 23°CA BTDC, θ_m = TDC)

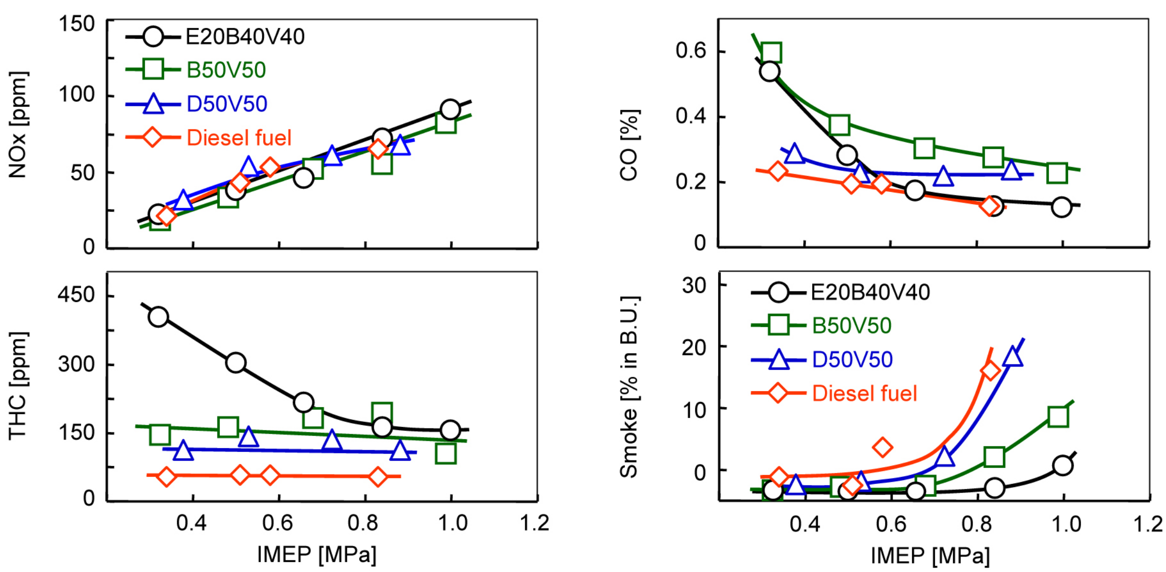


Fig. 11. Exhaust gas emissions with the three vegetable oil blended fuels and regular unblended diesel fuel for various IMEP (O_{2in} = 15%, θ_p = 23°CA BTDC, θ_m = TDC)

blends are higher than with diesel fuel and the vegetable oil + diesel fuel blend over a wide IMEP range, especially with E20B40V40 at low and medium loads.

Figure 12 shows the engine noise and the thermal efficiency related parameters for the three blended fuels and diesel fuel for various IMEP values. With E20B40V40, the pilot injection suppresses engine noise, but the engine noise is still higher than with the other blends and diesel fuel over a wide IMEP range. The Indicated specific fuel consumptions (ISFC) of the alcohol blend fuels are higher than the other fuels over a wide IMEP range due to the lower heating value. However, the indicated thermal efficiencies with the alcohol blends are higher than with diesel fuel and D50V50, especially at medium and high loads.

Figure 13 shows the in-cylinder pressure and the rate of heat release at low and high loads with the three blended

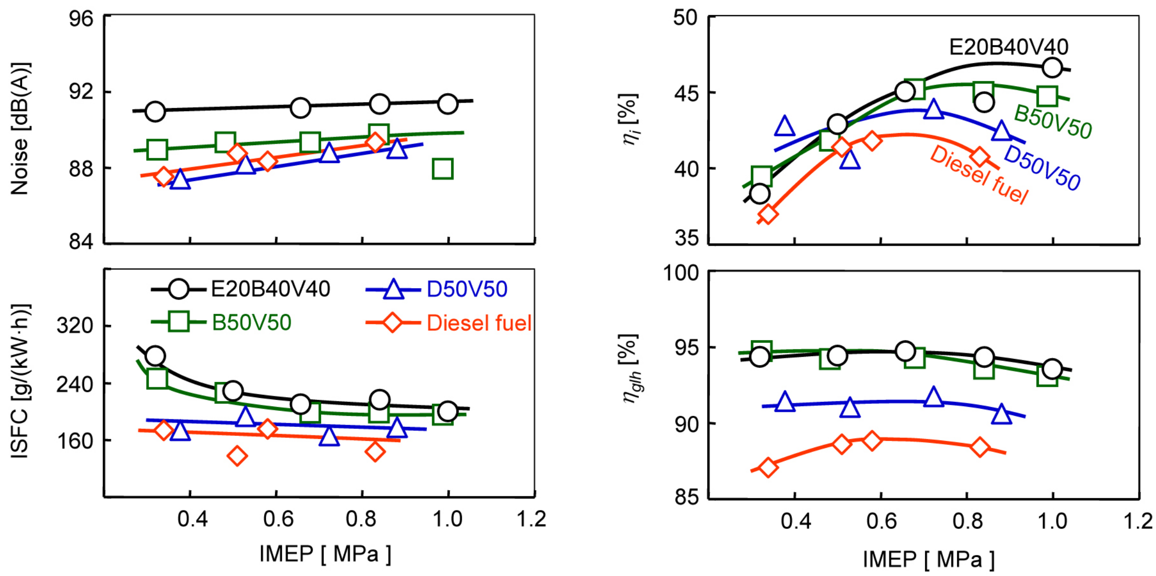
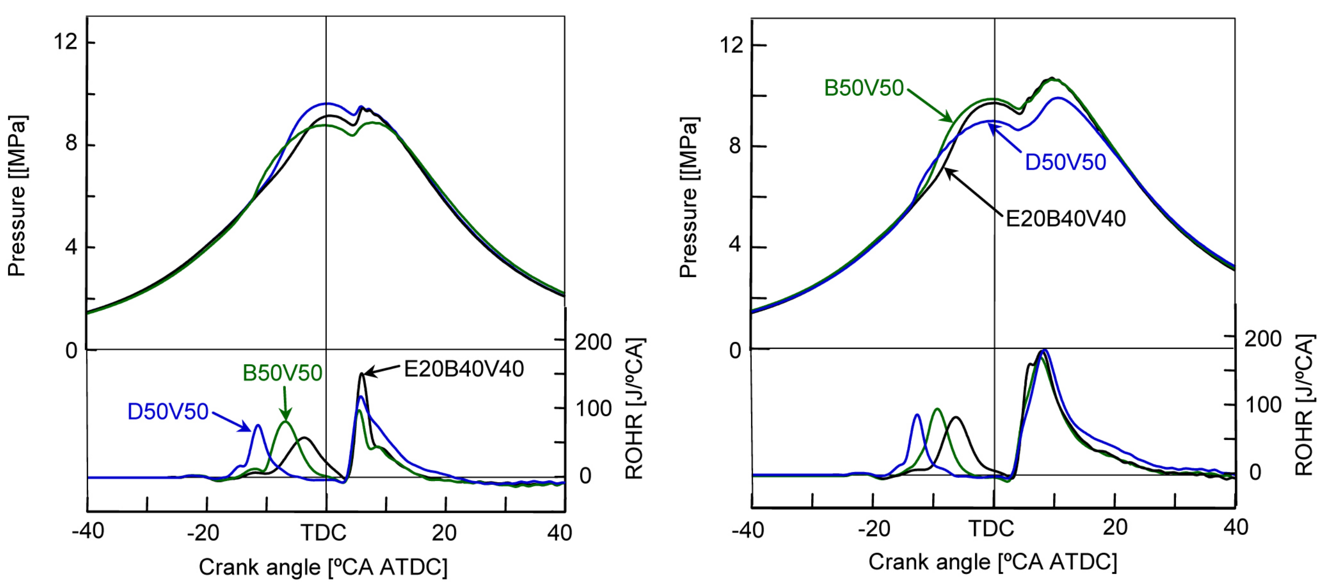


Fig. 12. Engine noise, the indicated specific fuel consumption (ISFC), the indicated thermal efficiency (η_i), and the degree of constant volume heat release (η_{glh}) with the three vegetable oil blended fuels and regular unblended diesel fuel for various IMEP (O_{2in} = 15%, θ_p = 23°CA BTDC, θ_m = TDC)



(a) Low load ***(b) High load***

Fig. 13. In-cylinder pressure and the rate of heat release (ROHR) for E20B40V40, B50V50, and D50V50 at low and high load conditions (O_{2in} = 15%, θ_p = 23°CA BTDC, θ_m = TDC)

fuels investigated here. The pilot injection with a suitable EGR rate establish moderate (not over rapid) combustion both with the pilot and main injections with all the blended fuels at both low and high loads. The rate of heat release with the pilot injection is retarded to near TDC and the afterburning is also shortened with the alcohol blends at both loads, resulting in an increase in the degree of constant volume heat release and higher indicated thermal efficiency, as indicated in Fig. 12.

SUMMARY/CONCLUSIONS

In this research, alcohols and nonesterified vegetable oil blend combustion is examined in a supercharged diesel engine with pilot injection and high EGR rates. The results may be summarized as follows:

1. Fuel blends for a high-speed small diesel engine with stable solubility, enabling sufficient ignitability, and low viscosity can be produced with 1-butanol + ethanol + vegetable oil or 1-butanol + vegetable oil blends.

2. Silent, low NOx, and smokeless combustion is possible over a wide IMEP range with the alcohols and vegetable oil blended fuels here with optimized quantities of pilot injection and EGR rates.

3. Premixed combustion with pilot injection occurs near TDC with the alcohols + vegetable oil blend fuels due to the poor ignitabilities, which make it possible to increase the quantity of pilot injection and reduce the after burning with the main injection, resulting in improvements in the indicated thermal efficiency due to the increase in the degree of constant volume heat release.

4. Smokeless operation is possible with the alcohols and vegetable oil blends even at low injection pressure and large EGR rate conditions.

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DEFINITIONS/ABBREVIATIONS

B50V50 - 50% 1-butanol and 50% vegetable oil blend

BTDC - Before top dead center

CA - Crank angle

$\mathbf{d}\boldsymbol{p}/\mathbf{d}\boldsymbol{\theta}_{\mathbf{max}}$ - The maximum rate of pressure rise [MPa/°CA]

D50V50 - 50% diesel fuel and 50% vegetable oil blend

DPF - Diesel particulate filter

E20B40V40 - 20% ethanol, 40% 1-butanol, and 40% vegetable oil blend

LHV - Lower heat value [MJ/kg]

ISFC - Indicated specific fuel consumptions [g/(kW·h)]

$\boldsymbol{O_{2in}}$ - Intake oxygen concentration [%]

$\boldsymbol{Q_p}$ - Pilot injection quantities [mm^3/cycle]

$\boldsymbol{p_{inj}}$ - Injection pressure [MPa]

RHOR - The rate of heat release [kJ/°CA]

TDC - Top dead center

$\boldsymbol{\theta_m}$ - Main injection timing [°CA]

$\boldsymbol{\theta_p}$ - Pilot injection timing [°CA]