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Effects of ethyl *tert*-butyl ether addition to diesel fuel on characteristics of combustion and exhaust emissions of diesel engines

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ABSTRACT

The effects of ethyl *tert*-butyl ether (ETBE) addition to diesel fuel on the characteristics of combustion and exhaust emissions of a common rail direct injection diesel engine with high rates of cooled exhaust gas recirculation (EGR) were investigated. Test fuels were prepared by blending 0, 10, 20, 30 and 40 vol% ETBE to a commercial diesel fuel. Increasing ETBE fraction in the fuel helps to suppress the smoke emission increasing with EGR, but a too high fraction of ETBE leads to misfiring at higher EGR rates. While the combustion noise and NO_x emissions increase with increases in ETBE fraction at relatively low EGR rates, they can be suppressed to low levels by increasing EGR. Though there are no significant increases in THC and CO emissions due to ETBE addition to diesel fuel in a wide range of EGR rates, the ETBE blended fuel results in higher aldehyde emissions than the pure diesel fuel at relatively low EGR rates. With the 30% ETBE blended fuel, the operating load range of smokeless, ultra-low NO_x (<0.5 g/kWi h), and efficient diesel combustion with high rates of cooled EGR is extended to higher loads than with the pure diesel fuel.

1. Introduction

To meet the increasingly stringent regulations for exhaust gas emissions from diesel vehicles, exhaust gas aftertreatment has become a necessity in most industrialized countries. Meanwhile, from the viewpoint of maintaining the functioning of exhaust gas aftertreatment devices and fuel economy in terms of vehicle running cost, a further reduction in the engine-out emissions through advanced fuel and combustion technologies is urgently required. Conventionally, there are relatively less total hydrocarbon (THC) and carbon monoxide (CO) emissions in the exhaust gas from diesel engines than from gasoline engines, and the challenge in achieving clean diesel combustion is to simultaneously reduce nitrogen oxides (NO_x) and smoke emissions.

Exhaust gas recirculation (EGR) is very effective to reduce NO_x, but because of the trade-off between NO_x and smoke emissions, EGR is conventionally limited to relatively low rates despite the potentials for further reduction of NO_x emissions. In recent years, several concepts for premixed low temperature diesel combustion have been proposed and investigated to simultaneously reduce NO_x and smoke emissions at institutions worldwide. Kitamura et al. developed a concept where NO_x is reduced by a large quantity of EGR and smoke is suppressed by retarded fuel injection to elongate ignition delay as well as with a very high swirl ratio to enhance fuel–air mixing [1]. In contrast, some other researchers adopted a strategy of early fuel injection combined with very high rates of EGR to simultaneous reduce NO_x and smoke emissions [2–5]. Furthermore, the effects of injection timing, injection pressure, and multiple fuel injections on the premixed low temperature diesel combustion were investigated [6–8], and study on a fundamental diesel flame in low oxygen environment was also conducted [9]. In these researches, however, the premixed low temperature combustion suffers from great increases in THC and CO emissions, and it is generally limited to low load operations. At higher loads, the increased fuel injection quantity needs more time to mix with air before ignition, while ignition delay tends to decrease due to the increased in-cylinder temperature. A further reduction in in-cylinder oxygen concentration by EGR may help to extend ignition delay, but this strategy would result in further increases in THC and CO emissions, and unacceptable deterioration in combustion efficiency. Therefore, it is extremely difficult to resolve the trade-off between NO_x and smoke emissions at higher loads while maintaining high thermal efficiency only by means of engine combustion technologies.

Fuel properties influencing engine combustion and exhaust emissions have been extensively investigated. Miyamoto and Ogawa et al. reported that an increase in oxygen content of fuels can dramatically reduce smoke, enabling more extensive utilization of EGR to control NO_x emissions [10,11]. In addition, it is known that a decrease in fuel cetane number leads to elongation in ignition delay, and further the present authors found that when increasing EGR, the effect of decreased cetane number on elongating ignition delay becomes more pronounced, allowing more time

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for fuel–air mixing before ignition [12,13]. Moreover, Senda et al. demonstrated that addition of low boiling point component into diesel fuel promotes spray evaporation and mixture formation processes [14].

Ethyl *tert*-butyl ether (ETBE) can be synthesized by reacting bioethanol (47% v/v) and isobutene (53% v/v) with heat over a catalyst, it can be considered a "bio-fuel", therefore ETBE helps to reduce the vehicle-out carbon dioxide (a green house gas) introduced to the atmosphere. As an additive to gasoline, ETBE has been extensively examined with regard to its impact on exhaust emissions, exhaust gas aftertreatment systems, evaporative emissions, cold strtability, materials used in the fueling systems and others in spark ignition engine-powered vehicles [15–17]. The fundamental characteristics regarding to ignition and combustion of both the pure ETBE and ETBE blended fuels have been studied as well [18–20]. ETBE has the properties of low auto-ignitability, low boiling point, oxygenated, and infinite solubility in diesel fuel. Therefore, ETBE, as an additive to diesel fuel, has the potentials for suppression of the smoke emissions increasing with EGR and extending smokeless and low NO_x diesel combustion to higher loads by promoting fuel–air mixing as well as by its oxygenated property. Nevertheless, some concerns should be addressed when using ETBE as an additive to diesel fuel. For instance, the lowered fuel cetane number due to addition of ETBE causes a too high rate of in-cylinder pressure rise and deteriorate thermal efficiency or fuel economy. In addition, it is concerned that addition of ETBE to diesel fuel, like ethanol addition to diesel fuel [21,22], might cause some increases in unregulated toxic emissions such as carbonyl or aldehyde emissions. However, so far only few published reports with respect to ETBE as an additive to diesel fuel are available [23], and more extensive studies regarding to the effects of ETBE addition to diesel fuel on engine performance and exhaust emissions are needed before it can be widely used.

The objective of this study is to investigate the effects of ETBE addition to diesel fuel on the combustion and exhaust emissions of a common rail direct injection diesel engine with high rates of cooled EGR. In addition, the operating load range of smokeless, low-NO_x, highly-efficient diesel combustion with ETBE blended diesel fuel is discussed.

2. Experimental

2.1. Engine and operating conditions

Table 1 shows the engine specifications and operating conditions. Experiments were conducted on a single cylinder, naturally-aspirated, four-stroke, direct injection diesel engine with a common rail system. A disk peripherally marked by 1 mm-width slits at every 20° crank angle was installed on the engine output axle, and the crank angle signal was obtained by using a phototransistor (PD32: NEC) reading the slit. The in-cylinder pressure was measured by a piezo-type pressure pick-up (6061B: KISTLER), and along with the injector needle lift signal, it was monitored by an oscilloscope. The top dead center was determined by the peak pressure when motoring the engine. The ignition delay increases with EGR, and the injection timing was advanced so that the ignition timing was maintained at top dead center (TDC). Here the ignition timing is an approximation and estimated by the apparent change of the rate of pressure rise in the experiments. The fuel injection pressure was set at 120 MPa. The swirl and compression ratios were 2.2 and 16, respectively. The fuel injection quantity (mm^3/stroke) was set so as to keep the same total energy input Q_f (kJ/cycle) to the engine when comparing the effects of different fuels on the engine performance and exhaust emissions. The total energy input of 1.1 kJ/cycle corresponds to 50% load or indicated mean effective pressure (IMEP) of 0.5 MPa under no EGR condition. The engine speed and coolant temperature were fixed at 1320 rpm and 80 °C, respectively. The EGR was realized by diverting part of the cooled exhaust gas into the intake port with gate valves. The EGR rate is defined by

$$\text{EGR rate} = \frac{M_{air0} - M_{air}}{M_{air0}} \quad (1)$$

where M_{air0} and M_{air} are mass flow rates of the intake fresh air without and with EGR. The flow rate of intake fresh air was obtained by using a manometer to measure the pressure difference between the inlet and outlet of an orifice on the intake surge tank. The EGR gas was cooled by a hand-made cooler with water as coolant. The temperature of the mixture of the intake fresh air and EGR gas was 30 ± 3 °C under all operating conditions. When increasing EGR, there is a direct correspondence between EGR rate and intake oxygen concentration, and the intake oxygen concentration were measured with a paramagnetic-type portable oxygen tester (POT-101: SHIMAZU). The rate of heat release (ROHR) was calculated from the in-cylinder pressure data and it is an average of 45 cycles.

2.2. Property of fuel used in experiments

A commercial diesel fuel (JIS#2) for Japanese market was used in this study. Table 2 shows the properties of the diesel fuel and ETBE. Test fuels were prepared with blending ETBE to the diesel fuel by 0%, 10%, 20%, 30% and 40% in volume. Fig. 1 shows the cetane number of the test fuels. Here the cetane number was calculated based on the volumetric fractions. Menezes et al. demonstrated that the cetane number measured with ASTM D

Table 1
Engine and operating conditions.

Engine name		Yanmar NF19
Cylinder number	–	1
Bore × stroke	mm	Ø110 × 106
Displacement	cm^3	1007
Rated power	kW/rpm	11.8/2200
Piston cavity shape	–	Toroidal
Compression ratio	–	16.0
Swirl ratio	–	2.2
Intake system	–	NA
Valve number	–	2
Fuel injection system	–	Common rail
Nozzle hole	mm	Ø0.20 × 4–150°
Injection pressure	MPa	120 MPa
Engine speed	rpm	1320 rpm

Table 2
Fuel properties.

Property	Unit	Diesel	ETBE
Density at 15 °C	kg/m^3	821.7	747.0
Kinetic viscosity at 30 °C	mm^2/s	3.36	–
Cetane number	–	58	2.5
Boiling point[a]	°C	283	71.7
Lower heating value	MJ/kg	43.1	37.9
Sulfur contents	Mass ppm	3	0
CHON contents			
C	wt%	86.1	70.5
H	wt%	13.8	13.8
O	Mass ppm	<1	15.7
N	Mass ppm	<1	0
HPLC			
Saturated	vol%	80.3	–
Olefins	vol%	0	–
Aromatics	vol%	19.7	–

[a] 50% distillation temperature for diesel fuel.