Energy 119 (2017) 44–52

Contents lists available at ScienceDirect

Energy

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

Emission, injection and combustion characteristics of biodiesel and oxygenated fuel blends in a common rail diesel engine

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ARTICLE INFO

Article history:
Received 30 May 2016
Received in revised form
12 December 2016
Accepted 18 December 2016

Keywords:
Biodiesel
Solketal
Ethanol
Injection
Emission
Combustion

ABSTRACT

In this study, pure petroleum diesel fuel, blends of canola-safflower biodiesel and oxygenated fuel additives such as solketal and ethanol were tested in a common rail diesel engine under three engine speeds (1500 rpm, 2000 rpm and 2500 rpm) and the medium engine load (100 Nm) test conditions. Detailed and comparative injection, combustion and emission analysis of the test fuels were performed. The results showed that brake specific fuel consumption (BSFC) of biodiesel and its blends (15% ethanol-85% biodiesel and 15% solketal-85% biodiesel) with oxygenated fuels were higher than those of petroleum diesel fuel. Solketal and ethanol additions to biodiesel increased BSFC. Maximum cylinder pressures were close to each other for all test fuels. Main and pilot injection characteristics of the test engine changed significantly when diesel fuel and biodiesel were used. According to the emission results, biodiesel emitted higher NO_x and CO_2 emissions while lower CO and THC emissions compared with diesel fuel. In addition, solketal and ethanol fuel blends caused an increase in NO_x emissions and provided lower CO_2, CO and THC emissions on average compared to biodiesel. Ethanol-biodiesel and solketal-biodiesel blends gave similar results to each other.

1. Introduction

More than 170 countries have just signed Paris Climate Deal in USA to reduce the global greenhouse gas emissions. One way to overcome this problem is using alternative fuels instead of petroleum based fuels. Renewable oxygenated fuels such as biodiesel and ethanol are environmentally friend fuels and consumptions of these fuels have increased during the recent years [1]. Productions of ethanol and biodiesel are important due to reducing dependence of the countries especially which do not have any or enough petroleum sources. Ethanol and biodiesel productions in the world were about 100 and 30 billion liters in 2015 [2], respectively. EN 228 gasoline and EN 590 diesel fuel standard specifications allow to using 5% ethanol in gasoline and 7% biodiesel in diesel fuel. At the same time, E15 (15% ethanol, 85% gasoline) has been approved by many vehicle manufacturers [3]. Biodiesel can be used as pure form without any modification in diesel engines and many major engine manufacturers give warranties for biodiesel usage in diesel fuel containing up to 5% or 20% biodiesel [4].

Ethanol can be basically produced from renewable and agricultural feedstocks such as sugar beet, corn, wheat, sugar cane etc. and agricultural wastes as well. This fuel has many desirable properties such as perfect octane qualifications and better boiling characteristics for use in spark ignition (SI) engines. On the other hand, ethanol usage in diesel fuel reduces cetane number, lubricity, flash point and viscosity of diesel fuel while it increases volatility [5,6]. Due to these physical and thermodynamic characteristics, ethanol does not seem to be an alternative fuel for compression ignition (CI) engines. However, using ethanol in diesel engines provides better cold flow properties and reduction in sulfur, smoke and particulates emissions [6,7]. In addition, 15% ethanol in diesel fuel is recommended for diesel engine when the additives are used to provide better blend stability and higher flash point values [5]. Ethanol fuel can be used in diesel engines with mixing diesel fuel (diesohol), ethanol addition into air mass flow (fumigation) and dual fuel injection (individual injection systems for both ethanol and diesel fuel). Mixing ethanol in diesel fuel as an additive seems to be more effective and feasible way among these techniques [6].

Biodiesel is a petroleum-free alternative to diesel fuel, which can be produced from the feedstocks such as animal fat or

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http://dx.doi.org/10.1016/j.energy.2016.12.069

vegetable oils. The production process used to convert the feedstocks to biodiesel fuel is called transesterification. After transesterification reaction two phases occur; biodiesel and glycerol. Glycerol is an important material that is used in many areas of production. Cyclic acetals and ketals productions with using glycerol are the most attractive glycerol implementation for fuel intermediates [8]. Solketal ($C_6H_{12}O_3$) can be used as a diesel fuel additive which is produced from the reaction of glycerol with acetone in the presence of different catalysts [9,10]. When solketal is used as a fuel additive for petroleum diesel fuel or biodiesel, it improves cold flow properties, distillation temperatures and flash point values [11]. These advantages and reproducibility of solketal from glycerol bring it into the forefront like ethanol.

Researchers have investigated oxygenated fuels usage in diesel engines. Armas et al. [12] studied regulated gaseous emissions of E10 (10% ethanol - 90% diesel fuel) and pure diesel fuel in a turbocharged, common rail direct injection diesel engine. They revealed that E10 emitted slightly higher NO_x emissions while lower CO emissions. Rakopoulos et al. [13] performed an experimental investigation about the effects of using blends of ethanol with petroleum diesel fuel in a turbocharged direct injection diesel engine. They found that the NO_x and CO emissions reduced slightly, while smoke density was lowered significantly with using the blends containing 5% and 10% ethanol. Shi et al. [14] used the blend (5% ethanol, 20% biodiesel, 75% diesel fuel) in a heavy duty diesel engine. According to the results, the blend showed increase in NO_x emissions and reduction in THC emissions.

How et al. [15] investigated performance, emissions and combustion characteristics of coconut biodiesel blends (B10, B20, B30, B40) with diesel fuel in a common rail diesel engine. Biodiesel usage provided lower CO and smoke emissions, and caused higher NO_x emissions. As for combustion characteristics, biodiesel blends produced lower peak heat release rate than baseline diesel fuel and there were not significant variations in the cylinder pressure profiles among the blends and diesel fuel. He et al. [16] worked on biodiesel spray characteristics with an electronic unit-pump. They determined that biodiesel usage caused higher injection pressure due to its higher viscosity, density and bulk modulus under the same ambient temperature and injection duration. Boudy and Seers [17] presented the effects of biodiesel fuel properties on the injection mass flow rate of common rail injection system. They stated that density is more important parameter that influences the injection process than fuel viscosity and bulk modulus.

Park et al. [18] conducted a study about the injection and atomization characteristics of ethanol-biodiesel blend. They measured injection rate (mg/ms) versus time after start of energizing of injector (ms). They found that the density reduction with using ethanol-biodiesel blend affects the decrease of the peak injection rate (maximum injection amount) and shortening of injection delay. They indicated that ethanol usage as an additive in biodiesel improved the atomization characteristics due to lower viscosity. In another study, Yilmaz et al. [19] prepared ethanol-biodiesel-diesel fuel blends containing up to 25% biodiesel and ethanol. The ethanol and biodiesel amount was kept equal and the rest was diesel fuel in the blends. They showed that ethanol-biodiesel-diesel fuel blend generated lower HC emissions than those of diesel fuel at medium and high engine loads.

When looked at the literature, it seems that there are enough studies about ethanol and biodiesel usage in diesel engines. However, investigations of solketal usage in diesel engines are not sufficient. Most studies are generally about solketal production and property characterization as can be seen in the literature. Therefore, in this study, impact of solketal addition to the key fuel properties of biodiesel was investigated. A common rail direct injection diesel engine was fuelled with pure petroleum diesel fuel, biodiesel, solketal-biodiesel and ethanol-biodiesel blends. Effects of these fuels on the engine performance, emissions, injection and combustion characteristics and how the common rail injection system responded to the different fuel types were studied under different engine running conditions. In addition, it has been researched whether solketal is an alternative fuel additive for diesel engines like ethanol or not. According to author's knowledge, this is the first study which compares both engine tests of solketal and ethanol as additives in biodiesel.

2. Materials and methods

In this study, diesel fuel was bought from a local gas station. Biodiesel produced from oil mixture of canola oil and safflower oil (50%–50%, volume base) was obtained from a biodiesel producer. The purity of solketal and ethanol were 97% and 99.9%, respectively. The basic fuel properties of diesel fuel, solketal, ethanol, biodiesel and its blends with solketal and ethanol were given in Table 1. Fatty acid distribution of biodiesel ($C_{18.94}H_{34.99}O_2$) determined according to IUPAC 2.301 test method was shown in Table 2. The prepared test fuels are diesel fuel (D), biodiesel (CSB), solketal (S), ethanol (E), CSBS15 (15% S, 85% CSB) and CSBE15 (15% E, 85% CSB). As seen in the literature, 15% ethanol is one of the most preferred blends by the researchers. Therefore, solketal and ethanol amount was kept to be 15% in biodiesel. The test fuels were characterized in the Alternative Fuels R&D Center in Kocaeli University (AFRDC).

Diesel fuel, biodiesel and the blends containing oxygenated fuel additives were used as test fuels in a water-cooled, turbocharged-intercooled common rail direct injection diesel engine. Engine specifications were shown in Table 3. The diesel engines for passenger cars are generally used in the range of 1000–3000 rpm at low or medium engine loads. Therefore, three different engine speeds (1500 rpm, 2000 rpm and 2500 rpm) in this range and medium engine load (100 Nm, 50% load of maximum load) were chosen for the engine tests. There was not any modification on the diesel engine during the engine tests. A schematic diagram of the engine setup was shown in Fig. 1. K type thermocouples with a digital indicator were used to measure the temperatures of the intake air, fuel, engine oil and engine coolant.

Intake air mass flow was determined by AVL Flowsonix-Air product. The fuel temperature was controlled by a heat exchanger

Table 1
Basic fuel properties of the test fuels.

Fuel	Density (15 °C, kg m^{-3})	Viscosity (40 °C, mm^2 s^{-1})	Higher Heating Value (MJ kg^{-1})	Flash Point (°C)
Test Methods	ASTM D4052	ASTM D445	ASTM D240	ASTM D93
D	831.7	2.58	45.98	63
CSB	884.3	4.35	40.10	168
Ethanol	793.4	1.16	29.58	<21
Solketal	1071.1	5.21	25.91	84
CSBE15	869.7	3.07	38.12	<21
CSBS15	906.8	4.42	37.82	95