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Performance and emission characteristics of a diesel engine running on optimized ethyl levulinate–biodiesel–diesel blends

Tingzhou Lei [a], Zhiwei Wang [a, b, *], Xia Chang [c], Lu Lin [d], Xiaoyu Yan [e], Yincong Sun [b], Xinguang Shi [b], Xiaofeng He [a, b], Jinling Zhu [a, b]

[a] *Henan Key Lab of Biomass Energy, Zhengzhou, Henan 450008, PR China*
[b] *Energy Research Institute Co., Ltd, Henan Academy of Sciences, Zhengzhou, Henan 450008, PR China*
[c] *Biological Developing Center, Henan Academy of Sciences, Zhengzhou, Henan 450002, PR China*
[d] *School of Energy Research, Xiamen University, Xiamen, Fujian 361005, PR China*
[e] *Environment and Sustainability Institute, University of Exeter Penryn Campus, Penryn, TR10 9FE, UK*

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ABSTRACT

In this study, biomass-based EL (ethyl levulinate) was evaluated as an additional fuel to biodiesel and diesel. Physical and chemical properties, including intersolubility, cold flow properties, spray evaporation, oxidation stability, anti-corrosive property, cleanliness, fire reliability and heating value of twelve different EL–biodiesel–diesel blends were analyzed. The results show that the fuel blends that were in line with China's national standard for biodiesel blend fuel (B5) have similar physical and chemical properties to pure diesel with improved cold flow properties. Optimized fuel blends based on grey relational analysis and analytic hierarchy process were selected to evaluate engine performance and emissions using an unmodified diesel engine test bench. The results show that engine power and torque with the fuel blends were in general similar to those with diesel (less than 3% differences). Both brake specific fuel and energy consumption were lower with the fuel blends than with diesel, suggesting higher fuel conversion efficiencies for the fuel blends. HC (Hydrocarbon) and CO (carbon monoxide) emissions and smoke opacity reduced significantly with the fuel blends compared with diesel while NO_x (nitrogen oxides) and CO_2 (carbon dioxide) emissions increased. Our study suggests that EL produced from lignocellulosic biomass could be used as a blending component with biodiesel and diesel for use in unmodified diesel engines and could potentially be a promising environment-friendly fuel.

1. Introduction

The depletion of fossil fuel resources, global climate change and local environmental degradation associated with the production and consumption of fossil fuels are among the most significant challenges facing the world. Energy security is also of great concern for many countries. China's transport sector is a perfect example of the scale of these challenges and concerns. Its demand for oil has been rising steadily along with the rapidly-increasing vehicle numbers in recent decades [1]. As a result, China is currently the second-largest oil consumer (after the US) and the largest oil importer [2]. Its dependence on imported oil grew from 32% in 2000 to 58% in 2013 [3] and is projected to reach 80% in 2030 [1]. China is also the world's largest GHG (greenhouse gas) emitter and its transport sector is among the fastest-growing sources of GHG emissions [4]. In addition, emissions from road vehicles are becoming major contributors to urban air pollution, which is one of China's most pressing environmental problems [1].

The Chinese government has made great efforts to respond to these challenges. For example, biofuels such as ethanol and biodiesel are promoted in China as alternatives to petroleum-based fuels [4]. Biodiesel can be produced from oil crops and various waste materials and is a promising fuel for existing diesel engines without expensive modifications [5–7]. It could also potentially reduce the emissions of GHG and some criteria pollutants [8–10]. However, there is currently only a small amount of biodiesel produced in China mainly from used cooking oil and the potential for future production from vegetable oils is likely to be rather limited with concerns over food security and impacts from potential land-

* Corresponding author. Energy Research Institute Co., Ltd, Henan Academy of Sciences, Zhengzhou, Henan 450008, PR China. Tel.: +86 371 56863117.
E-mail address: bioenergy@163.com (Z. Wang).

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use change [11]. There are also technical barriers to the use of biodiesel in cold climates such as its higher viscosity and pour point and lower volatility compared with diesel [12].

EL (Ethyl levulinate), one of the levulinate esters with an oxygen content of 33%, has recently been gaining attention as a potential oxygenated additive for diesel and bio-based cold flow improver for biodiesel [13,14]. It was reported that a blend of 20% EL and 79% petroleum diesel with 1% co-additive had a 6.9% oxygen content, and was significantly cleaner-burning than diesel [15]. The blend had high lubricity and low sulfur content, and met all the diesel fuel specifications required by ASTM D-975. Researchers have also analyzed the distillation curves of EL–diesel blends and fatty acid–levulinate ester biodiesel blends and investigated the cloud points, pour points and cold-filter-plugging points of blends of biodiesel produced from cottonseed oil and poultry fat with EL contents of 2.5, 5, 10, and 20 vol% [16,17].

EL is an industrially important derivative of levulinic acid, made by esterifying its carboxylic group with fuel-grade ethanol [18]. Various biomass feedstocks, including starch and sugar crops and cellulosic biomass, have been used to produce levulinic acid [19,20] and ethanol [21,22]. The US Biofine process, for example, can convert approximately 50% of the mass of six-carbon sugars to levulinic acid, with 20% being converted to formic acid and 30% to tars [23]. This process can make EL available at low production costs. Agricultural residues such as wheat straw can also be used as potential raw materials for the production of ethyl levulinate by direct conversion in an ethanol media [24]. The production of EL from cellulosic feedstocks is considered to be sustainable [25].

China is a major agricultural country with 600–800 million tonnes of crop straw produced every year [26]. Forestry residue is also an important biomass feedstock in China due to its vast forest base [27]. Although China has abundant crop straw, it suffers from a significant waste of this potential energy resource resulted from crop straw being discarded or burnt directly in the field and the associated adverse environmental impacts. Therefore, use of these lignocellulosic biomass resources for the production of liquid fuels such as EL could be highly beneficial for enhancing oil security, alleviating the pressure from the demand for fossil energy and resource, reducing environmental pollution, and developing the rural economy.

Most studies on diesel oxygenated additives focus on biodiesel and most of them have found that biodiesel addition can have little effect on or reduce engine performance, lower HC, CO and particular matter emissions while having higher NO_x emissions [28,29]. In China, the performance and exhaust emissions of EL as an additive to the conventional diesel fuel has been studied in a horizontal single-cylinder four stroke diesel engine, with EL percentages at 5%, 10%, 15% (with 2% n-butanol) and 20% (with 5% n-butanol) [30]. These studies show that available commercial diesel engine can run on EL–diesel blends with up to 20% EL without the need for modification. The emission tests under optimal engine operation conditions (engine speed of 1200 rpm and engine power of 5.3 kW for this particular engine) suggest that HC emissions of EL–diesel blends (except for the 20% EL blend) are higher than that of diesel while having a generally decreasing trend with increasing EL content. CO and NO_x emissions had an opposite trend, with low-level blend such as 5% EL blend lower than diesel but increasing with increasing EL content. Smoke opacity of the EL–diesel blends was consistently lower than diesel with a decreasing trend with increasing EL content.

Although China's national standard for biodiesel blend fuel B5 (GB/T25199-2010) [31] has been established, there are no standards for or studies on biodiesel blends containing EL. In this study, EL will be assessed as an addition fuel component to biodiesel and diesel. Physical and chemical properties, including intersolubility, cold flow properties, spray evaporation, oxidation stability, anticorrosive property, cleanliness, fire reliability and heating value, of twelve different blends of EL–biodiesel–diesel will be analyzed. The most appropriate fuel blends will then be selected based on these properties to evaluate engine performance and emissions using an unmodified diesel engine test bench. The overarching aim is to provide scientific evidence for the promotion of biomass-based EL as a renewable fuel in China.

2. Experiment material and methods

2.1. Experiment material

Diesel (0#) was obtained from the Henan Branch (in Zhengzhou, China) of China Petroleum and Chemical Corporation. EL (>99.9 wt %) was purchased from Shanghai Zhuorui Chemical Industry Co. Ltd (in Shanghai, China). Biodiesel was purchased from Zhengzhou Qiaolian Bio-Energy Co. Ltd (in Zhengzhou, China).

The fuel blends in this paper are labeled as BxEx, where B represents biodiesel, E represents EL, x represents the volume percentages of biodiesel or EL the in fuel blends. For example, B1E4 represents a fuel blend that contains 1% biodiesel, 4% EL and 95% diesel by volume. According to China's national standard, biodiesel fuel blends should contain 2%–5% vol of biofuel and 95%–98% vol of diesel [31]. Therefore, twelve different fuel blends that conform to this standard, including B0E2, B0E3, B0E4, B1E4, B2E3, B2.5E2.5, B3E2, B4E1, B5E0, B4E0, B3E0 and B2E0, were prepared by blending different volumes of biodiesel, and EL with diesel.

2.2. Experiment methods

Physical and chemical properties of different EL–biodiesel–diesel blends were studied based on the vehicle diesel test methods in China's national standard for biodiesel fuel blend (B5) [31]. A detailed list of the properties tested and the methods used are shown in Table 1. Fuel blends that were not up to the standard were disregarded. The qualified fuel blends were then optimized using GRA (grey relational analysis) and AHP (analytic hierarchy process). Experimental investigations were conducted to evaluate and compare the engine performance and exhaust emissions of the optimized fuel blends in a horizontal single-cylinder four stroke diesel engine. The following parameters were measured: torque, power, BSFC (brake-specific fuel consumption), emissions of unburned HC (hydrocarbon), NO_x (nitrogen oxides), CO (carbon monoxide) and CO_2 (carbon dioxide), and smoke opacity. Fig. 1 provides an overview of the experimental and analytical methods for the assessment of the fuel blends.

3. Properties of fuel blends

Good intersolubility is beneficial to fuel blend storage and combustion and was tested first. The fuel blends were enclosed in reagent bottles and put into a temperature test chamber (EL-04KA from Espec company, China) (Fig. 2). Phase separation and cloudiness were not observed in these blends for more than 72 h at 4 °C, 10 °C, 15 °C, 20 °C, 25 °C, and 30 °C using a temperature programmable controller of the chamber, implying good intersolubility for blends in which the total volume of EL and biodiesel was no more than 5%.

Using the test methods listed in Table 1 and experimental apparatus conforming China National Standards and Codes, the physical and chemical properties of the fuel blends were measured and shown in Table 2. The following observations were made in comparison with diesel: