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Experimental investigation of the impact of biodiesel on the combustion and emission characteristics of a heavy duty diesel engine at various altitudes

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HIGHLIGHTS

- This experiment was conducted at various high altitudes.
- The emissions of CO, THC and PM decreased when using biodiesel at each altitude.
- Reduction of THC and PM emission caused by biodiesel decreased at higher altitude.
- Slight decrease of NO_X emission of biodiesel were observed at each altitude.

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ABSTRACT

As a widely recommended alternative fuel for diesel engines, biodiesel has been proven to be useful for the reduction of emissions from diesel engines, especially particle emissions. Equipped with an on-board engine test bench and a portable emission measurement system designed for mobile tests, this work investigated the emission of a Euro III emission standard heavy-duty diesel engine fueled with petroleum diesel and soybean-oil biodiesel at four different altitudes. Combustion data were also collected during the emission test at each altitude, which was helpful for the analysis of the emission results. These results showed that the use of biodiesel at high altitude advanced the start of ignition and reduced the proportion of the premixed combustion stage. The PM (particulate matter), THC (total hydrocarbon) and CO (carbon monoxide) emissions of the engine fueled with biodiesel were reduced at each investigated altitude, but the reduction of PM and THC emissions caused by biodiesel decreased as the altitude increased. The NO_X (nitrogen oxides) emission of both fuels showed no obvious variation with altitude, and the use of biodiesel led to a slight reduction in NO_X emission.

1. Introduction

Due to the adverse impact on human health and the increasing vehicle population, diesel emission has attracted an unprecedented level of attention. In China, areas above an altitude of 1000 m account for over 58% of the territory, while those above an altitude of 2000 m account for 33%. Some provincial capital cities in China, such as Kunming, Xining and Lhasa, are at altitudes of 1900 m or above. Therefore, it is quite important to improve diesel emissions at higher altitudes.

It had been proven that ambient conditions are very important to the performance of diesel engines. The decreasing ambient pressure caused by increasing altitude will result in lower intake air flow, which will adversely affect the engine performance, in such way as reducing the power output and deteriorating the emissions [1–3]. A number of research papers about the effect of altitude on diesel engine emissions have been published [4–8]. According to their experimental work, the variation of HC, CO, and PM emissions at different altitudes are similar and increase dramatically with increasing altitude. However, the characteristics of NO_X emissions have not been agreed upon.

Abbreviations: BSFC, brake specific fuel consumption; CO, carbon monoxide; ELPI, electric low pressure impactor; HFID, heated flame ionized detector; NDIR, non-dispersive infrared; NO_X, nitrogen oxides; NDUV, non-dispersive ultraviolet analyzer; PM, particulate matter; THC, total hydrocarbon; SOC, start of combustion.

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Biodiesel has been recognized as an alternative fuel with the potential to improve diesel engine emissions. Many researchers have compared diesel engine emissions using biodiesel and petroleum diesel as engine fuel. The differences in fuel properties between biodiesel and petroleum diesel lead to different emission characteristics. Lapuerta et al. conducted a comprehensive review of this issue [9]. Although biodiesel would increase the brake specific fuel consumption, most researchers have found that the emissions of CO, HC and PM were dramatically lower for biodiesel than petroleum diesel, while a slight increase in NO_X emissions was observed.

However, the majority of these experimental studies on biodiesel were conducted in the laboratories at fixed locations, most of which were at low altitudes. Few studies have investigated the effect of biodiesel on diesel engine performances at higher altitudes. Using an atmosphere simulation test platform, Chen et al. investigated the power output, brake specific fuel consumption, smoke opacity and noise of a direct injection diesel engine at different atmospheric pressures when the test engine was fueled with petroleum diesel and biodiesel [10]. They found a decrease in power output and fuel economy of the two investigated fuels with increasing altitude, while the effect of altitude on the power output and fuel economy deterioration was lower when the engine was fueled with biodiesel rather than diesel. The smoke opacity was greatly reduced by the use of biodiesel at each simulated altitude. Benjumea et al. examined the effect of altitude and palm oil biodiesel on the performance and combustion characteristics of a high speed direct injection diesel engine at altitudes of 500 m and 2400 m [11]. It was found that the premixed combustion duration was shortened and the brake thermal efficiency increased when biodiesel was used. The transition between premixed combustion and diffusion combustion became less obvious. It was also concluded that with the increasing altitude, the use of biodiesel led to a lower percentage of reduction in the brake thermal efficiency and in the quality of the energy stored in the exhaust gases.

In the literature on the issue of effect of altitude on diesel engines, most experimental works were conducted in a fixed laboratory using an altitude simulation system. These systems are generally convenient and reasonably affordable. However, the use of simulation systems from different manufacturers might result in unwanted differences in the uncertainty of experiment results and discrepancies between researchers.

In this work, an on-board engine test bench and portable emission measurement system designed for mobile tests was employed for a real-world experimental investigation of a heavy-duty diesel engine fueled with biodiesel and petroleum diesel at different altitudes, and a real-world estimation of the effects of biodiesel on diesel engine emissions at various altitudes was conducted.

2. Experimental setup

2.1. Test engine and fuel properties

This test was performed on a Euro III heavy-duty diesel engine (CA6DF3-20E). The CA6DF3-20E investigated in this experimental study was an in-line 6-cylinder, 4-stroke, turbocharged, intercooled diesel engine with an electronically controlled BOSCH common-rail fuel injection system, for which the specifications are listed in Table 1. No modification had been made to this engine except the installation of a cylinder pressure sensor (Kistler 6052C), which was used to measure the instantaneous cylinder pressure. No after-treatment devices were installed on this engine in this study. This engine was fueled with commercial diesel and soybean-based biodiesel whose specifications are listed in Table 2.

Table 1
Test engine specifications.

Manufacturer	FAW Wuxi Diesel Engine Works, China
Emission standard	Euro III
Type	In-line 6-cylinder
Bore	107 mm
Rod	125 mm
Compress ratio	17:1
Cylinder volume	6.7 L
Max torque	760 Nm (1400 r/min)
Rated power	147 kW
Fuel system	Bosch Common Rail System

2.2. Test bench and instrumentation

An on-board engine test bench specially designed for mobile testing was employed in this experiment, which enabled the engine to operate under real-world conditions of different altitudes. The dynamometer of the engine test bench was an eddy current dynamometer (CW440D) manufactured by the CAMA Electromechanic Co., Ltd. A Pitot-tube flow meter (SENSORS, USA) was used for the exhaust flow rate measurement. The fuel consumption was measured by the fuel consumption meter CMFD010 (TOCEIL, China), which was in accordance with the Coriolis theorem. A schematic of the test bench is provided in Fig. 1.

A DEWETRON 5000 series combustion analyzer was used in the test system to receive and store cylinder pressure and crank angle data collected by the cylinder pressure sensor and optical encoder, respectively. Based on these data, the real-time combustion parameters such as the heat release rate and mass burned fraction, could be calculated and displayed on the screen.

A SEMTECH-DS portable emission measurement system (SENSORS, USA) was employed for gaseous pollutant measurement. It measured the THC by HFID (heated flame ionized detector), NO_X by NDUV (non-dispersive ultraviolet analyzer), and CO and CO_2 by NDIR (non-dispersive infrared). At each altitude, the gaseous measurement modules were calibrated with standard gases and zero gas before the experiments to ensure the validity of the emission data. Because of the low ambient pressure at the altitudes of 4560 m and 3280 m, the oxygen content in the ambient air was not sufficient to allow the ignition of the HFID module, therefore, the THC measurement was not conducted at these two altitudes.

The particle emission was measured by the ELPI (electric low pressure impactor, DEKATI, Finland), which could determine the particle size by aerodynamic diameter in the range of 0.007–10 μm with 12 channels, as shown in Table 3. Prior to the ELPI, a two-stage dilution system (DEKATI, Finland), composed of two ejector dilutors in series was employed to dilute the exhaust. The compressed dilution air was generated by an air compressor, and

Table 2
Fuels specifications.

Parameters	Diesel	Biodiesel
Sulfur content (%, by weight)	0.0032	0.0009
Heat Value (MJ/kg)	42.77	39.50
Cetane number	53.1	54.6
Density at 20 °C (kg/m^3)	835.5	878.1
Viscosity at 20 °C (mm^2/s)	4.364	7.292
Carbon content (%, by weight)	85.95	76.36
Hydrogen content (%, by weight)	13.39	12.03
Oxygen content (%, by weight)	<0.2	12.11
Methanol (%)	–	<0.1
Monoglyceride (%)	–	0.290
Free glycerol (%)	–	0.004
Stoichiometric air–fuel ratio	14.473	12.327
Pour point (°C)	1.8	3.3