

Combustion Characteristics of Emulsified Blends of Water and Diesel Fuel in a Diesel Engine with Cooled EGR and Pilot Injection

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ABSTRACT

Water and diesel fuel emulsions containing 13% and 26% water by volume were investigated in a modern diesel engine with relatively early pilot injection, supercharging, and cooled EGR. The heat release from the pilot injection with water emulsions is retarded toward the top dead center due to the poor ignitability, which enables larger pilot and smaller main injection quantities. This characteristic results in improvements in the thermal efficiency due to the larger heat release near the top dead center and the smaller afterburning. With the 26% water emulsion, mild, smokeless, and very low NO_x operation is possible at an optimum pilot injection quantity and 15% intake oxygen with EGR at or below 0.9 MPa IMEP, a condition where large smoke emissions are unavoidable with regular unblended diesel fuel. Heat transfer analysis with Woschni's equation did not show the decrease in cooling loss with the water emulsion fuels. Single spray combustions with the water emulsions and the regular unblended diesel fuel in a constant volume combustion vessel were analyzed with a high-speed video and a 2-D two-color method. With the water emulsion fuel, premixing is promoted with longer ignition delays, and the duration and the scale of the luminous and high temperature flame decreases.

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INTRODUCTION

Improvements in the exhaust gas emissions and engine performance with emulsified blends of water and diesel fuel are well known [1, 2, 3], but the combustion characteristics in modern diesel engines with supercharging, cooled EGR, and common rail fuel injection systems have not been elucidated yet. Especially, there are several reports with different results for thermal efficiencies with water emulsified fuels and the improvements have not been explained in sufficient detail. In this report, water and diesel fuel emulsions containing 13% and 26% water by volume and a regular unblended diesel fuel were investigated in a modern diesel engine with pilot injection, supercharging, and cooled EGR.

In the experiments, the quantity of the pilot injection and the intake oxygen concentration, controlled by changing the EGR rate, were examined in operation with the relatively early pilot injection that is often applied in modern diesel engines. Firstly, the exhaust gas emissions and engine performance with the emulsified fuels and the regular unblended diesel fuel were investigated in a wide IMEP range at the optimum pilot injection and intake oxygen concentration to suppress the rate of pressure rise and the NO_x emissions to sufficiently low levels. In this case, the shapes of the rate of heat release diagram of the water emulsified fuels and the regular unblended diesel are different due to the lower ignitability that results from increasing water contents. Secondly, similar shapes of the rate of heat release

diagram with the water emulsified fuels and the regular unblended diesel were obtained with the same small energy quantity of pilot injection, making it possible to distinguish the influence of the rate of heat release arising from the differences in ignitability. Thirdly, single spray combustions with the 13% and 26% water emulsions and the regular unblended diesel fuel in a constant volume combustion vessel were analyzed with high-speed color video and a 2-D two-color method [4].

EXPERIMENTAL APPARATUS AND PROCEDURES

EXPERIMENTS WITH A DIESEL ENGINE

Experiments were conducted on a single cylinder, four-stroke cycle, 0.83 L direct injection experimental diesel engine converted from a commercial four cylinder engine, with a supercharger and a common rail fuel injection system. The specifications for the engine are a bore of 98 mm, a stroke length 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 a schematic outline of the experimental setup for the diesel engine. Supercharging was 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. The fuel injection pressure was set to 120 MPa, the pilot injection timing was at 23°CA BTDC, the earliest timing when the fuel spray does not directly hit the top of the piston, and the main injection timing was at TDC for all experiments. The pilot and main timings are suitable to establish low NO_x and smoke emissions without deterioration of the thermal efficiency.

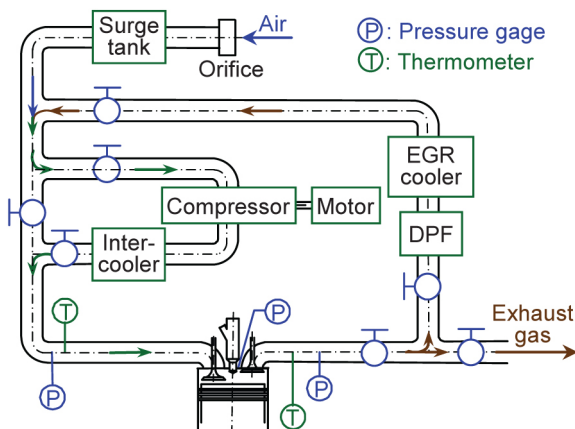


Fig. 1. Experimental setup for the diesel engine

Water and diesel fuel emulsions containing 13% and 26% water by volume (EM13 and EM26) were tested, and a regular unblended diesel fuel (JIS No. 2) was used as a reference, the properties of the fuels are listed in [Table 1](#). Here, EM26 was selected under consideration of ignitability lowered with water addition to maintain stable combustion.

Table 1. Particulars of the tested diesel and water emulsion Fuels

Fuels	Diesel fuel	Water emulsions	
Abbreviation	–	EM13	EM26
Diesel fuel [vol %]	100	85	70
Water [vol %]	0	13	26
Surfactant [vol %]	0	2	4
Density [g/cm ³]	0.833	0.839	0.862
LHV [MJ/kg]	43.0	37.1	30.7

EXPERIMENTS WITH A CONSTANT VOLUME COMBUSTION VESSEL

A shallow cylindrical constant volume combustion vessel ([Fig. 2](#)) with a diameter of $\phi 85$ mm, a thickness of 40 mm, and a volume of 227 cm³ was used to analyze the combustion processes of the emulsified blends. A high temperature and high pressure atmosphere like in a diesel engine at 21% oxygen concentration was created with a premixed combustion of an ethylene + oxygen + nitrogen mixture ignited with a spark plug. [Figure 3](#) shows an outline of the experimental setup. The initial content of ethylene, oxygen, and nitrogen was set to generate a combustion gas with the target residual oxygen concentration of 21 vol% after the premixed combustion. After the spark ignited premixed combustion the fuel was injected with a 50 MPa injection pressure system when the pressure and temperature had decreased to the target value with the cooling. A single hole 0.3 mm diameter nozzle and an injector of a common rail fuel injection system were used for the single fuel injection. The pressure at the fuel injection was set at 3.1 MPa and the temperature was 930 K for all experiments. A motor driven stirrer was installed in the sidewall of the vessel to create a uniform mixture. The same water and diesel fuel emulsions containing 13% and 26% water by volume (EM13 and EM26) and the regular unblended diesel fuel (JIS No. 2) as in the diesel engine experiments in [Table 1](#) were also tested here. The energy content of the injected fuel was kept constant at 1.57 kJ for all the tests, by adjusting the injection quantities and considering the heating values which are different among the fuels. The overall excess air ratio was around 5.3.

The temperature and the KL factor distributions were obtained with the 2-D two color method [4]. Direct flame images and two color flame images from the same conditions were taken separately with a high speed video camera (NAC GX-8) at 5000 frame/s. Two color flame images were

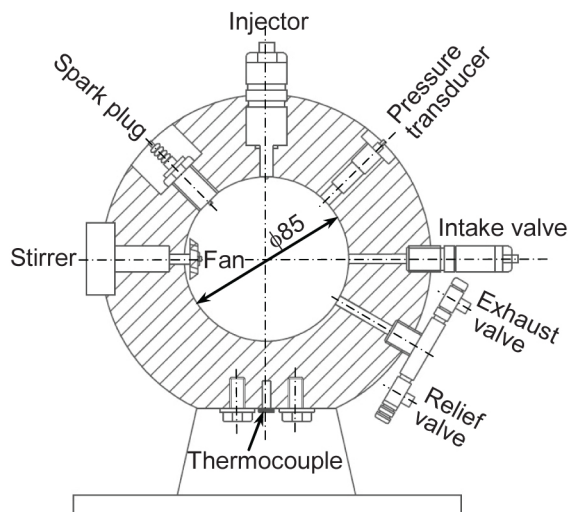


Fig. 2. Outline of the constant volume combustion Vessel

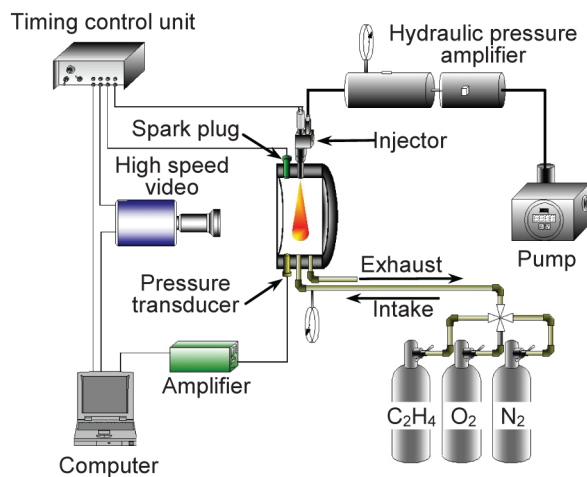


Fig. 3. Experimental setup for the constant volume combustion Vessel

obtained with a band pass filter which selectively passes the two wavelengths of 478 nm (a half-value width of 24 nm) and 607 nm (a half-value width of 26 nm). The transmissivities of the band pass filter at the central wavelengths are 60% for both wavelengths. The pressure in the vessel during the taking of the flame images was simultaneously measured with a piezo-type pressure transducer.

EXPERIMENTAL RESULTS AND DISCUSSION

EFFECT OF PILOT INJECTION QUANTITY ON COMBUSTION AND EMISSIONS WITH THE WATER AND DIESEL FUEL EMULSIONS

High ratios of water in fuels generally cause large ignition delays and excessively rapid combustion due to the decreases

in ignitability, but employing a pilot injection can suppress the rapid combustion. Figure 4 shows the effects of the pilot injection quantity on the maximum rate of pressure rise ($dp/d\theta_{max}$), NOx, and smoke emissions with water and diesel fuel emulsions containing 13% and 26% water by volume (EM13 and EM26) and with a regular unblended diesel fuel as a reference. Here, the indicated mean effective pressure (IMEP) was set to 0.7 MPa, 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 (not shown in Fig. 4), however, the pilot injection suppresses the rapid combustion to acceptable levels for all the 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 combustion with the water and diesel fuel emulsions (EM13 and EM26) were larger than with regular unblended diesel fuel, as shown in Fig. 4. The optimum pilot injection quantities are 3 mm³/cycle for the regular unblended diesel fuel, 4 mm³/cycle for EM13, and 6 mm³/cycle for EM26. The NOx decreases with increasing water contents and with decreasing pilot injection quantities for all fuels, maintaining at a low level for all cases due to the low intake oxygen concentration with the cooled EGR. The smoke emissions with EM26 are maintained at the zero level in Bosch units regardless of the pilot injection quantity while there are slight smoke emissions with EM13 and the regular unblended diesel fuel.

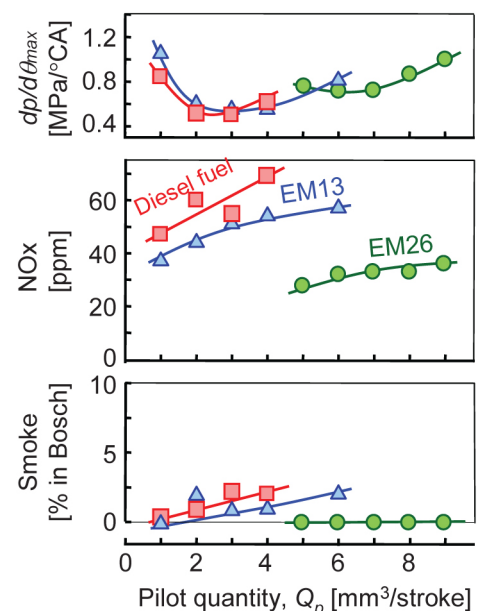


Fig. 4. Effects of the pilot fuel injection quantity on the maximum rate of pressure rise ($dp/d\theta_{max}$), the NOx and smoke emissions with EM13, EM26, and the regular unblended diesel fuel (IMEP: 0.7 MPa, O_{2in} = 15%)