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Comparison of combustion characteristics and brake thermal efficiency of a heavy-duty diesel engine fueled with diesel and biodiesel at high altitude

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HIGHLIGHTS

- ▶ Peak heat release rate of biodiesel was lower and earlier than diesel.
- ▶ BTE of biodiesel dropped 0.6%, BSEC, BSFC, volumetric BSFC rose 2%, 17%, 11%.
- ▶ The start of combustion and combustion duration for the two fuels were similar.
- ▶ CA50 for biodiesel was 0.4°CA postponed in both operating conditions.

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ABSTRACT

A comparative study of combustion characteristics and brake thermal efficiency of a diesel engine fueled with diesel and biodiesel (FAME100%) at high altitude (4500 m) were conducted. A 6.7 L heavy-duty turbocharged, common-rail diesel engine meeting EURO III standard was employed. In this present paper, tests were carried out on an on-board engine bench system in high altitude regions instead of simulating devices in laboratories. Two operating conditions were selected to reflect the engine performance in low-speed high-load and high-speed high-load conditions. Calibration of the engine was kept unchanged when the test engine was fueled with diesel and biodiesel respectively. Experiment results revealed that the peak heat release rate of biodiesel operations in premixed combustion duration was a little earlier but lower than that of diesel operations. The start of combustion and combustion duration for diesel and biodiesel operations were very similar. CA50 for biodiesel was 0.4°CA postponed in both operating conditions. By fuelling with biodiesel, there was a decrease of about 0.6% in BTE of the engine. Meanwhile, increases of approximately 2%, 17% and 11% in BSEC, BSFC and volumetric BSFC were observed. Comparison of exhaust mass flow inferred that biodiesel fuelling was helpful to reduce the fresh air consumption when the engine was operating at high altitude.

1. Introduction

Increasing concerns over energy crisis and ambient air pollution pushes the research on clean alternative fuels for internal combustion engines. For compression ignition engines, biodiesel is an ideal alternative due to its various advantages, such as abundant sources, biodegradation and environmental friendliness over mineral diesel [1].

Many researchers ever investigated the engine behaviors with pure biodiesel or diesel/biodiesel blends implement. These results had been well reviewed by a few authors from different perspectives. Agarwal conducted a comprehensive review involving several aspects, including transesterification, property, tribology, and economic feasibility as well as combustion and emission characteristics of biodiesel application [2]. Similar literatures were reported by Basha and Fazal respectively [3,4]. Biodiesel was compared with other renewable diesel by Knothe; in this article, a series of social issues brought by the application of alternative fuels were raised and discussed [5]. Lapuerta et al. summarized the effects of biodiesel fuels on the emission characteristics of diesel engines [6]. On NOx emissions, a specific review was performed by Hoekman [7]. With respect to engine performance of biodiesel engines, a literature survey was conducted by Dwivedi et al. [8].

Abbreviations: ATDC, after top dead center; BSEC, brake specific energy consumption; BSFC, brake specific fuel consumption; BTDC, before top dead center; BTE, brake thermal efficiency; CA90, crank angle towards 90% fuel mass burning; CA50, crank angle towards 50% fuel mass burning; LHV, low heat value; SOI, start of injection.

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Lately, the understanding of biodiesel applications near sea level was relatively comprehensive. However, the studies on biodiesel operations in high altitude regions had been rarely reported.

Benjumea et al. conducted a comparative research at 500 m and 2400 m on the combustion characteristics of a HSDI diesel engine fueled with diesel and palm oil biodiesel. They also established an energy balance based on second-law to assess the thermal efficiency of biodiesel applications [9]. It was observed that biodiesel was beneficial to lessening premixed combustion duration and enhanced the in-cylinder temperature and brake thermal efficiency. By fuelling with biodiesel, the transition between premixed and diffusion combustion durations became less evident. For both fuels, shrinkage in BTE was observed as altitude rose; cumulative exergy destruction was even greater for biodiesel operations.

Chen et al. examined the engine performance, fuel economy, smoke opacity and noise of both diesel and biodiesel operations at various altitudes [10]. A decrease in engine power and fuel economy of both fuels was found with the rising of altitude. Nevertheless, power and economy deterioration for biodiesel operations appeared to be minor than that for diesel. In addition, biodiesel application could facilitate the reduction of noise at higher loads.

Some studies on combustion and emission characteristics of diesel engines were conducted. Shen et al. conducted a study on the combustion characteristics of turbocharged and naturally aspirated diesel engines at three altitudes [11]. It yielded that in-cylinder pressure and temperature descended corresponding to the decrease in atmospheric pressure at high altitude. With the rising of altitude, peak rate of heat release was enlarged but postponed. Ignition delay at higher altitude was longer than that at sea level, while combustion duration for high altitude operations was shortened.

A novel evaluation of the effects of high altitude on the emission characteristics of a heavy-duty diesel engine was performed by He et al. [12]. An increase of approximately 35%, 30% and 34% in CO, HC and smoke opacity was obtained at higher altitude. As for particulate matter, particle number at higher altitude was 1.6–4.2 times larger than that near sea level, and the aerosol diameter of exhausted particles became smaller in high altitude operations.

Given inconvenience encountered during the experiment conducting at various altitudes, a majority of prior research had adopted simulating devices to mimic the low atmospheric pressure in high altitude regions. This algorithm provides great convenience for the experiment conducting; but different design of simulating devices might bring uncertainty to the experiment results, and the discrepancy between laboratory simulation and real-world measurement remained indefinite.

This current scenario hindered the further implement of biodiesel in high altitude regions. Among 6 million vehicles registered in the tableland areas in China, diesel vehicles took up a significant portion. If biodiesel application had contributed to the reduction of vehicular emissions at high altitude as it was near sea level, considerable toxic pollution could have been expected to reduce in the following years. Similar problems might also be encountered in some other countries with plentiful mountains, like India and Columbia.

In view of this, this present paper mainly devoted to a comparison of combustion characteristics and brake thermal efficiency of a heavy-duty diesel engine fueled with diesel and soybean biodiesel at 4500 m, aiming at better understanding the effects of biodiesel fuelling on engine performance in high altitude regions. To avoid the uncertainty caused by simulating devices, this real-world research was conducted on an on-board engine bench system.

2. Apparatus and methodology

In order to carry out an accurate real-world assessment of engine performance at altitude as high as 4500 m, the tests in this article were conducted on an on-board engine bench system manufactured by CAMA. This platform allowed flexible real-world measurement at any available altitude, and thereby overcoming the disadvantages of simulating devices in laboratories.

The on-board engine bench system consisted of an engine dynamometer, the combustion test subsystem and the emission measurement subsystem. Fig. 1 sketched the experiment system in this present paper.

In this system, the eddy-current dynamometer CW440D was employed to control the rotation speed and torque of the test engine. The resolution for engine speed and torque control was 1 r/min and 1 N m respectively. Two operating conditions, 244 N m at 1200 r/min and 528 N m at 1800 r/min, were selected to represent high-load output at low and high speed respectively. These conditions could partially reflect typical operations of heavy-duty vehicles in urban and rural driving.

Combustion test subsystem was made up of three main devices. A piezoelectric sensor Kistler 6052C, which was affixed in the cylinder head of cylinder No. 1, was used to collect the instantaneous in-cylinder pressure and temperature data. An optical encoder Kistler 2613 was installed in the front of crankshaft so as to define the dead centers and diagnosed simultaneous crank position. Data from the piezoelectric sensor and the optical encoder were transferred to the combustion analyzer Dewetron 5000 series and were stored in it. Based on these data, real-time *P*–*V* diagram, gross heat release rate, fuel mass burning were calculated and screened.

Although emission characteristics were not reported in this present paper, emission measurement was employed to monitor the excess air ratio and exhaust mass flow. Also, fuel consumption of the engine was calculated on the basis of carbon balance of the exhaust stream.

Both regulated gaseous pollutions and particulate matter were tested by the emission measurement subsystem. Carbon oxides, nitric oxides and hydrocarbons were measured by the on-vehicle emission analyzer SEMTECH-DS. The test of these three pollutants was in accordance with NDIR, NDUV and heated FID methods. And the precision of the measurement was 10 ppm, 0.01% and 1.0 ppmC, respectively. Resolution time of this emission analyzer was 1 ms.

DEKATI ELPI (electric low pressure indicator) was employed to measure the particulate matter in the exhaust stream. It utilized the principle that a charged particle would deflect in electric fields and classified the particles in the exhaust stream into 12 levels by their aerosol diameters.

Table 1 listed the specifications of the test engine adopted in this article. No modification was made to the prototype except for the in-cylinder pressure measurement. Calibration of the engine was kept unchanged when the test engine was fueled with different fuels. SOI and rail pressure of the common-rail system was constant when the engine was fueled with diesel and biodiesel. However, when the engine was regulated at fixed torque, longer injection duration was required by biodiesel operation due to relatively low heat value. Thus, the injection duration of biodiesel was longer than diesel at constant brake torque.

The biodiesel (FAME100%) consumed in this present paper came from soybean sources. Some fundamental physical and chemical properties of the commercial diesel and biodiesel employed in this present paper were compared in Table 2.

At the beginning of each test, the engine was fully warmed. All the test apparatus were pre-warmed and calibrated as manufactures requested to ensure the credibility of the results. Filters of emission measurement devices were replaced and sample pipes