

Influence of Fuel Properties on Operational Range and Thermal Efficiency of Premixed Diesel Combustion

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ABSTRACT

The influence of fuel properties on the operational range and the thermal efficiency of premixed diesel combustion was evaluated with an ordinary diesel fuel, a primary reference fuel for cetane numbers, three primary reference fuels for octane numbers, and two normal heptane-toluene blend fuels in a single-cylinder DI diesel engine. The fuel injection timing was set at 25°CA BTDC and the maximum rate of pressure rise was maintained below 1.0 MPa/°CA when lowering the intake oxygen concentration by cooled EGR. With increasing octane numbers, the higher intake oxygen concentration can be used, resulting in higher indicated thermal efficiency due to a higher combustion efficiency. The best thermal efficiency at the optimum intake oxygen concentration with the ordinary diesel fuel is lower than with the primary reference fuels with the similar ignitability but higher volatility. The deterioration with diesel fuel is due to an increase in fuel which does not contribute to the effective combustion, as the high distillation components of diesel fuel adhere to the wall of combustion chamber. The operational range with normal heptane-toluene blend fuels shifts to higher intake oxygen concentrations, compared with primary reference fuels with the similar octane numbers, showing poorer ignition characteristics in the premixed diesel combustion.

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INTRODUCTION

Premixed diesel combustion, as an effective approach to achieve simultaneous reductions of NO_x and particulate emissions as well as high thermal efficiency, has attracted much attention [1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13]. For premixed diesel combustion with direct injection strategies, a long ignition delay is necessary to remove over-rich mixture before the ignition and the thermal efficiency is closely related to the combustion phasing that strongly affects the degree of constant volume heat release. Lower ignitability fuels can lead to longer premixing times, the time between the end of fuel injection and ignition, and may also induce a more retarded combustion phasing, combustion occurring closer to the top dead center [7, 8, 9, 10]. Fuel volatility also has a strong influence on mixture formation during the premixing period. Due to the low volatility of diesel fuels, wall wetting and oil dilution with impinging fuel spray on the cylinder walls, result in deterioration of the thermal efficiency, and are not easily avoided. Higher volatility fuels including gasoline may offer advantages by decreasing the wall-wetting, and also improve the mixture formation process

during the ignition delay. Recent research has shown that, with gasoline, high thermal efficiency can be obtained in premixed diesel combustion [11, 12, 13]. To obtain the optimal fuel properties, however, more extensive investigation of the influence of fuel properties on the characteristics of premixed diesel combustion is essential.

In the present research, the influence of fuel properties including ignitability, volatility, and compositions on the practical operational range and the thermal efficiency of premixed diesel combustion were investigated in a DI diesel engine with supercharging and a common rail fuel injection system. Ordinary diesel fuel, a primary reference fuel for cetane number (DPRF53), and a primary reference fuel for octane number (PRF20) were tested to establish the influence of fuel volatilities, further, three primary reference fuels (PRF0, 20, and 40) with octane numbers from 0 to 40 were compared to identify the influence of ignitability, and two normal heptane and toluene blend fuels (NTF) with octane numbers similar to the PRF (20 and 40) were used to investigate the influence of fuel compositions on premixed diesel combustion.

EXPERIMENTAL SETUP

The experiments were conducted on a single-cylinder, supercharged, four-stroke cycle, direct injection diesel engine with a low pressure loop cooled EGR and a common-rail fuel injection system. The specifications of the engine are shown in Table 1. The boost pressure was set at 160 kPa (absolute) with a supercharger driven by an electric motor, and an electric heater and an intercooler were installed after the supercharger to maintain the intake gas temperature at 25°C. The cooled EGR was realized with real exhaust gas passed through a diesel particulate filter (DPF) and the EGR cooler. The EGR gas was returned to the intake air before the supercharger with the low pressure loop, and the EGR rate was defined as the volume fraction of EGR gas in the total intake charge under the standard condition. The exhaust gas pressure was maintained with a throttle valve at 160 kPa, the same as the boost pressure. The fuel injection timing was always set at 25°C BTDC, the fuel injection pressure at 160 MPa, the engine speed at 2000 rpm, and the coolant and lubricant temperatures at 80°C.

The knocking limit is defined as the condition where the maximum of pressure rise rate reaches 1.0 MPa/°CA and the stable combustion limit is where the coefficient of variance (COV) in IMEP exceeds 5%.

Table 2 shows the properties of the tested fuels. The effect of fuel volatility was investigated with the differences among the primary reference fuel for octane number (PRF20), an ordinary diesel fuel (JIS No. 2), and the primary reference fuel for cetane number (DPRF53), which have similar ignitabilities but different volatilities. The effect of fuel ignitability was evaluated with the three primary reference fuels (PRF0, 20, & 40) with octane numbers from 0 to 40. The effect of fuel compositions was investigated with the difference between the PRF and normal heptane-toluene blend fuels (NTF) with similar research octane numbers (PRF20&40 vs. NTF17&34). In Table 2 the numbers after

PRF show the octane numbers and the numbers after NTF show the volume fractions of toluene in the blends; the research octane numbers of NTF17, NTF34 are estimated to be around 20 and 40 respectively. A lubricity improver (R655) was added to the PRF and NTF fuels in a volume fraction of 300 ppm.

Table 1. Engine specifications

Number of cylinders	1
Bore × stroke	85 × 96.9 mm
Displacement	550 cm ³
Compression ratio	16.3
Fuel injection system	Common rail system
Nozzle hole	0.125 × 7 – 156°

EXPERIMENTAL RESULTS AND DISCUSSION

Stable Operational Range and Combustion Characteristic of the Premixed Diesel Combustion

Figure 1 shows the range of intake oxygen concentrations, O_{2in} , for stable premixed diesel operation, and the excess air ratio with ordinary diesel fuel (JIS No. 2) for various IMEP (indicated mean effective pressure). The operation becomes impossible due to knocking when the oxygen concentration exceeds the solid line, and also when the oxygen concentration decreases and reaches the blue dashed line, here due to unstable combustion at low IMEP and at the green dashed line due to deterioration of the combustion efficiency at high IMEP. With increases in IMEP, the stable operational range of intake oxygen concentrations between the knocking and stable limits becomes narrower. The square symbols and the solid lines in Fig. 2 show the optimum intake

Table 2. Properties of the tested fuels

Property	Fuels						
	Diesel	DPRF53 ^c	PRF0 ^f	PRF20	PRF40	NTF17	NTF34
n-Heptane fraction [%]	—	—	100	80	60	83	67
Density [g/cm ³]	0.828	0.776	0.684	0.685	0.686	0.718	0.748
10% Distillation temperature [°C]	175	247~287 ^a	99.4 ^b	—	—	—	—
50% Distillation temperature [°C]	286						
90% Distillation temperature [°C]	354						
Octane number (RON ^c)	—	—	0	20	40	20 ^c	40 ^c
Cetane number	54.2	53	60 ^d	50 ^d	40 ^d	50 ^d	40 ^d
Carbon [wt%]	86.2	84.93	83.90	83.95	83.99	85.12	86.34
Hydrogen [wt%]	13.8	15.07	16.10	16.05	16.01	14.87	13.65
Stoichiometric ratio	14.5	14.95	15.16	15.15	15.14	14.90	14.62
Lower caloric value [MJ/kg]	43.02	44.08	44.56	44.51	44.47	43.95	43.35

^a Range of boiling point ^b Boiling point ^c RON = Toluene content × 1.2 ^d Cetane number = 60 – RON/2

^e DPRF: primary reference fuel for cetane number ^f PRF: primary reference fuel for octane number

oxygen concentrations, O_{2in} , and excess air ratios where the best indicated thermal efficiency is obtained in the stable premixed diesel operational range shown in Fig. 1. The optimum intake oxygen concentrations for the indicated thermal efficiencies are always obtained relatively near the knocking limit line for the various IMEP.

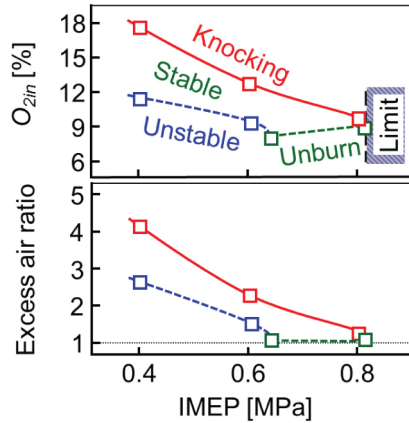


Fig. 1. Practical premixed diesel operational range of intake oxygen concentrations, O_{2in} , and excess air ratios (Diesel fuel)

Figure 3 shows thermal efficiency related parameters including the indicated thermal efficiency, η_i , the degree of constant volume heat release, η_{glh} , the combustion efficiency, η_u , and the unknown loss, ϕ_w with ordinary diesel fuel at the optimum thermal efficiency conditions shown in Fig. 2.

Here, the unknown loss, ϕ_w is calculated by the following equation based on the heat balance.

$$\eta_i = \eta_{glh} \cdot \eta_u \cdot (1 - \phi_w) \cdot \eta_{th}$$

η_{th} : The theoretical thermal efficiency of the Otto cycle

η_i : The indicated thermal efficiency calculated by the fuel consumption per cycle and the in-cylinder pressure

η_{glh} : The degree of constant volume heat release obtained from the rate of heat release

η_u : The combustion efficiency calculated from the CO and THC concentrations in the exhaust gas

The unknown loss, ϕ_w includes the following:

1. Cooling loss (main component)

2. Unburned fuel mixed into the lubricant oil

3. Oxidized fuel after the apparent heat release in the cylinder during the expansion and exhaust strokes as well as in the exhaust manifold before the exhaust gas sampling

As shown in Fig. 3, high indicated thermal efficiencies can be obtained at all IMEP conditions except above 0.8 MPa IMEP, where the combustion efficiency deteriorates markedly. Here a much higher degree of constant volume heat release and smaller unknown loss (mainly cooling loss)

than ordinary diesel combustion is realized, but the combustion efficiency is very low. This is a general characteristic of premixed diesel combustion.

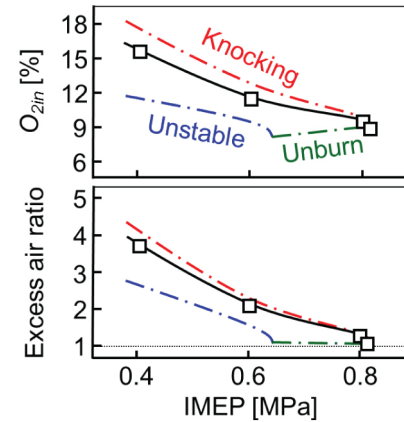


Fig. 2. Optimum intake oxygen concentrations, O_{2in} , and excess air ratios for the best indicated thermal efficiencies (Diesel fuel)

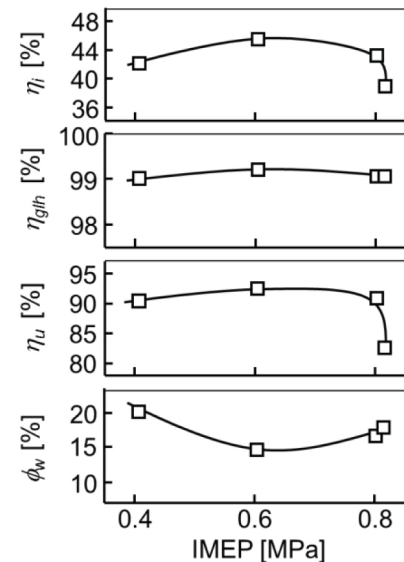


Fig. 3. Thermal efficiency related parameters with diesel fuel at the optimum intake oxygen concentrations

Figure 4 shows the exhaust gas emissions and the maximum rates of pressure rise at the optimum intake oxygen concentrations for the thermal efficiencies shown in Fig. 2. The NO_x emissions are everywhere below 20 ppm and smokeless operation is realized under all these conditions. The levels of CO and THC emissions are relatively low below 0.8 MPa IMEP, but increase significantly above 0.8 MPa IMEP when the excess air ratio is close to unity and the operation becomes impossible, even though the rate of pressure rise and COV are sufficiently low.