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Performance, emissions, combustion and injection characteristics of a diesel engine fuelled with canola oil–hazelnut soapstock biodiesel mixture

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ABSTRACT

This study investigates performance, emissions, combustion and injection characteristics of a diesel engine fuelled with blends of diesel fuel No. 2 and a mixture of canola oil–hazelnut soapstock biodiesels. The hazelnut soapstock biodiesel was mixed with the canola oil biodiesel to improve some properties of the canola oil biodiesel and to reduce the cost of the fuel. The experiments were performed on a single-cylinder direct injection diesel engine running with No. 2 diesel (D100) and No. 2 diesel/biodiesel blends containing 5% (B5) and 10% (B10) biodiesel fuels. The experimental results showed that the injection and ignition delays and the maximum heat release rates decreased with the biodiesel addition while the injection and combustion durations increased. In addition, it was determined that the oxygen content of B5 enhanced the combustion resulting in increased NO_x emission and decreased THC, CO and smoke emissions. However, B10 fuel deteriorated the combustion due to higher density, viscosity and surface tension. Therefore THC, CO and smoke emissions increased while NO_x emission decreased. CO_2 emissions for both blends were very similar to those of No. 2 diesel.

1. Introduction

The number of diesel engines continuously increases every year because of having high efficiency, enhanced fuel economy and low emissions. Diesel engines are preferred over spark ignition engines in almost all heavy-duty applications [1,2]. Therefore, the world's demand for diesel fuel increases every year. Since the fossil fuel resources gradually diminish and fossil fuels cause air pollution and global warming, it is required to find renewable energy sources and fuels [3,4]. Biodiesel fuels produced from different vegetable oils are biodegradable and non-toxic alternative renewable fuels for diesel engines. In general, they are blended with diesel fuels and the blends are used in diesel engines without any modification. However, it should be pointed out that their properties should be within the limits of biodiesel standards, especially EN 14214 + A1 and ASTM 6751-12. Otherwise, they cause various problems in diesel engines such as injector and filter plugging, corrosion of fuel line components, formation of carbon deposit and degradation of lubrication oil [5].

Price of the biodiesel fuel is an important parameter for usage of biodiesel fuels [6–8]. It is known that feedstock cost is the main part of the biodiesel production cost. Since the prices of edible vegetable oils are high, the use of edible oils in biodiesel production increases the prices of biodiesel fuels. The low-priced feedstocks, such as used waste oils, soapstocks, non-edible vegetable oils and animal fats, can be seen as a solution for low priced biodiesel fuels [5,6,9]. However, the use of cheap oil sources having high free fatty acid (FFA) also increases the cost of the biodiesel fuel due to extra steps in the production [8,10].

The properties of biodiesel fuel mainly depend on the fatty acid composition of the oil and the production technique. Although suitable techniques are used in biodiesel production, the properties of biodiesel fuel may not be within the limits of the biodiesel standards due to the fatty acid composition of the oil. The most important biodiesel properties depending on the fatty acid composition of the oil are cold flow properties, iodine value, viscosity and oxidation stability [5,11,12]. Especially, the polyunsaturated fatty acid bonds result in decreasing the oxidation stability of the fuel, thus the fuel reacts with oxygen in a short time and cannot be long-term stored [13,14]. The cold filter plugging point (CFPP) of biodiesel is an important property affecting the usage of biodiesel fuel in cold weathers. The biodiesel fuel having high CFPP may cause the plugging of fuel line and filters and wear increase in fuel system due to insufficient lubrication and fuel supply [13,15]. Cold flow properties, iodine value and oxidation stability can be improved with mixing of different biodiesels [15–18]. The previous studies revealed that the cold flow properties, iodine value and viscosity of a biodiesel mixture vary nearly linear with blend ratio of different biodiesels [10,16,19,20]. Moreover, oxidation stability and cold flow properties can be kept within the standard limits by using antioxidants and cold flow improvers [16].

There are different studies related to engine tests of biodiesel fuel blends. Most of them only include classical information about

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performance and emissions [9,21–23]. However, detailed engine combustion analyses are required to investigate combustion of biodiesel fuels in diesel engines [1,24]. There are limited numbers of comprehensive studies about combustion of biodiesel fuels in the literature. Labecki et al. [25] tested rapeseed oil blends in multi-cylinder direct injection (DI) diesel engine and stated that the premixed and diffusion combustion phase durations influenced NO_x and smoke emissions, respectively. In addition, they pointed out that the combustion could be affected with high fuel viscosity causing poor atomization and mixture formation. Rakopoulos [26] indicated that there were interactions between injection parameters and NO_x emissions in diesel engines. Besides, it was found that biodiesel additions resulted in lower the maximum cylinder pressures and temperatures, and the heat releases delayed towards the end of combustion. Additionally, it was concluded that heat release analyses were needed for the investigation of NO_x and soot characteristics. Ozsezen and Canakci [27] tested canola and waste palm oil methyl esters in a six-cylinder DI diesel engine. They reported that the high density of biodiesel caused early injection in the volumetric injection pump leading to short ignition delay and high NO_x. In addition, they found that the premixed combustion durations of the biodiesel were longer than those of the diesel fuel due to slowly vaporization of biodiesel. It should be pointed out that the combustion and injection analyses are very important to investigate the emissions and performance of engines fuelled with biodiesel.

In this study, the biodiesel fuel produced from hazelnut soapstock as a cheap source was mixed in 20% v/v ratio with canola oil biodiesel to decrease the price of the biodiesel and improve the iodine value, oxidation stability and CFPP properties of the biodiesel. Then, the biodiesel mixture was blended with No. 2 diesel fuel in 5 and 10% v/v, and diesel fuel/biodiesel blends were tested in a single-cylinder DI diesel engine. The detailed combustion and injection analyses were performed to investigate the performance and emission parameters. According to the best knowledge of the author, there is no any study on combustion analysis of a diesel engine fuelled with diesel fuel/canola oil–hazelnut soapstock biodiesel fuels in the literature.

2. Material and methods

2.1. Fuels

In this study, biodiesel fuels produced from refined canola oil and hazelnut soapstock were used. The canola oil and hazelnut soapstock were obtained from the oil factories in Turkey. As can be seen in Table 1, canola oil and hazelnut soapstock were mainly composed of oleic (C18:1) in 58.9% and 40.26% ratios and linoleic (C18:2) fatty acids in 20.57% and 42.34% ratios, respectively. Also, the canola oil contained unsaturated fatty acid composition (C18:3 in 9.34%) while the hazelnut soapstock contained saturated fatty acid composition (C16:0 in 7.8%) [28].

Table 1
Fatty acid compositions of canola and soapstock oils.

Fatty acid	Canola (wt.%)	Soapstock (wt.%)
Caprylic (C8:0)	–	0.06
Capric (C10:0)	–	–
Lauric (C12:0)	–	–
Myrictic (C14:0)	0.05	0.09
Palmitic (C16:0)	4.14	7.80
Palmitoleic (C16:1)	0.20	0.13
Stearic (C18:0)	1.91	3.90
Oleic (C18:1)	58.90	40.26
Linoleic (C18:2)	20.57	42.34
Linolenic (C18:3)	9.34	0.26
Arachidic (C20:0)	0.63	0.38
Gadoleic (C20:1)	1.35	0.03
Behenic (C22:0)	0.37	0.70
Erucic (C22:1)	0.06	0.05
Others	2.48	4.00

In order to remove the water in the feedstock, the canola oil and soapstock were heated up to 100 °C. Since the FFA value of refined canola oil (0.1%) was lower than 0.5%, the conversion to biodiesel from the canola oil was provided with 97% ratio by using only alkaline catalysis. However, the soapstock had the FFA value of 61.05% and contained impurities; it could not be converted to biodiesel using only alkaline catalysis. Therefore it was required to use acid catalysis and then alkaline catalysis. FFA value was decreased by using acid catalysis and biodiesel production was performed by using alkaline catalysis. In addition, it was required to use acid catalysis application in two steps to decrease FFA in an acceptable value. In the first step, 20:1 methanol/FFA ratio and 10% sulfuric acid were used in 60 min and the FFA value was decreased up to 2.55%. In the second step, 40:1 methanol/FFA ratio and 10% sulfuric acid were used in 90 min and the FFA value was decreased up to 2.17%. For both steps, the reaction temperature was kept at 60 °C. The glycerine and ester were separated by allowing to form two layers overnight. The esters were washed three times with distilled water. Finally, the esters were heated up to 100 °C to remove any residual.

The properties of the biodiesel fuels were determined in TUBITAK-MAM (the Scientific and Technological Research Council of Turkey-Marmara Research Center) and were shown in Table 2. It can be seen that the oxidation stability and iodine value of canola oil biodiesel were not within the limits of the standards. Also, CFPP value of the soapstock biodiesel did not satisfy the limits of the standards. The other properties of the biodiesels were within the limits of EN 14214 standards.

Since the iodine value of the canola biodiesel used in this study was higher than the maximum limit (120 g iodine/100 g) of EN 14214, the canola oil biodiesel (80% in vol) was mixed with the soapstock biodiesel (20% in vol) to produce the biodiesel mixture having iodine number as 119.4 g iodine/100 g which is lower than maximum limit of the standard. Meanwhile the CFPP of the mixture was an acceptable value (−5 °C). However, the oxidation stability of the mixture did not meet the minimum value of EN 14214 standard. Oxidation stability can be improved by adding antioxidants and Usta et al. [16] reported that pyrogallol is an efficient antioxidant for biodiesel fuels. In this study, 500 ppm pyrogallol was found sufficient for the mixture.

The biodiesel fuel used in the engine tests was prepared by mixing of canola oil and the soapstock biodiesels at 80/20 v/v ratio. Then, this mixture of biodiesel fuel was blended with No. 2 diesel fuel at volumetric ratios of 5% (B5) and 10% (B10) which are suitable ratios for the real life applications. Some properties of No. 2 diesel and biodiesel fuels are shown in Table 3.

2.2. Test engine and instruments

The engine tests were performed in Engine Test Laboratory equipped with the support of TUBITAK (the Scientific and Technological Research Council of Turkey) under the grant number 108M228 at Gazi University. A schematic of the test apparatus used in this study is shown in Fig. 1 and the specifications of the diesel engine are given in Table 4. The engine was loaded with Cussons brand P8160 model DC type dynamometer measuring up to 10 kW at 4000 rpm. The engine torque was calculated from the force values acquired with a strain-gauge type load cell and the engine speeds were obtained with a magnetic collector type sensor. The inlet air flow rates were measured with Merriam brand Z50MC2-4F model laminar flow meter. The inlet air, the lubrication oil and the exhaust gas temperatures were measured using NiCr–Ni type thermocouples. In order to minimize the variations of the inlet air temperature, PID (ENDA ETC. 9420) controlled air heater (Farnam Flow Torch 400) was used. The fuel consumption values were measured using an electronic balance with high precision.

The in-cylinder gas pressures were acquired with AVL-8QP500c water cooled pressure transducer and Cussons P4110 combustion