Energy 115 (2016) 539–549

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Experimental study on the combustion and emissions fueling biodiesel/n-butanol, biodiesel/ethanol and biodiesel/2,5-dimethylfuran on a diesel engine

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A R T I C L E I N F O

Article history:
Received 18 February 2016
Received in revised form
7 July 2016
Accepted 6 September 2016

Keywords:
Biodiesel
n-butanol
Ethanol
2,5-Dimethylfuran (DMF)
Low temperature combustion
Diesel engines

A B S T R A C T

The effects of biodiesel and its blends on the combustion and emissions were investigated on a single-cylinder diesel engine fueling three blends included biodiesel/n-butanol, biodiesel/ethanol and biodiesel/2,5-dimethylfuran. The results show that the indicated thermal efficiency (ITE) of pure biodiesel and three fuel blends are lower than that of diesel fuel at low load. With the increase of load, pure biodiesel and three fuel blends present higher ITE than that of diesel fuel, especially at high load and high EGR rates. The ability to reduce smoke can be sequenced as E20 > DMF20 > Bu20 > biodiesel. Pure biodiesel, B20 and DMF20 exhibit higher NOx emissions than that of diesel fuel, while E20 has lower NOx emissions than diesel. For three fuel blends, their HC and CO emissions are higher than those of diesel fuel at low load, but lower than diesel at higher loads. It is beneficial to further improve the thermal efficiency and reduce smoke at high load by increasing the blending ratio of high octane number oxygenated fuels. At 50% EGR rate, the soot reduction percentages are 79% and 99.4% for Bu50 and DMF50 respectively compared to diesel, and the thermal efficiency is further improved compared with 20% blending ratio.

1. Introduction

With the continuous consumption of fossil fuels and increasingly stringent emission regulations, the research on employing biofuels in internal combustion engines has attracted more attention worldwide in recent years [1–5]. The first-generation biofuels, mainly biodiesel [6–9] and bioethanol [10–12], are produced from food raw materials such as sugars and starches by fermentation, and their applications in engines have been extensively researched. With the fast development of biotechnology, the second-generation biofuels, which are produced from non-food raw materials such as woody stem, agricultural residues, corn and straw fiber, gradually catch researchers' attention, in which n-butanol presents more potential to be applied in engines [13–16], while DMF also attracts high attention due to the progress of production technology in the last few years [17–19].

For alcohol fuels, ethanol has been widely studied in the past few decades and commercially used as fuels of gasoline engine. In diesel engines, the oxygen content of ethanol is beneficial to reduce smoke emissions [11,12], but the miscibility between ethanol and diesel is limited. So, biodiesel was used as co-solvent for ethanol/diesel blended fuels [20,21] or was blended with ethanol directly [22–24]. Compared with ethanol, n-butanol shows some advantages such as higher energy density, lower volatility and hydrophilicity, which means it is less corrosive to the fuel system and is more suitable for transportation and storage [15,16]. DMF is regarded as one of the typical representatives of the second-generation biofuels, whose octane number is higher than ethanol, and energy density is higher than n-butanol (similar to gasoline). Meanwhile, the cost consumed in production process of DMF may be reduced by more than 60% compared to ethanol and it can be produced from more kinds of raw materials, such as glucose, cellulose, etc., which shows its better potential in engine application [17,18].

Low temperature combustion (LTC) is considered as one of the competitive combustion concepts of diesel engine to meet the strict emission regulations in the future. LTC generally use exhaust gas recirculation (EGR) combined with fuel injection strategies to achieve ultra-low smoke and NOx emissions [25–28]. The goal of employing EGR in low temperature combustion can be mainly attributed to the following two aspects: one is to prolong the

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http://dx.doi.org/10.1016/j.energy.2016.09.054
0360-5442/

ignition timescale to provide enough time for fuel/air mixing [29], the other is to substantially reduce the combustion temperature to avoid the formation of smoke and NOx [30,31]. However, the effect of EGR on smoke is fairly complex, a soot-bump region usually exists with increase of EGR rate although smoke can be significantly reduced by further increase the EGR rate, HC and CO emissions increase sharply and fuel economy deteriorates under heavy EGR low temperature combustion conditions [32,33]. Therefore, the main challenge of low temperature combustion is to simultaneously reduce smoke and NOx emissions while maintaining high thermal efficiency.

To address the problem mentioned above, many control strategies have been proposed, such as intake boosting [34], variable valve actuation (VVA) [35] and multiple injection strategy [36,37]. Meanwhile, fuel property also plays a very important role in fuel/air mixing and combustion process, and has attracted more attention in recent years [38–40]. Some investigations indicated that adding biofuels in diesel is an effective way to reduce smoke and increase thermal efficiency of low temperature combustion [41–43]. Guarieiro et al. [44] compared three types of fuels with different biofuel contents, i.e., B5 (95% of diesel and 5% of biodiesel), B5E6 (89% of diesel, 5% of biodiesel and 6% of ethanol), and B100 (100% of biodiesel). They reported that B5E5 showed increased HC emissions and reduced NOx emissions compared to B5. In addition, although B100 showed a reduction in HC emissions, however, the highest NOx emission and particle number of smaller diameter was observed among the studied fuels. Soloiu et al. [45–47] investigated massive and professional works about butanol by port-injection and binary mixtures with ULSD (ultra-low sulfur diesel)/Biodiesel at idling condition and different loads and showed that using butanol and biodiesel could greatly optimize the combustion parameters and improve the NOx-soot tradeoff relationship. An et al. [48] investigated the impacts of oxygen concentration, cetane number and C/H ratio of various blended fuels using KIVA-CHEMKIN code, and indicated that the effect of oxygen concentration was the main factor dominating the major intermediates and emission formation processes. The research of Imtenan et al. [49] on a multi-cylinder diesel engine showed that the addition of n-butanol and diethyl ether into diesel-biodiesel blends improved both the combustion and emission characteristics, and 10% of n-butanol and diethyl ether showed higher improvement than 5% blending ratio. Chen [50] investigated the combustion and emission characteristics of a multi-cylinder diesel engine fueled with DMF/diesel, n-butanol/diesel and gasoline/diesel blends. They pointed out that compared to diesel and gasoline/diesel blends, the addition of n-butanol and DMF can significantly improve the trade-off relationship between NOx and soot and extend the low emission region (NOx<0.4 g/kW.h, soot<0.01 g/kW.h) without deteriorating fuel economy. DMF shows advantage in reducing soot emissions compared to n-butanol and gasoline should be due to the prolonged ignition delay in their further study [51].

In summary, biofuels are important study direction for internal combustion engine, and fuel properties can significantly affect the combustion and emissions of engines. However, previous studies mainly focused on biofuels like biodiesel, ethanol, n-butanol separately. There are only a few relevant studies on DMF as CI engine fuel, and the systematic comparison between the first-generation and second-generation biofuels is also scarcely reported. In addition, the effects of fuel properties on combustion and emission characteristics might alter as engine operation condition and combustion control parameter change. Therefore, it is necessary to investigate the typical biofuels under different boundary conditions. In this study, n-butanol, ethanol and DMF were blended into biodiesel separately to formulate different blended biofuels. The study mainly focused on the effects of biodiesel and its blends on combustion and emission characteristics at different loads and EGR rates, especially the low temperature combustion conditions. Meanwhile, the effect of blending ratio on combustion and emissions was also investigated and discussed.

2. Experimental setup and method

The single cylinder, 4-stroke, 4-valve diesel engine used in this experiment was modified from a six-cylinder heavy-duty diesel engine. The test single cylinder was equipped with independent intake, exhaust and high pressure common-rail fuel systems. A cooled EGR system was employed and the EGR rate can be controlled by adjusting EGR valve and backpressure valve. The detailed specifications of the test engine are shown in Table 1 and the schematic of the engine setup is shown in Fig. 1.

The in-cylinder pressure was measured by a piezoelectric transducer (Kistler 6125C01U20). The charge signal of cylinder pressure was amplified and converted to voltage signal by a charge amplifier (Kistler 5108A1033) and then sent to the data acquisition system. The cylinder pressure data was recorded in half degree crank-angle increment, triggered by an encoder (Kistler 2614A4). For each operating point, the cylinder pressures of 50 cycles were collected. Then the combustion parameters, such as indicated mean effective pressure (IMEP), heat release rate, ignition delay, combustion duration and combustion phasing could be derived with a combustion analysis software package based on the in-cylinder pressure data. An external air compressor was employed to simulate boosted condition of the engine. The intake temperature was kept at 40 °C and the injection pressure was kept at 80 MPa for all test cases. Gaseous emissions and EGR rate were measured by a gas analyzer (Horiba MEXA-7100DEGR) and smoke was measured by a filter paper smoke meter (AVL 415S). The uncertainties and resolution/sensitivity of the main instruments are shown in Table 2.

In the current study, n-butanol, ethanol and DMF were blended with base biodiesel separately to investigate their effects on combustion and emissions. Two blending ratios, i.e., 20% and 50% volume ratios were selected. The fuel blends of n-butanol/biodiesel, ethanol/biodiesel, DMF/biodiesel with the two blending ratios were referred as Bu20/Bu50, E20/E50, DMF20/DMF50, respectively. The results of pure diesel and biodiesel were also presented for comparison. The main physical-chemical properties of diesel, biodiesel, n-butanol, ethanol and DMF are listed in Table 3.

The experiments were conducted at engine speed of 1500 r/min and three equivalent fuel consumptions were set here, which corresponded to 20 mg/cycle (about 3.4 bar IMEP), 40 mg/cycle (about 7.3 bar IMEP) and 60 mg/cycle (about 10.7 bar IMEP) diesel fuel mass conditions, respectively. For biodiesel and its fuel blends, the cyclic fuel mass should be recalculated according to their low heating values, i.e., fuels with smaller low heating values should increase the injection duration to ensure the same energy input. At the three engine loads, the intake pressures were set as 0.12 MPa, 0.15 MPa and 0.18 MPa, respectively. Three EGR rates of 0, 30% and

Table 1
Engine specifications.

Rated engine speed (r/min)	2500
Bore × Stroke (mm)	105 × 125
Connecting rod length (mm)	210
Compression ratio	16:1
Displacement(L)	1.0818
Combustion chamber	Reentrant type
Injection system	High pressure common-rail
Number of holes	8
Hole diameter (mm)	0.15
Included spray angle (deg)	150