

Performance and exhaust emissions of a DI diesel engine fueled with waste cooking oil and inedible animal tallow methyl esters

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Abstract

The performance and exhaust emissions of a direct injection diesel engine were experimentally investigated using 2 biodiesel fuels with promising economic perspective, one obtained from inedible animal tallow and the other from waste cooking oils. Inedible animal tallow, which is obtained from a mixture of slaughtered cattle and sheep fats collected from a local slaughterhouse during meat preparation process, was transesterified using methyl alcohol and an alkaline catalyst to produce the inedible animal tallow methyl ester. Biodiesel from waste cooking oil was produced from waste cooking oils and methyl alcohol via a transesterification reaction, and provided by a commercial biodiesel producer. In order to investigate the performance and exhaust emissions, the experiments were conducted at different engine speeds under the full load condition of the engine. The experimental results showed, compared with diesel fuel, that the biodiesel fuels resulted in a reduction in brake torque and in an increase in brake specific fuel consumption. Although both biodiesels caused reductions in carbon monoxide (CO), the NO_x emissions were higher for waste cooking oil biodiesel and lower for inedible animal tallow biodiesel as compared to diesel fuel.

Key Words: Inedible animal tallow, waste cooking oils, performance, emission

1. Introduction

Biodiesel is a renewable diesel fuel that is obtained from vegetable oils such as canola oil, cotton seed oil, soybean oil, waste cooking oils, or animal fats. To produce biodiesel, these fats and oils are chemically converted by an alcohol such as methanol in the presence of a catalyst to fatty acid methyl ester known as biodiesel. Biodiesel has higher cetane number than diesel fuel, and contains no aromatics, and almost no sulfur and oxygen content (Alptekin and Çanakçı, 2008). Using biodiesel in diesel engines reduces emissions of unburned hydrocarbons (HCs), carbon monoxide (CO), sulfur dioxide (SO_2), and particulate matter (PM). In contrast to these decreases, generally, biodiesel increases NO_x emissions when used as fuel in diesel engines (Tat et al., 2007; Özsezen et al., 2009; Keskin et al., 2010). In addition, biodiesel is over double the price of petroleum diesel. The high price of biodiesel is mainly due to the high price of the feedstock (Demirbaş, 2007). One of the ways to reduce the price of biodiesel fuel is to use waste fats of animal and vegetable origin (Lebedevas et al., 2009). It has also been reported by Supple et al. (1999) and Zhang et al. (2003) that the use of waste

cooking oil instead of food-grade oil to produce biodiesel is an effective way to reduce the raw material cost because it is estimated to be about half the price of food-grade oil. Therefore, researchers are searching for low-cost feedstocks such as inedible or waste feedstocks for biodiesel production to reduce the production costs. Low-cost feedstocks as biodiesel source have been investigated, and some of them are described below.

Lapuerta et al. (2008), for instance, evaluated the performance and emissions of biodiesel obtained from waste animal fat (one obtained from 100% animal fat and the other from 50% soybean oil/50% animal fat) in a DI common-rail diesel engine. In that study, it was reported that biodiesel fuels reduced hydrocarbon emissions, smoke opacity, and particulate matter. NO_x emissions were also increased with the 50:50 animal fat and soybean oil compared to the reference diesel fuel but decreased with the pure animal fats. Inedible animal tallow, which is produced as a co-product during the meat production process in slaughterhouses, was evaluated as a biodiesel feedstock by Öner and Altun (2009). In that study, it was reported that, when inedible animal tallow methyl ester was used as fuel in a diesel engine, emissions of carbon monoxide (CO), oxides of nitrogen (NO_x), sulfur dioxide (SO_2), and smoke opacity reduced. Lin and Li (2009) compared the performance and emissions of a diesel engine fueled with marine fish-oil and waste cooking oil biodiesel. They reported that, compared with commercial biodiesel from waste cooking oil, marine fish-oil biodiesel has greater NO_x emissions and black smoke opacity and a lower brake-specific fuel consumption rate and CO emission. In another study, the use of methyl ester obtained from waste frying oil (WFO) in a direct injection diesel engine was evaluated. Results showed that amounts of emissions such as CO, CO_2 , NO_x , and smoke darkness of waste frying oils are less than those of No. 2 diesel fuel (Utlü and Koçak, 2008).

As summarized above, different studies show that biodiesel fuels obtained from low-cost feedstocks such as waste cooking oils or animal fats can be used in diesel engines without modification. However, the experimental results especially on NO_x emissions show different results. Some researchers have reported higher NO_x emissions while others have shown lower NO_x emissions. In this context, a comparison among the biodiesels with different feedstocks as fuel in diesel engines is important to understand which kind of biodiesel is more useful in reducing exhaust emissions of a diesel engine. The objective of this work was also to compare the effect of different biodiesels as fuel on performance and exhaust emissions of a direct injection diesel engine without modification. Therefore, in this study, the performance and exhaust emissions of a direct injection diesel engine were experimentally investigated using 2 biodiesel fuels with promising economic perspective, one obtained from inedible animal tallow and the other from waste cooking oils. The experimental results were compared with those of diesel fuel and with each other.

2. Materials and methods

Inedible animal tallow methyl ester (biodiesel) was produced in a small-scale set up consisting of a heater with thermostat, reactor tank, and mechanical stirrer, constructed and installed in the Automotive Laboratory of Machine Education in Batman University, Batman, Turkey. Inedible animal tallow was provided by a local slaughterhouse (Katiboğlu meat production corp., located in Elazığ, Turkey). These inedible fats can be obtained from abdominal parts of slaughtered cattle and sheep during the meat preparation process, and they are collected in a caldron and then melted. Afterwards, they are filtered and marketed for soap production. Methanol (purity 99.7%) for transesterification was used and purchased from a commercial supplier. Sodium hydroxide with purity of 98% was used as the alkali catalyst in the reaction. Inedible animal tallow methyl ester (ATME) was prepared by base-catalyzed transesterification of inedible animal tallow with methyl alcohol

in the presence of NaOH as catalyst. The reaction conditions had been determined in a previous study (Öner and Altun, 2009). Biodiesel was produced using a methyl alcohol to tallow ratio of 6:1 with sodium hydroxide (NaOH) as catalyst (0.5% of tallow by weight). The mixture of alcohol and catalyst was added to the melted tallow. Then the mixture of oil-alcohol-catalyst was stirred rigorously for 3 h at 60 °C. The mixture was then allowed to cool at room temperature. After the methyl ester and glycerol layers separated, the ester was purified by washing with distilled water and drying at room temperature.

The waste cooking oil biodiesel (WCOME) used in this study was produced from waste cooking oils and methyl alcohol via a transesterification reaction, and provided by a commercial biodiesel producer (Kolza biodiesel and petroleum products corp., an authorized waste oil collector), located in İstanbul, Turkey. The waste oil collector obtained these oils from restaurants, hospitals, and the food industry. Petroleum based diesel fuel (DF), as reference fuel, was obtained from a commercial supplier (Petrol Office Firm, located in Adana, Turkey), and it was used to obtain the baseline data of the engine.

Some fuel properties of biodiesels and diesel fuel were determined at the Fuel Analysis Laboratory of Department of Automotive Engineering in Çukurova University, Adana, Turkey, and are presented in Table 1. The density and viscosity of biodiesels are higher than those of diesel fuel while the heating value is lower. The kinematics viscosity in biodiesel standard has been determined as 1.9-6.0 mm²/s in ASTM D 6751 and 3.5-5.0 mm²/s in EN 14214, and the viscosity of the biodiesels used in this study was within the given standard, but the inedible animal tallow methyl ester’s viscosity was slightly outside of the specification EN 14214, as seen in Table 1. The density in EN 14214 biodiesel standard has been determined as 860-890 kg/m³. In this study, the density of biodiesel fuels was between these values. The heating value is also not specified in the biodiesel standards. Cetane number of inedible animal tallow methyl ester is higher than those of waste cooking oil biodiesel and diesel fuel. The cetane number in ASTM D 6751 and EN 14214 biodiesel standards has been determined as 47 min and 51 min, respectively. In this study, the cetane numbers were in agreement with ASTM D 6751 and EN 14214. It can be said that fuel properties of biodiesels are suitable for diesel engines as fuel, besides the higher viscosity of inedible animal tallow methyl ester, which may cause poor injection and atomization characteristics.

Table 1. The fuel properties of diesel fuel and biodiesels.

Properties	Unit	Procedure	Equipment	DF	WCOME	ATME
Density	kg/m ³	ASTMD4052	KEM DA-130 Density Meter	833	878	865
Viscosity	mm ² /s	ASTM D445	KIC Kinematic Viscometer	2.95	4.43	5.628
Heating value	MJ/kg	ASTM D 240	IKA C2000 basic calorimeter	45.65	36.6	39.8
Cetane number	CN	ASTM D613	ZX-440 CN Analyzer	54.63	53.57	59.27

The inedible animal tallow and waste cooking oil biodiesels were used as fuel to investigate the performance and exhaust emissions, and the results were compared with those of petroleum diesel fuel and with each other. All experimental studies were performed at the Automotive Engineering Laboratory of the Faculty of Engineering at Çukurova University, Adana, Turkey. Engine performance and exhaust emission tests were conducted on a commercial 4-cylinder, 4-stroke, and naturally aspirated, water-cooled direct injection diesel engine. The basic specifications of the test engine are presented in Table 2. The engine was started with petroleum diesel fuel and warmed up for a sufficient time in order to reach steady state operational conditions for each fuel. The fuels were tested from 1000 to 2250 rpm with an interval of 250 rpm at full load conditions.

Table 2. The basic specifications of the test engine.

Engine Brand	Mitsubishi Canter Diesel
Engine type	Naturally aspired, water-cooled
Operating principle	Four stroke, direct injection
Number of cylinders	Inline 4 cylinders
Bore × stroke	104 mm × 115 mm
Fuel injection pump	Mechanically controlled in-line type
Maximum torque	243 Nm at 1600 rpm

A hydraulic dynamometer (Netfren brand) was connected to the test engine to provide brake load. A magnetic pick-up sensor was used to measure the speed of the engine. The load on the dynamometer was measured using an S-type load cell (strain gauge load sensor). Fuel consumption was measured with a gravimetric fuel consumption meter. The exhaust emissions were measured by an exhaust analyzer (Testo 350-XL), which was calibrated before each test. A schematic diagram of the experimental setup is shown in Figure 1. Before running the engine with a new fuel, it was allowed to run for some time to consume the remaining fuel from the previous experiment.

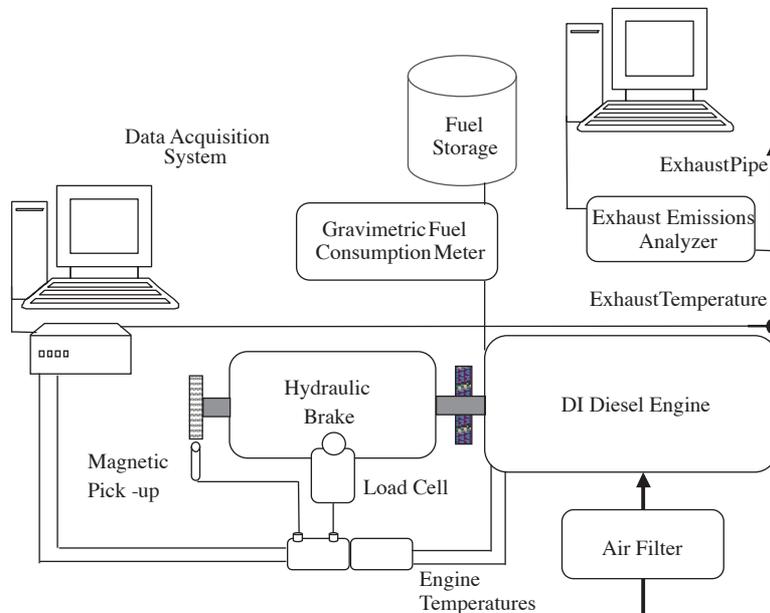


Figure 1. Schematic diagram of the experimental setup.

3. Results and discussion

3.1. Engine performance

Variation in the brake torque values of the fuels tested is shown in Figure 2. The brake torque with all fuels tested is reduced at higher engine speeds, and the tendency does not change in relation to the type of used fuels. However, when the engine was operated on different biodiesels, the brake torque was reduced with respect to diesel fuel.

The maximum brake torque (236.5 Nm) at 1500 rpm was obtained with diesel fuel, followed by waste cooking oil and inedible animal tallow methyl ester. On average over the speed range at full load condition, the brake torque of waste cooking oil and inedible animal tallow biodiesels decreased by 7.5 and 12%, respectively, compared with those of diesel fuel. Moreover, compared with inedible animal tallow biodiesel, waste cooking oil biodiesel showed slightly higher brake torque, although its heating value was lower than that of inedible animal tallow biodiesel. The higher viscosity of inedible animal tallow methyl ester, which may cause poor injection and atomization characteristics, may be given as a possible reason for the brake torque decrease.

Figure 3 shows that BSFC decreases with the increase in engine speed and reaches a minimum (in the maximum torque region) and then increases again. The BSFCs for both of the biodiesels were higher than that of diesel fuel, as shown in Figure 3.

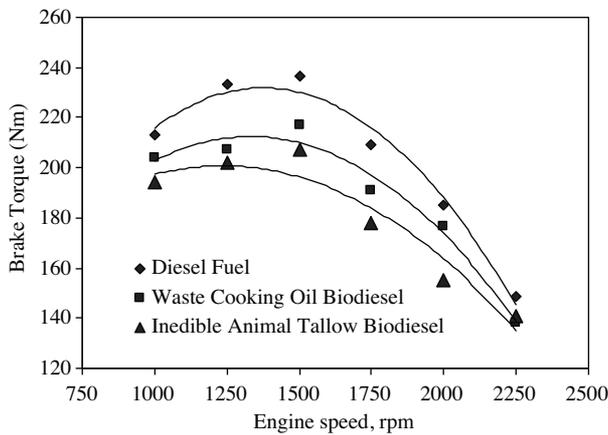


Figure 2. The variation in brake torque using biodiesels and diesel.

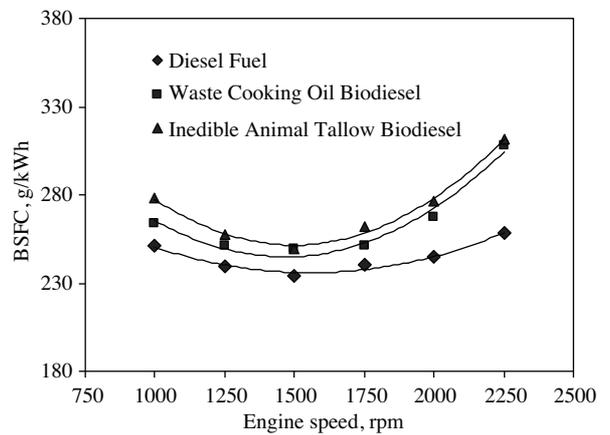


Figure 3. The variation in BSFC using biodiesels and diesel.

At the engine speed of 1500 rpm, the BSFCs run with waste cooking oil biodiesel increased by 6.1%. For inedible animal tallow biodiesel, the same trend can be seen from the figure; the increase in BSFC was 6%. On average, BSFCs for waste cooking oil and inedible animal tallow biodiesels were higher by 7.7% and 10.2% than that of diesel fuel, respectively. Biodiesel fuels have lower heating values than petroleum diesel fuel, and this results in higher BSFC, as affirmed by most studies (Özkan et al., 2005; Gümüş and Atmaca, 2008). Although inedible animal tallow biodiesel showed slightly higher BSFC with respect to waste cooking oil biodiesel, in general there was no significant difference between the BSFCs of these fuels.

3.2. Exhaust emissions

Figure 4 shows the carbon monoxide (CO) emissions versus engine speed with the use of diesel and biodiesel fuels. In comparison with diesel fuel, CO emissions for biodiesel fuels are lower. On average, CO emissions of all engine speeds for waste cooking oil and inedible animal tallow biodiesel compared to those of diesel fuel decreased by 7% and 11.8%, respectively. This can be attributed to molecular oxygen content in biodiesels, which leads to lower CO emissions. It was reported by Özsezen et al. (2009) that the oxygen content of biodiesel improved the hydrocarbon oxidation since the measured CO, unburned HC emissions, and smoke opacity with the use of the biodiesel significantly decreased. Reduced CO emissions are also reported by other researchers (Ergeneman et al., 1997; Çelikten and Arslan, 2008; Di et al., 2009) when using different biodiesel fuels. Although waste

cooking oil and inedible animal tallow biodiesel have oxygen content, inedible animal tallow biodiesel shows a greater reduction in CO emissions, as seen in Figure 4. Besides the oxygen content, other fuel properties, such as cetane number, may also influence CO emission, because inedible animal tallow biodiesel had the highest cetane number and it showed the lowest CO emission. These results are similar to those reported by Wu et al. (2009). In that study, they concluded that oxygen content and cetane number have combining effects on HC and CO emissions.

Figure 5 shows the variations in nitrogen oxides (NO_x) emissions values of test fuels with engine speed. The burning of the inedible animal tallow biodiesel produced lower NO_x emissions than did the waste cooking oil biodiesel and diesel fuel. In the case of waste cooking oil biodiesel, higher NO_x emissions were obtained with respect to diesel fuel. At the engine speed of 1500 rpm, the NO_x emissions were higher for waste cooking oil biodiesel by 3% and lower for inedible animal tallow biodiesel by 18.6% as compared to diesel fuel, on average. Compared to waste cooking oil biodiesel, the average NO_x emissions of biodiesel from inedible animal tallow were reduced by 20.8%. Experimental studies have shown that biodiesel can result in higher NO_x , and the oxygen content in biodiesel can lead to higher NO_x formation as the higher oxygen content of biodiesel provides better combustion, and hence the combustion temperature increases. As a matter of fact, the study by Labeckas and Slavinskas (2006) shows that the maximum NO_x emissions increase proportionally with the mass percent of oxygen in the RME–Diesel blends. On the other hand, advanced injection timing, which can lead to higher in-cylinder temperature, can be given as a reason as the higher bulk modulus, viscosity, and sound velocity of biodiesel lead to an advanced start of injection, as stated by Kegl (2009). Reducing NO_x emissions when using biodiesel fuels obtained from more saturated fatty acids such as animal fats has been reported in some studies (Kerihuel et al., 2006; Lapuerta et al., 2008; Öner and Altun, 2009). Reduced NO_x emissions with these fuels can be attributed to the higher cetane number, which causes shorter ignition delay. As a matter of fact, İçingür and Altıparmak (2003) reported that NO_x emissions decrease about 10% when the fuel cetane number is increased from 46 to 61.

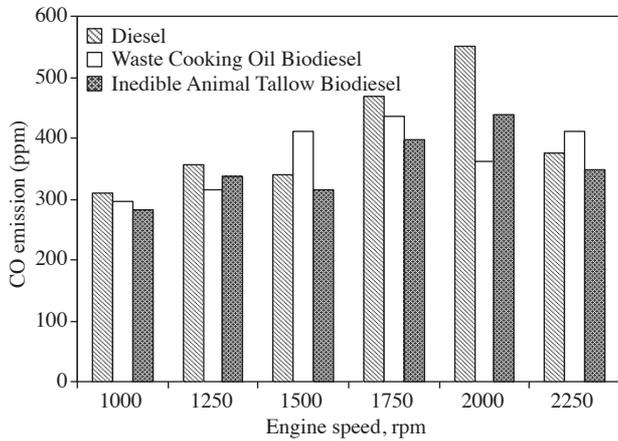


Figure 4. CO emissions versus engine speeds.

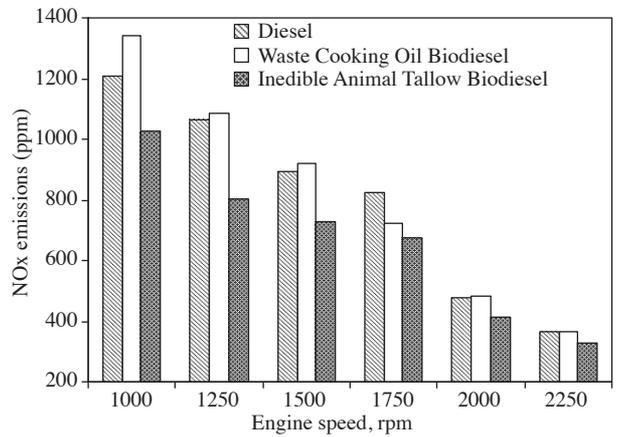


Figure 5. NO_x emissions versus engine speeds.

4. Conclusions

In this study, the effects of 2 biodiesel fuels with different feedstocks on performance and exhaust emissions of a direct injection diesel engine were experimentally investigated. The brake torque with diesel fuel was higher

than those with both of the biodiesels, and also the biodiesel from inedible animal tallow showed slightly lower brake torque than waste cooking oil biodiesel. The BSFCs for both of the biodiesels were higher than that of diesel fuel, and also the BSFCs for both of the biodiesels were comparable to each other. Both inedible animal tallow and waste cooking oil biodiesels produced less CO emissions than diesel fuel. The comparison of decreases in CO emissions between inedible animal tallow and waste cooking oil biodiesels indicates that inedible animal tallow is more effective than waste cooking oil. NO_x emissions were higher with waste cooking oil and lower with inedible animal tallow when compared with those of diesel fuel. NO_x emissions were highest with waste cooking oil biodiesel.

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