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Effects of altitude and fuel oxygen content on the performance of a high pressure common rail diesel engine

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HIGHLIGHTS

- Fuel oxygen content has a more significant effect on soot emission reduction than the altitude effect.
- The BED fuel with basically the same oxygen content as the BD fuel can reduce soot emissions more.
- The BSFC of the BED fuel with basically the same oxygen content as the BD fuel is lower.

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ABSTRACT

The change of intake oxygen content caused by altitude variation and the change of fuel oxygen content both affect the performance of diesel engines. In this paper, comparative experiments were performed on a high pressure common rail diesel engine fueled with pure diesel and biodiesel–ethanol–diesel (abbreviated as BED) blends with oxygen content of 2%, 2.5%, and 3.2% in mass percentage at different atmospheric pressures of 81 kPa, 90 kPa, and 100 kPa. Moreover, in order to study the effect of different fuel blends with the same oxygen content on the performance of the diesel engine, tests were conducted on the diesel engine fueled with the BED blend and a biodiesel–diesel (abbreviated as BD) blend at 81 kPa ambient pressure.

The experimental results indicate that the influence of altitude variation on the full-load engine brake torque is not significant when the pure diesel fuel is used. With the increase of BED fuel oxygen content, the engine brake torque reduces. When the pure diesel fuel is used, with the increase of atmospheric pressure, the brake specific fuel consumption (BSFC) decreases. As the fuel oxygen content increases, there is no significant difference in brake specific fuel consumption of the BED blends. And the values of brake specific energy consumption (BSEC) gradually decrease. Soot emissions of the diesel engine decrease with the increase of atmospheric pressure and fuel oxygen content. The effect of soot emission reduction by increasing the oxygen content of the fuel is more significant than the effect of increasing atmospheric pressure. The effects of BD and BED fuels with basically the same oxygen content on the full-load performance, fuel economy, and soot emissions of the diesel engine are different. The BSFC and soot emissions of the BED fuel are lower than those of the BD fuel.

1. Introduction

Extensive exploitation and application of petroleum fossil fuels and their limited resources, together with the current situation of increasingly serious problems of environmental pollutions, have made seeking versatile and sustainable green alternative energy sources a pressing need. Among various alternative fuels, bioethanol and biodiesel have received great attention as hot topics in engine fuel research due to their excellent performance and adaptability, and they have been widely used in many countries and regions [1–7].

Both bioethanol and biodiesel are oxygenated fuels. Previous research showed that using oxygenated fuels can be helpful on improving the combustion process of diesel engines and reducing soot emissions [8–15]. However, there are no clear conclusions on the mechanism of soot emission reduction caused by oxygenated fuels. Some researchers suggested that the soot emissions in the diesel engine exhaust gas were mainly affected by the oxygen content of the fuel, and the benefit of diesel engine emissions reduction was mainly dependent on the oxygen concentration and almost irrelevant to the type of oxygenated fuels and the way of adding oxygen element [8–10]. On the other hand, Liotta and Montalvo [11] reported that the effect of soot emission

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reduction was strongly dependent upon the molecular structure of oxygenated fuels. The research work by Chen et al. [12] indicated that the effects of ethanol–diesel and biodiesel with the same oxygen content on soot emissions were different, and the effect of ethanol on reducing soot formation was more prominent. Salamanca et al. [15] found that the degree of unsaturation of the fatty acid esters could play a significant role on soot reduction.

In addition to the impact of fuel oxygen content, altitude level also affects the combustion process and the performance of diesel engines. Shen et al. [16,17] reported that engine power, fuel economy, reliability, and emissions were affected by altitude level as the atmospheric pressure and the intake air density reduce at high altitude. Using oxygenated fuels can compensate the lack of air at high altitude to a certain extent and may improve engine performance. Previous researchers have studied the effects of different altitude conditions and oxygenated biomass fuels on diesel engine performance [18,19]. However, very little research has conducted to date on the effects of intake oxygen content variation caused by altitude level change and fuel oxygen content on diesel engine performance. The purposes of this work are to explore different effects of intake oxygen content caused by altitude variation and fuel oxygen content on diesel engine performance and the effects of different types of fuels with the same oxygen content on engine performance under high altitude conditions, and to provide a theoretical foundation for the application and promotion of biomass oxygenated alternative fuels in high-altitude regions.

2. Experimental materials and methods

2.1. Testing equipment and experimental methods

The experimental test was carried out on a high pressure common rail diesel engine, YN30CR, as shown in Table 1. Other experimental devices included a hydrodynamic dynamometer (WE31, China), a fuel consumption meter (AVL 733, Austria), and a smoke meter (FQD-102A, China).

The simulated device for varying atmospheric conditions uses a system of "micro-computer controlled simulated atmospheric condition" to achieve simulated pressures and temperatures at different altitude and ambient pressure conditions. And it mainly consists of a dynamometer, an inlet and exhaust simulating device, a controller, and several sensors of pressure, temperature, and air flow rate [16,17].

During the test, all test data collections were performed after stable operation of the engine. Under the same measurement conditions, three measurements were carried out for each data collection. And the average of the three measurements was used to represent the test result.

2.2. Fuels used in the experiments

Based on the stability study of biodiesel–ethanol–diesel blend fuels [20], several BED blends with different oxygen contents were prepared with different proportions of the No. 0 diesel fuel, an anhydrous ethanol fuel (having 99.5% concentration), and a biodiesel fuel (made from waste oil). Particularly for this experiment, three types of BED fuels were prepared, denoted as BxEx (x means volume fraction). They are: B10E3 (containing 10% biodiesel in volume percentage in the blend fuel, 3% ethanol, and 87% petroleum diesel), B15E3 (containing 15% biodiesel, 3% ethanol, and 82% petroleum diesel), and B15E5 (15% biodiesel, 5% ethanol, and 80% petroleum diesel). Their oxygen contents are 2%, 2.5%, and 3.2%, respectively. In addition, another type of BD fuel was prepared, which contained 70% diesel in volume blending with 30% biodiesel, denoted as B30. The physicochemical properties of the single fuels and blend fuels used in the experiment are listed in Table 2.

The lower heating values of bioethanol and biodiesel are both lower than that of the pure diesel fuel. Therefore, it is necessary to introduce a parameter "brake specific energy consumption (BSEC) (g/kW h)" to fully reflect the fuel economy of the engine that is fueled with BED and BD blends. The calculation formula of BSEC is defined as follows in Eq. (1). The BSFC (g/kW h) shown in Eq. (1) is brake specific fuel consumption. ρ_{BED} (g/cm^3) is the density of biodiesel–ethanol–diesel blend fuel at 20 °C. V_E, V_B, and V_D are the volume fractions of ethanol, biodiesel, and diesel, respectively. H_{VE} (MJ/cm^3), H_{VB} (MJ/cm^3), and H_{VD} (MJ/cm^3) are the volumetric lower heating values of ethanol, biodiesel, and diesel fuels, respectively. H_{MD} (MJ/g) is the gravimetric lower heating value of the diesel fuel.

$$\begin{aligned}\text{BSEC} = (&\text{BSFC}/\rho_{BED} \times V_E \times H_{VE} + \text{BSFC}/\rho_{BED} \times V_B \times H_{VB} \\ &+ \text{BSFC}/\rho_{BED} \times V_D \times H_{VD})/H_{MD}\end{aligned} \tag{1}$$

The experiment was conducted at the altitude level of 1912 m with the atmospheric pressure of 81 kPa. Since the purpose of the experiment was to investigate a relative and straight comparison among different types of fuels, the base engine calibration and design were not modified or adjusted, and it was not necessary to correct the experimental data to standard environmental conditions.

3. Results and discussions

3.1. Effects of altitude and fuel oxygen content on diesel engine performance

3.1.1. Analysis of engine full-load performance

Engine testing was carried out on the diesel engine at full load using the pure diesel fuel under three atmospheric pressures (81 kPa, 90 kPa, and 100 kPa) and using four different types of fuels (the pure diesel and three BED fuels, which were B10E3, B15E3, and B15E5) with different oxygen contents under the atmospheric pressure of 81 kPa. Table 3 shows the collected torque data of the diesel engine using the pure diesel fuel at full load at 81 kPa ambient pressure and the uncertainties of the data. Fig. 1 shows the effect of different altitude levels on full-load engine performance.

Table 1
Engine specifications.

Engine Configuration	YN30CR BOSCH common rail system, turbocharged and intercooled
Number of cylinders	In-line, 4 cylinders
Bore × stroke	95 mm × 105 mm
Engine displacement	2.977 L
Engine compression ratio	18:1
Peak torque	289 N m at 2200 r/min
Rated power	79 kW at 3200 r/min

Table 2
Physicochemical properties of fuels.

Fuel type	Density at 20 °C (kg/m^3)	Cetane number	Lower heating value (MJ/kg)	Oxygen content (% in weight)
Diesel	837.9	53.1	42.845	0
Biodiesel	880	56	39.5	10
Ethanol	789.3	8	26.778	34.8
B10E3	835	52.037	42.32	2
B15E3	839	52.182	42.05	2.5
B15E5	837	51.28	41.8	3.2
B30	850	53.79	41.8	3.1