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An experimental study on the combustion and emission characteristics of a diesel engine under low temperature combustion of diesel/gasoline/n-butanol blends

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HIGHLIGHTS

- The effects of EGR and diesel/gasoline/n-butanol blends were studied in CI engine.
- The addition of gasoline or n-butanol increase BSFC and NOx but decrease soot.
- As EGR ratio increased, the total PM number concentrations of four fuels increased.
- Gasoline or n-butanol decreases the total PM number concentrations.
- At 25%EGR approximately, the emissions of D70B30 reached the optimum values.

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ABSTRACT

Based on a small-scale high-speed diesel engine, the low temperature combustion and emission characteristics of four different fuels were experimentally investigated at different EGR ratios. The following fuels were studied: pure diesel (D100), a diesel and gasoline blend with a volume ratio of 70:30 (D70G30), a diesel and n-butanol blend with a volume ratio of 70:30 (D70B30) and a blend of diesel, gasoline and n-butanol with a volume ratio of 70:15:15 (D70G15B15). During the combustion of all four kinds of fuels, when the EGR ratio was smaller than 25%, the increase of EGR ratio sorted little effects on the maximum pressure rising ratio, as well as on the emission of soot, CO and total hydrocarbons (THC). Conversely, the emission of NO_x decreased significantly as the EGR ratio increased. At the same EGR ratio, the variation of fuel characteristics by adding gasoline or n-butanol into diesel did not sort significant effects on the NO_x emission, whereas it was found to greatly affect the maximum pressure rising ratio. When the EGR ratio was greater than 25%, the emissions of soot, CO and THC increased rapidly with the rising EGR ratio due to the decrease in excess air coefficient and to the excessively long ignition delay period. The D70B30 blended fuel exhibited more remarkable results in soot emission reduction than the D70G30 blended fuel. When the EGR ratio was close to 40%, NO_x emissions almost approached zero. As the EGR ratio increased, the number concentration of nucleation-mode particles ($Dp < 50$ nm) during the combustion of the examined fuels first decreased and then increased; the number concentration of accumulation-mode particles ($50\text{ nm} < Dp < 1000$ nm) increased continuously. When the EGR ratio was smaller than 25%, the total particulate matters (PM) number concentration during the combustion of the four fuels did not present a clear trend; when the EGR ratio was higher than 25%, the total PM number concentration during the combustion of the four tested fuels increased rapidly, with a descending order of rising amplitude, D100 > D70G30 > D70G15B15 > D70B30. At a fixed EGR ratio, the count median diameters (CMD) corresponding to the peak values of the number concentration of both nucleation-mode and accumulation-mode particles had an ascending order of D70B30 < D7 0G15B15 < D70G30 < D100. The emissions of soot, NO_x, CO and THC and the number concentration of particles reached their optimum values during the combustion of D70B30 at an EGR ratio of approximately 25%.

1. Introduction

Diesel engines are nowadays employed in a number of applications due to their high fuel-efficiency, reliability and adaptability.

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However, soot and NOx emissions from diesel engines are difficult to control, which is inevitably detrimental to the environment and to public health. In order to meet the emission regulations which are becoming increasingly stringent, many advanced technologies have been proposed and investigated, including new combustion concepts such as homogenous charge compression ignition (HCCI) [1–3], premixed charge compression ignition (PCCI) [4,5] and low temperature combustion (LTC) with high levels of exhaust gas recirculation (EGR) [6,7]. LTC in diesel engines has been regarded as an effective way of reducing soot and NO_x emissions simultaneously. However, previous research results demonstrate that, with the increase of EGR, the trend in soot emission presents a maximum, the so-called soot-bump region, which appears at medium and high EGR rates and is hard to eliminate (it should be noted that higher EGR values can reduce soot emission at the expense of thermal efficiency).

Because of the high cetane number and boiling point of diesel fuel, diesel-fueled LTC has a limited premixing time due to the short ignition delay and the difficulty to achieve spray vaporization at low temperature and pressure. However, gasoline fuel, which is another widely used petroleum product for internal combustion engines, is characterized by a high volatility and a low cetane number [8,9]. Recent research results on fuel volatility show that, due to the quick evaporation of this low boiling point fuel, the spray liquid penetration is shortened [10], and liquid wall wetting and fuel-in-oil dilution problems can be avoided. Moreover, fast fuel evaporation may lead to a more intense premixed heat release, i.e. to a higher percentage of fuel being mixed with air, which results in less smoke and more significant NO_x emissions [11]. Du et al. [12] and Lu et al. [13] investigated the effects of gasoline/diesel blends on the combustion process and on the emissions of a multi-cylinder light duty diesel engine. Their results indicate that an increasing volume fraction of gasoline can reduce smoke emissions at higher operating loads through an increase in charge premixing due to the longer ignition delay and to higher fuel volatility. The cetane number plays a more significant role in fuel–air mixing with respect to volatility. An appropriate reduction of the cetane number can increase the ignition delay, leading to a reduction in smoke emission owing to sufficient fuel–air mixing [14].

In recent years, butanol has been extensively investigated and regarded as a promising prospective additive for diesel and gasoline [15–20]. Compared with methanol and ethanol, n-butanol is more easily soluble in diesel fuel and hydrophilic, which decreases the risks of corrosion of carbon steels. Moreover, n-butanol has a higher gross calorific value, a higher carbon content and a higher cetane number, whereas its evaporating pressure and auto-ignition temperature are lower; moreover, it has a wider range of air–fuel ratio and a higher flashing point [21–24]. n-Butanol can also be carried by current fuel transportation equipment sets with higher security. In addition, as an oxygenated fuel, the addition of n-butanol to diesel can bring more oxygen in the fuel-enriched area, and oxygen atoms could react with soot precursors to reduce soot emission [25]. Valentino et al. [26] studied the influence of the inlet oxygen concentration on the combustion and emission performances of n-butanol/diesel fuel blends in low temperature combustion, conducting tests at constant speed and constant load. Their results showed that an increase in the inlet oxygen concentration leads to a decrease in soot emissions.

Many researchers [27–32] have investigated the engine performance and the exhaust emissions in diesel engines fueled with diesel/n-butanol blends; however, only a few papers are focused on the application of such blends to low temperature combustion and on their effects on engine performance and exhaust emissions. In particular, very few studies related to particulate emissions, number concentration and size distribution under different EGR rates are available.

Diesel vehicles are known to be one of the major sources of particulate in the urban atmosphere. Most of the particles emitted from diesel engines have a diameter smaller than 100 nm: in particular, particles with a diameter ranging from 50 to 100 nm are defined as accumulation mode particles [33]. Zhang et al. [34] and Nabi et al. [35] have found that the addition of blended oxygenated fuels can reduce both the mass and the number of emitted particles. In order to understand the correlations between PM emission and health effects [36–38], it is necessary to investigate the particle characteristics, such as their number, size distribution and mass concentration.

However, the effects of diesel/gasoline/n-butanol blends on the combustion and emission characteristics of a diesel engine under low temperature combustion still lack a deep investigation. Only a few studies have discussed the particulate matter emission characteristics of diesel/gasoline/n-butanol blends. The objective of this study is to investigate the effects of blending diesel fuel with gasoline and n-butanol on the combustion and emissions (NOx, THC, CO and soot) of a turbocharged common rail direct injection diesel engine with different EGR ratios and to compare the results with the case of pure diesel. The particle emission characteristics, such as their size distribution, number concentration and mass concentration are also studied. The blends considered here were constituted by diesel fuels with 30% (by vol.) gasoline and n-butanol and diesel fuels with 15% (by vol.) gasoline 15% (by vol.) n-butanol.

2. Experimental apparatus and procedures

2.1. Test engine and apparatus

The experiments were performed on a modern four-cylinder, 4-valve, four-stroke, water-cooled, variable-geometry turbocharger (VGT), diesel engine equipped with a common rail fuel injection system. Table 1 lists some key specifications of the engine and Fig. 1 displays the schematic of the experimental setup.

A measurement, calibration and diagnostic software (INCA, by ETAS) and a Bosch open-type ECU (Engine Control Unit) was used to control the common rail fuel injection system. The control system (ECU) was capable of adjusting the engine speed, torque, injection fuel mass, injection timing, rail pressure and pilot injection. The INCA software was employed to adjust the opening of the EGR valve and the nozzle flow area to control the EGR ratio and inlet pressure. The cylinder pressure was measured by a pressure sensor (Kistler 6052CU20) equipped with a charge amplifier and a data acquisition system. Pressure data were measured every 0.5° crank angle degree and the reported data were averaged over an ensemble of 100 consecutive engine cycles. Using these data measured by the piezo-transducer, the rate of heat release and pressure rise was calculated.

2.2. Emission measurement

Gaseous emission samples were collected at downstream of the exhaust back pressure ball valve and analyzed by a Horiba MEXA

Table 1
Key technical specifications of test engine.

Item	Specification
Number of cylinders	4
Cylinder diameter (mm)	85
Number of valves	16
Stroke (mm)	88.1
Displacement (L)	1.99
Maximum torque (N m)	286
Compression ratio	16.5
Rated power (kW)/Speed(r/min)	100/4000