AN INVESTIGATION OF EFFECT OF BIODIESEL AND AVIATION FUEL JetA-1 MIXTURES PERFORMANCE AND EMISSIONS ON DIESEL ENGINE

by

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Original scientific paper
DOI: 10.2298/TSCI130410007Y

Biodiesel is an alternative fuel for diesel engines which does not contain pollutants and sulfur; on the contrary it contains oxygen. In addition, both physical and chemical properties of sunflower oil methyl ester are identical to diesel fuel. Conversely, diesel and biodiesel fuels are widely used with some additives to reduce viscosity, increase the amount of cetane, and improve combustion efficiency. This study uses diesel fuel, sunflower oil methyl ester and its mixture with aviation fuel JetA-1 which are widely used in the aviation industry. Fuel mixtures were used in 1-cylinder, 4-stroke diesel engine under full load and variable engine speeds. In this experiment, engine performance and emission level are investigated. As a conclusion, as the JetA-1 ratio increases in the mixture, lower nitrogen oxide emission is measured. Also, specific fuel consumption is lowered.

Key words: *methyl ester, diesel engine, performance, emission*

Introduction

Economical development, an increasing population, and technological improvements have increased countries' energy needs. Today, the majority of waste that energy produces is from fossil fuels, which have limited reserves. In order to meet these energy consumption levels, new energy sources need to be developed as fossil fuels are insufficient in terms of meeting the increased energy need. Also, the combustion of fossil fuels produce CO_2 ,which is one of the greenhouse gases that enhances radioactive forces that contributes to global warming, causing the average surface temperature of the Earth to rise in response.

One of the solutions to reduce the emissions of diesel engines is the usage of oxygen based fuels which are not produced from fossil fuels. Alternative diesel fuel, known as biodiesel, can be produced from animal fat and vegetable oil. Biodiesel fuel can effectively reduce engine-out emissions of unburned hydrocarbons, particulate matter, and carbon monoxide in compression ignition (CI) engines. However, a slight increase in emissions of nitrogen oxides has been observed in the use of oxygenated fuels in general [1-3]. High viscosity, a low ignition point, and unsaturated hydrocarbons molecules are the disadvantages of biodiesel fuels. High viscosity affects the fuel flow in an engine, whereas a low ignition point and unsaturated hydrocarbons reduce the reaction capability. Also, the heating value, low output, and high nitrogen levels are the other properties that need to be improved [4-6]. The high freezing point of the biodiesel fuels in particular creates a sucking problem in filters [7]. In order to solve this prob-

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lem, biodiesel fuels can be mixed with low freezing point fuels such as those used in aviation industry. Biodiesel fuels are non-toxic and do not contain aromatic and can be resolved in nature better than fuels used in the aviation industry. The most important point is that biodiesel fuel does not contain sulphur [8, 9]. Two different biodiesel fuels are mixed with JP-8 at different ratios. Emission and fuel consumption values are measured in a 1 cylindered engine. The fuel performance of the mixtures and the JP-8 were compared, and similar performance levels were observed in these fuels. In addition to this, a steep drop was observed in particle matter (PM) emissions [10].

JetA-1 fuel contains a fuel system icing inhibitor, which results in high enthalpy and an enhanced adaptation to cold weather conditions [11]. On the contrary, the most important disadvantage of fuels used in the aviation industry is their poor lubrication characteristics. Because of these poor characteristics, in high speed engines, a wear problem is observed [12]. Poor lubrication characteristics of fuels used in the aviation industry can be improved with biodiesel fuels, and on the contrary low heating value of the biodiesel fuel can be improved with fuels used in the aviation industry.

The JP-8 and diesel fuel were tested in various injection pressures. JP-8 has a longer delay ignition than the diesel fuels. This is due to the higher cetane number of in diesel fuels than in the JP-8 fuel. Smoke emission of aviation fuels is better than the emission level of diesel fuel as JP-8 has a better mixture characteristic in the air. However, HC and NO_x emissions are higher than diesel fuel [13]. The tribological effect of the fuel used in the aviation industry is observed by 10 different acid esters. It can be observed that the lubrication characteristics of the aviation fuel do not change. However, it was determined that the addition of acid esters can cause damage to the fuel pump [14].

The JP-5 aviation fuel was mixed with various percentages of biodiesel fuel. These mixtures were experimented on in a one cylindered engine. Measurements determined that biodiesel has significantly lower PM emission; however, it has a higher NO_x emission and specific fuel consumption than diesel fuel. It can be seen that under a high engine load, the fuel consumption of diesel fuel increased [15].

The aim of this study is to carry out performance and emission testing on a four d-stroke, a single-cylinder direct injection engine fuelled with biodiesel, petroleum-based diesel, and a mixture with aviation fuel JetA-1. The emissions data includes rates of smoke, CO, and NO_x. This experimental study gives us the opportunity to compare methyl ester and diesel fuel mixtures with aviation fuel JetA-1.

Material and method fuels

Biodiesel blending was carried out in the following ratios during the experiments: 95:5%v/v methyl ester-JetA-1 (BJA1-5), 90:10%v/v (BJA1-10), 75:25%v/v (BJA1-25) 100:0%v/v (B0). The experimental results were compared with the commercial fossil diesel (D0). The process of transesterification was assessed with sunflower oil (1000 ml), methyl alcohol (200 ml), and in the presence of a catalyst (4.9 g KOH). Some properties of the fuels are shown in tab. 1.

Experimental equipment and test procedure

Experiments were conducted in a one cylindered direct injection diesel engine. Table 2 shows the technical specification of the test engine.

Table 1. The properties of fuels used in the experiment

	Diesel	JetA-1	SME	Method
Density, [gcm^{-3}] at 15 °C	0.8372	0.775	0.8893	ISO 3675
Viscosity, [cSt]	2.8 (40 °C)	3.87 (–20 °C)	4.391 (40 °C)	ISO 3104
Cold filter plugging point, [(°C]	–5	–47	–2	ASTM D 2386
Flash point, [°C]	73	38	110	ISO 2719
Lower heating value, [kJkg^{-1}]	43750	42700	38470	ASTM D 4809
Cetane index	54	–	58	ISO 5165

Table 2. Technical specifications of the test engine

Engine type	4-stroke DI
Number of cylinder	1
Bore × stroke, [mm]	86 × 68
Volume, [cm^3]	395
Compression ratio	18/1
Maximum torque	22 Nm/2200 1/min
Injection pressure [bar]	180
Injection advance	24° bTDC

Table 3. Technical features of the VLT 2600 S smoke density measuring device

	Measurement range	Accuracy
Smoke density	0-99%	0.01
k smoke factor [m^{-1}]	0-10	0.01
Speed	0-9999 min^{-1}	1 min^{-1}

The test engine was coupled to a dynamometer (DC Cussons P8160) providing a maximum engine power of 10 kW with ±0.1 kW of uncertainty to control engine speed and load. The full-load characteristic of the engine fuelled with sunflower oil methyl ester (SME), its blends and aviation fuel were at the constant engine speeds, ranging from 1750 to 3000 rpm with an interval of 250 rpm. At each speed, the maximum engine torque was reached for each fuel. That is to say, the test engine was operated at different torques when different fuels were tested. Engine load was measured by strain gauge load cell. Engine speed was measured by magnetic sensor positioned on the gear of the dynamometer shaft. A weighing scale and chronometer were used to measure fuel consumption. VLT 2600 S opacimetry was used for smoke measurement. Technical features of the VLT 2600 S opacimetry are shown in tab. 3.

Emission was measured by a Testo 350 XL gas analyzer. The technical features of the Testo 350 XL emission measuring device are shown in tab. 4.

Experiments were conducted under full load conditions. The test set-up is shown in fig. 1.

Concerning engine performance, a measurement methodology was employed so that for each type of fuel utilized, the engine speed was initially set at 1750 rpm. At the full-load, the power output and torque were measured on the monitoring equipment available at the test bench. The engine speed was

Table 4. Technical features of the Testo 350 XL emission measuring device

	Measurement range	Accuracy
Oxygen	0-25% vol.	±0.2 m. v.
Carbon monoxide	0-10000 ppm	5 ppm (0-99 ppm)
Carbon dioxide	0-50% vol.	± 0.3%vol. +1% m. v. (0-25%vol.)
Hydrocarbon	0.01-4%	< 400 ppm (100-4000 ppm)

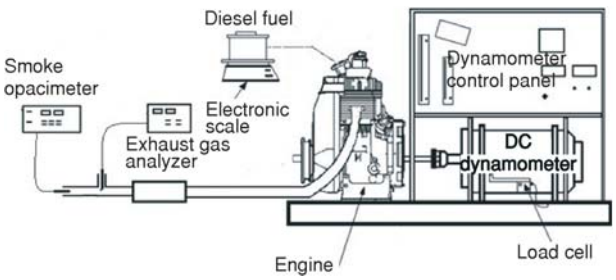

Figure 1. Schematic representation of the experimental apparatus

then increased to 2000 rpm and this procedure was repeated for other engine speeds. The determination of the power and torque curves was conducted following this technique by varying the speed from 250 to 3000 rpm. Firstly, diesel fuel (D0) was used in the engine. Then a mixture of SME and JetA-1 were named BJA1-5, BJA1-10, and BJA1-25. Finally, pure biodiesel fuel (B0) was used in the engine. At each speed, the engine was stabilized and then the measurement parameters were recorded.

Accuracy of the torque, power, specific fuel, and specific energy values (measured data) according to fuel types were tested by using one way ANOVA analysis. Obtained results show that the accuracy levels are smaller than 0.05 for all values. This means that all the variables reliability are greater than 0.95.

Engine characteristics were calculated from simplified approach shown in eq. (1-4):

– specific energy consumption
$$SEC = \frac{b_e H_u}{1000} \tag{1}$$

– efficiency
$$\eta = \frac{3600}{b_e H_u} \tag{2}$$

– specific fuel consumption
$$b_e = \frac{B}{P_e} \tag{3}$$

– effective power
$$P_e = \frac{M_e n}{9549} \tag{4}$$

Discussion of the experimental results

Full load engine tests were conducted in the range of 1750-3000 1/min and increased by 250 1/min. The engine performance and emissions of the diesel fuel, and the SME and SME-JetA-1 blend were investigated.

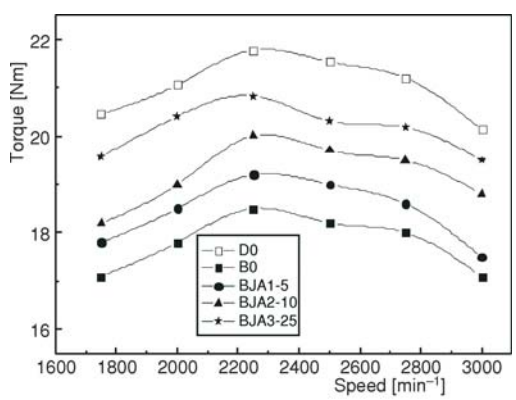

Figure 2. The brake torque *vs.* engine speed

Figure 2 shows the torque *vs*. the engine speed for the test fuel. The peak torque value measured at 2250 1/min for all fuels. The maximum engine torque was 21.77 Nm for D0 and 18.5 Nm for B0. The torque values for the mixtures were measured between D0 and B0. The measurements of the engine torque value for the BJA1-5, BJA1-10, and BJA1-25 fuels increased by 12.56%, 13.78%, and 15.27%, respectively. As biodiesel fuel has low heating value, high viscosity and surface tension, the injection of the biodiesel fuel in the cylinder were affected [16].

The engine power depending on engine speeds with differing fuels, are shown in fig. 3. Maximum engine power was obtained in the D0 fuel at 3000 rpm as 6.25 kW. B0 and the mixture of fuel power values were less than D0. It was 5.2 kW for B0. For the JetA-1 fuel mixtures, as they have a high viscosity and low heating value, the engine torque was measured closer to the engine torque in the diesel fuel. This is also as a result of the ease of the injection and evaporation characteristics of the JetA-1 fuel. In addition to this, as JetA-1 fuel contains cetane, the combustion efficiency and engine torque can be improved [17]. The higher viscosity of biodiesel, which may affect the engine torque and engine brake's effective power, especially in full-load conditions, increases the mixture momentum, and consequently, penetration depth in the cylinder.

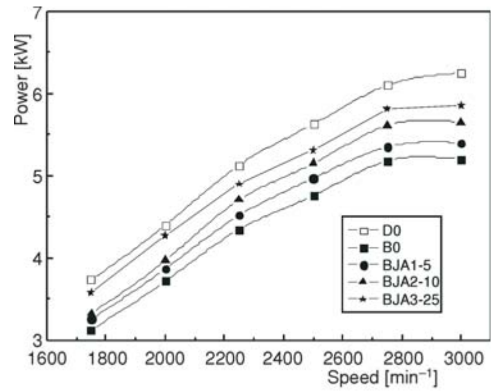

Figure 3. The power *vs.* engine speed

Figure 4 shows the brake specific fuel consumption (BSFC) and fig. 5 shows the specific energy consumption (SEC) under full load conditions for all fuels used in the experiment. For all fuels, the lowest value for BSFC measured 2250 1/min. The BSFC values for D0 and B0 fuels are measured as 354.9 g/kWh and 415.23 g/kWh, respectively. As the JetA-1 ratio increased in the mixture, the BSFC became closer to the D0. The BSFC values of the BJA1-5,

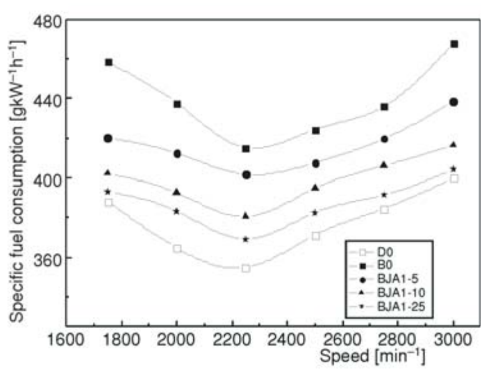

Figure 4. The specific fuel consumption *vs.* engine speed

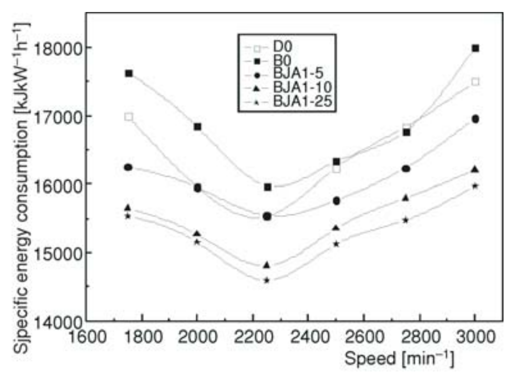

Figure 5. The specific energy consumption *vs.* engine speed

BJA1-10, and BJA1-25 mixtures are measured 13.21%, 7.26%, and 4.04%, higher than the BSFC value of the D0 fuel. Minimum SEC values were 2250 1/min for BJA1-25. The same engine speed max. SEC was B0. These changes in the BSFC and SEC value are a result of high viscosity, insufficient atomization, and a large fuel drop [18]. Thus, these factors extend the time in which fuel burning occurs and the cylinder performance decreases. In addition, the biodiesel may cause a changes in the combustion and injection timing due to the biodiesel's higher cetane number as well as injection timing changes.

The variations in thermal efficiencies values in relation to the engine speeds are displayed in fig. 6. Max. efficiency was calculated for BJA1-25 at 2250 1/min. A possible explanation for this increase was attributed to the atomization of the blends during injection and/or with

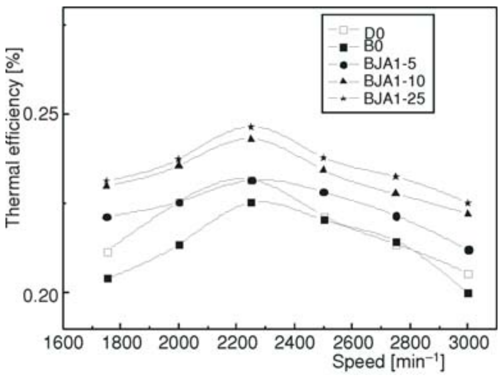

Figure 6. The thermal efficiency versus engine speed

the stability of the mixture of the fuels during storage, pumping and injection. Another possible reason may be the reduction in friction loss associated with higher lubricity [19].

Figure 7 (a) shows the nitrogen oxide (NO_x) variation of B0, D0, and their mixtures under full load conditions. The lowest NO_x was measured in the D0 fuel. The NO_x values of B0, BJA1-5, BJA1-10, and BJA1-25 were measured at 36%, 33%, 23%, and 20% higher than NO_x value of the D0 fuel, respectively. It can be seen in fig. 7(b), that NO_x emissions reduce with the engine speed. In addition, NO_x emissions decrease with the reducing aviation fuel proportion. As a result of combustion, due to high temperatures in the cylinder, nitrogen in air reacts with the oxygen giving NO_x produced. The major factors affecting NO_x production are: the combustion cylinder temperature, air-fuel ratio, and the speed of the chemical reaction. It is also known that humidity has an impact on the NO_x emission [20, 21]. As biodiesel fuels have high oxygen content, the NO_x emission of the biodiesel fuels is higher since oxygen increases the combustion efficiency, while emissions such as PM and CO are reduced.

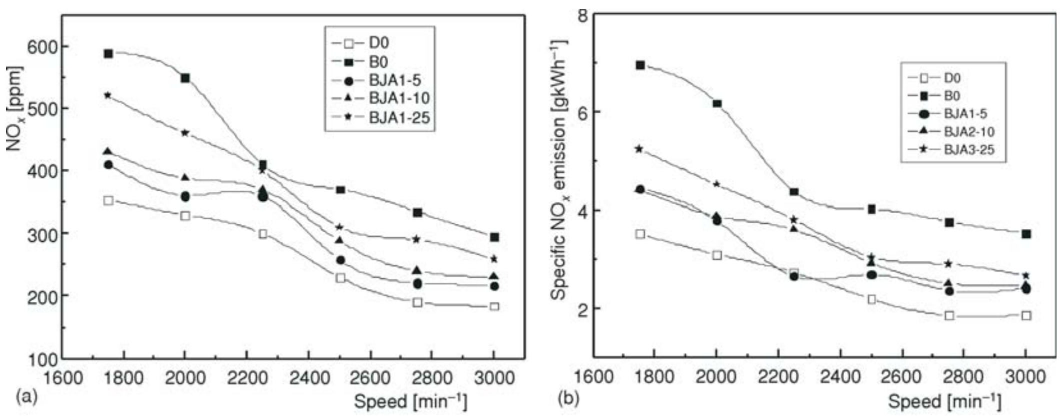

Figure 7. NO_x emission *vs.* engine speed (a) in ppm, (b) in g/kWh

Figure 8 shows the smoke emission of D0, B0 and their mixtures. Smoke is created during the combustion process of diesel fuels. During ignition, as hydrogen atoms are more active than the carbon atoms in oxygen, poor combustion occurs from a lack of oxygen. The smoke emission process is when the thermal braking of

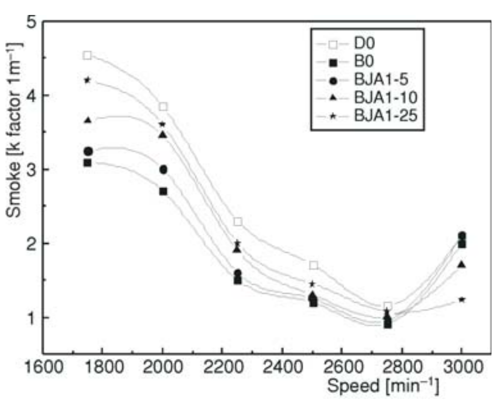

Figure 8. Smoke emission *vs.* engine speed

the HC occurs in the combustion area which has insufficient oxygen. As biodiesel contains oxygen, smoke emissions were lower than that of diesel fuel [22]. In the lower engine speed, smoke emissions were higher due to the fuel viscosity and the slow air flow. As engine speed increased, air flow through the combustion cylinder increases, which results in better combustion and lower smoke emission levels.

The smoke emission of fuels used in the experiments are measured in 2750 1/min. Smoke value of the D0, BJA1-25, BJA1-10, and BJA1-5 measured 27.7%, 18.9%, 11%, and 5.5% higher than that of B0 fuel, respectively. It is known that fuels which contain oxygen reduce the smoke and particle mater emissions. As biodiesel contains aromatics and sulphur, considerable reductions are observed in smoke emissions [23-25]. Smoke opacity is strongly dependent on the amount of air in the cylinder as well as the amount of oxygen in the fuel. It is obvious that fuel composition affects the amount of smoke produced by an engine. The sulphur and oxygen content of the fuel affects the smoke formation and oxidation, respectively [26].

Figure 9(a) shows the CO emission of D0, B0, and their mixtures. CO emission is toxic and an intermediate product in the combustion of a hydro carbon fuel, so it results from incomplete combustion. Emission of CO is, therefore, greatly dependent on the air-fuel ratio relative to the stoichiometric proportions. Observation indicates that diesel fuel and blends have higher CO emissions than biodiesel. CO emission of fuels used in experiments are measured in 2750 1/min. CO value of the D0, BJA1-5, BJA1-10, and BJA1-25 measured 12.5%, 25%, 41.6%, and 50% higher than that of B0 fuel, respectively. It can be seen that CO emissions increase along with increasing the aviation fuel similar to fig. 9(b). The reasons which have been given for the general decrease in CO emissions from biodiesel include the additional oxygen content in the fuel, which improves combustion in the cylinder. Biodiesel also has a higher cetane number, and is less compressible than diesel fuel. The increased cetane number of biodiesel fuel lowers the probability of forming fuel-rich zone. All these bring about longer combustion and an increase in complete combustion reaction regions [19].

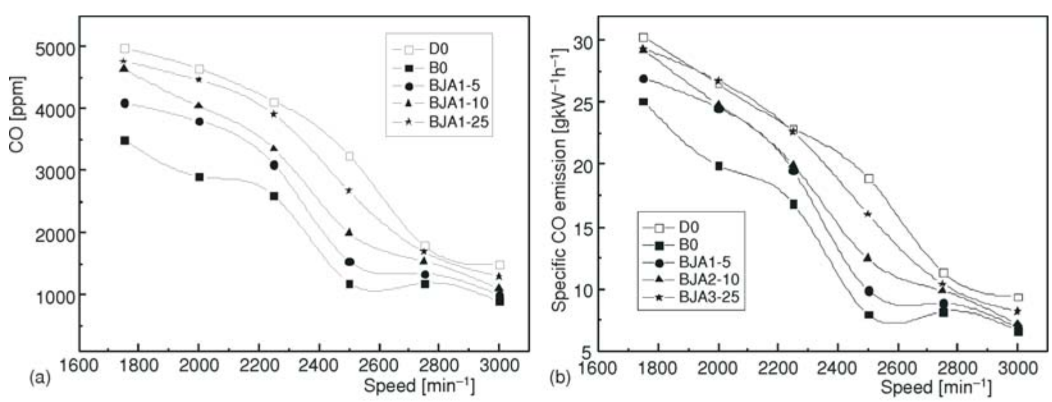

Figure 9. CO emission *vs.* engine speed (a) in ppm, (b) in g/kWh

Summary and conclusion

In this study, B0 and JetA-1 fuel, which is widely used in the aviation industry, is compared with diesel fuel. During the tests conducted, engine torque, brake specific fuel consumption, NO_x and smoke emissions were measured under full load conditions. Usage of B0 and

B0-JetA-1 as an alternative fuel for diesel fuels is crucial to increase fuel diversity and improve emission levels.

Considering the result of the test, the highest torque value was achieved with D0 fuel. Performance of B0 and aviation fuel mixtures were measured 12.56%, and 15.27% less than that of D0 fuel, respectively. As JetA-1 fuel ratio increases, measured torque value became closer to torque value of the diesel fuel. This is a result of low energy content and a high density of biodiesel fuel. BJA1-25 gives the best brake thermal efficiency and SEC of engine. On the other hand, the use of SME and JetA-1 blend has no positive effect on BSFC of the engine.

As the JetA-1 fuel ratio increases in the mixture, the BSFC value decreased and became closer to BSFC value of the diesel fuel. BSFC variation for the test fuels was between 4.04% and 13.21%. This variation is a result of viscosity differences between test fuels.

When NO_x emissions were compared, as JetA-1 fuel ratio increases in the mixture, it was observed that lower NO_x emissions were measured. NO_x emission of D0 fuel was measured lower than NO_x emissions from B0 fuel and its mixtures. Biodiesel CO level has minimal value. Diesel fuel CO level was higher compared to the values measured for blends. In addition to these, when smoke emission was considered, lowest smoke emission was measured in biodiesel fuel. Smoke emission increased as JetA-1 fuel ratio increases in the mixture. Smoke emission variation is mainly related to the oxygen content of the test fuels.

The results of the experiments showed that as JetA-1 fuel ratio increased in B0 fuel, engine torque increased and BSFC reduced. If emission levels are considered, as JetA-1 ratio increased in the mixture, the emission levels measured were reduced. Also, as JetA-1 fuel has low cold filter plugging point value; it had a positive impact on the usage of biodiesel fuel in winter conditions. As a result of this, research has been conducted into the use of biodiesel and JetA-1 fuel mixtures for the tactical vehicles in the army.

Nomenclature

B – fuel consumption
BJA1-5 – 95% SME + 5% JetA-1
BJA1-10 – 90% SME + 10% JetA-1
BJA1-25 – 75% SME + 25% JetA-1
BSFC/b_e – brake specific fuel consumption, [$gkWh^{-1}$]
B0 – 100% SME
CI – compression ignition engine
D0 – 100% diesel
H_u – lower heating value
M_e – torque
n – speed
P_e – effective power
PM – particulate matter
SEC – specific energy consumption
SME – sunflower oil methyl ester
η – efficiency

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Paper submitted: April 10, 2013
Paper revised: November 15, 2013
Paper accepted: December 30, 2013