THE DETERMINATION OF OPTIMUM INJECTION PRESSURE IN AN ENGINE FUELLED WITH SOYBEAN BIODIESEL/DIESEL BLEND

by

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In this study, the optimum blend rate and injection pressure in a four-stroke, single cylinder, direct injection diesel engine using soybean methyl ester were investigated experimentally. The tests were conducted at two stages. Firstly, the engine was tested with diesel fuel, B25 (25% biodiesel + 75% diesel fuel), B50, B75, and B100 fuels at full load and at a constant speed. According to the test results, it was determined that the most suitable fuel was B25 in terms of performance and emission. Secondly, the engine was tested at different loads with diesel fuel at original injection pressure and with B25 at different injection pressures (160, 180, 200, 220, and 240 bar) for comparison. It was determined from tests performed with B25 that the most suitable injection pressure in terms of performance and emissions was 220 bar. The specific fuel consumption and power values of the B25 were found to be nearly the same as those of diesel fuel at 220 bar injection pressure. In addition, HC, CO, and smoke emissions were reduced by about 33%, 9%, and 20%, respectively. On the other hand, NO_x *emission increased by about 12%.*

Key words: *soybean methyl ester, performance, emissions, biodiesel, injection pressure*

Introduction

The studies have been increasingly directed towards renewable fuels due to increased energy needs and limited fossil fuel reserves. Especially the developing countries have aimed to reduce the petroleum dependence by producing the alternative fuels. Besides, the use of the petroleum based fuels increases the air pollution. The motor vehicles have important roles in the smoke, NO_x, CO, and HC emissions.

The alternative fuels such as biodiesel, ethanol, methanol, and hydrogen have been used to reduce fossil fuel consumption and environmental pollution in the diesel engines. One of more promising approaches is biodiesel because it is practical and suitable for agricultural countries [1]. Vegetable oils have attracted attention as a potential renewable source for the production of an alternative fuel for petroleum based diesel fuel. Biodiesel is produced from the transesterification of vegetable oils or animal fats and is defined chemically as simple monoalkyl esters (typically methyl or ethyl) of long chain fatty acids. The advantages of biodiesel over conventional petroleum diesel fuels include superior lubricity, derivation from renewable sources, essentially no sulphur content, superior flash point and biodegradability, as well as a reduction regulated exhaust emissions. Biodiesel can be used directly as fuel for a diesel engine without having to modify the engine system. The cetane number, energy content, vis-

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cosity, and phase changes of the biodiesels are also similar to those of petroleum-based diesel fuel. Moreover, the engines fuelled by biodiesel emit significantly less amount of smoke, HC, and CO than those running on conventional diesel fuel. NO_x emissions, however, are slightly higher for the biodiesel operation [2-6].

Due to the fact that Turkey is an agricultural country, the use of biodiesel as alternative fuel has been becoming widespread in diesel engines. The soybean which is one of the vegetables has high potential of the production in Turkey, and it has been used in the biodiesel production [7].

Several studies have been conducted on the usage of soybean methyl ester (SME) as fuel in the diesel engines. Ali *et al.* [8] investigated the testing of alternative diesel fuel from tallow and soybean oil in Cummins N14-410 diesel engine. Engine performance, exhaust emissions and smoke of the each fuel blend were monitored and compared with those of diesel fuel. Engine performance was found satisfactory without significant drops in power and torque. There was a slight increase in specific fuel consumption (SFC). Most engine exhaust emissions were not affected. Valente *et al*. [9] investigated the effect of soybean biodiesel on fuel consumption and emissions in a diesel power generator. The engine was kept with its original settings for diesel operation. The fuel blends were prepared by adding 5%, 20%, 35%, 50%, and 85% soybean biodiesel to diesel. The results showed increased fuel consumption with higher biodiesel concentration in the fuel. With using fuel blends containing 35% of soybean biodiesel, CO emission was increased by nearly 40% and over 80% at low and moderate loads, respectively. The results obtained suggest that fuel injection system optimization is required in order to improve SFC and exhaust emissions if biodiesel is used as fuel. Celikten *et al*. [10] investigated the comparison of performance and emissions of diesel fuel, rapeseed, and soybean oil methyl esters injected at different pressures. The tests were carried out with a four-cylinder diesel engine for three different injection pressures of 250, 300, and 350 bar with each of these fuels. As a result, the performance and emission values of SME were found to be nearly the same as those of diesel fuels when injection pressure was increased to 300 bar. Soybean biodiesel had the lower engine torque and power for all injection pressures when compared with normal diesel fuel. Among the test fuels, soybean biodiesel has the high SFC. Smoke level and CO emission are less than the other test fuels but NO_x is relatively higher. Qi *et al*. [11] investigated the combustion and performance evaluation of a diesel engine fuelled with biodiesel produced from soybean crude-oil. The results showed that the power output of biodiesel was almost identical with that of diesel. The SFC was higher for biodiesel due to its lower heating value. Biodiesel provided significant reduction in CO, HC, NO_x, and smoke at full engine load. Canakci [12] investigated the combustion characteristics of a turbocharged direct injection (DI) compression ignition engine fuelled with petroleum diesel fuels and biodiesel. The tests were performed at steady-state conditions in a four-cylinder DI diesel engine at full load at 1400 rpm engine speed. The experimental results when compared with No. 2 diesel fuel showed that biodiesel from soybean oil provided significantly reductions in smoke, CO, and unburned HC. However, NO_x increased by 11.2%. Biodiesel had a 13.8% increase in SFC due to its lower heating value. Qi *et al*. [13] investigated the combustion characteristics and performance of a direct injection engine fuelled with biodiesel/diesel blends. From the results, a minor increase in SFC and a decrease in thermal efficiency were observed with biodiesel and its blends when compared with diesel fuel. The significant improvement in reduction of CO and smoke were found for biodiesel and its blends at high engine loads. Hydrocarbon had no evident variation for all the fuels tested. NO_x emissions were slightly higher for biodiesel and its blends. Sayin and Gumus [14] investigated the impact of compression ratio and injection parameters on the performance and emissions of a DI diesel engine fuelled with biodiesel-diesel fuel blends. The results showed that SFC and NO_x emissions increased while brake thermal efficiency, smoke opacity, CO, and HC decreased with the increase in the amount of biodiesel in the fuel blend. For all tested fuels, an increase in injection pressure leaded to decrease in the smoke opacity, CO, and HC emissions while NO_x emissions increase. Gokalp *et al*. [3] investigated the performance and emissions of a diesel tractor engine fuelled with marine diesel, SME, and their blends. The blends were prepared by adding 5%, 20%, and 50% soybean biodiesel to diesel fuel. The results indicated that the use of biodiesel produced lower smoke opacity (up to 74%), but higher SFC (up to 12%) compared to marine fuel. The measured CO emissions of B5 and B100 fuels were found to be 3% and 52% lower than those of the marine fuel, respectively. Pereira *et al.* [15] investigated the exhaust emissions and electric energy generation in a stationary engine using blends of diesel and soybean biodiesel. The results show that for all the mixtures tested, the electric energy generation was assured without problems. It was also observed that the emissions of CO, HC, and SO_2 decreased in the case of diesel-soybean biodiesel blends. Schumacher *et al*. [16] investigated the exhaust emission of the heavy-duty engine using soybean biodiesel/diesel fuel blends. A model 6V92TA Detroit Diesel Corporation diesel engine was fuelled with blends of 10, 20, 30, and 40% biodiesel/diesel fuel. The usage of the biodiesel/diesel fuel blends reduced particulate matter, HC, and CO, while NO_x increased . The optimum blend of biodiesel and diesel fuel was a 20/80 biodiesel/diesel fuel blend. Candeia *et al*. [17] investigated the influence of soybean biodiesel content on basic properties of biodiesel-diesel blends. The biodiesel enrichment caused an increase in viscosity, besides reducing the volatility of the blends. Therefore, the usage of high biodiesel levels in diesel engines has to be more carefully studied, in order to assure a proper engine operation .

The viscosity of the biodiesel is higher than that of diesel fuel. High viscosity of biodiesel affects atomization by increasing the mean droplet size which increases the spray tip penetration. As a result, the mixture formation and combustion worsen when biodiesel is used instead of diesel fuel. This problem can be resolved by blending diesel with biodiesel which will reduce the viscosity. The other way to improve atomization is to inject biodiesel at higher pressures which increase the atomization process by increasing dispersion of biodiesel spray [18, 19].

When the above literature review is examined, it is seen that there are few studies on usage of the SME at different injection pressure in diesel engine. The first aim of this study is to investigate the suitable soybean biodiesel-diesel fuel blend rate in terms of performance and emissions. The second aim is to determine the optimum injection pressure which compensates the negative effect of the high viscosity of the biodiesel on atomization and mixture formation.

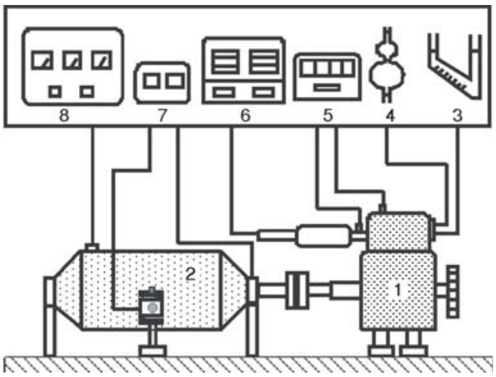

Figure 1. Test set-up
1 – engine, 2 – dynamometer, 3 – fuel flowmeter, 4 – fuel flowmeter, 5 – temperature indicators, 6 – exhausts gas analyzer, 7 – load and speed indicators, 8 – dynamometer control unit

Experimental study

The experimental se-tup, shown in fig. 1, consists of a test engine, dynamometer, fuel and air flow meters, exhaust gas analysis system, and various measuring equipments.

A Katana KM 170 F diesel engine was used in this study. Specifications of the engine are presented in tab. 1.

Table 1. Specifications of the test engine

General	Single cylinder, naturally aspirated and four stroke
Diameter × Stroke [mm]	70 × 55
Compression ratio	18/1
Rated power [kW]	3.5 at 3600 rpm
Injection type	Direct injection
Fuel system	Pump-nozzle (mechanical controlled)
Injector opening pressure [bar]	200
Injection timing (CA bTDC)	23°
Number of injector nozzle holes	4
Injector nozzle hole diameter [mm]	0.1

CO, CO_2, HC, NO_x, and smoke opacity emissions were measured with a MRU DELTA 1600 L exhaust gas analyzer with an accuracy of ±%0.01, ±%0.01, ±1 ppm, ±1 ppm, and ±%0.02, respectively.

Table 2. Properties of diesel fuel and SME

Property	Diesel	SME
Density [kgm^{-3}]	835	882
Kinematic viscosity at 40 °C [mm^{2}s^{-1}]	2.6	4.78
Lower heating value [kJkg^{-1}]	42640	37388
Cetane number	47	50
Pour point [°C]	–15	–3.9
Flash point [°C]	58	170

Biodiesel is a fuel composed by mono-alkyl-esters of long--chain fatty acids that can be produced from vegetable oils or animal fat. Biodiesel can be obtained from different processes, being transesterification the most commonly used at present. The transesterification process is based on the chemical reaction of a triglyceride with an alcohol in the presence of a catalyst, producing biodiesel and glycerine. The catalyst can be acid or alkaline, and the alcohol is preferably methanol or ethanol [13]. SME used in this study was supplied from a local producer. The biodiesel fuel was produced from the transesterification of soybean crude-oil with methanol (CH_3OH) catalyzed by potassium hydroxide (KOH). SME is primarily composed of five fatty acids; palmitic acid (~13%), stearic acid (~5%), oleic acid (~20%), linoleic acid (~54%), and linolenic acid (~8%). The fatty acid composition of the biodiesel affects the fuel properties. The properties of test fuels (diesel fuel and SME) are shown in tab. 2. Pour point of SME is not very low. If SME is to be used during winter period, the cold flow improver additive should be used to reduce pour point of SME.

The tests were performed at two stages. At first stage, in order to determine the suitable diesel-biodiesel blend rate in terms of performance and emissions, the test engine was run at maximum torque engine speed (2600 rpm) and full load; with B0 (diesel), B25 (75% diesel + 25% biodiesel), B50, B75, and B100 (biodiesel) fuels. All the data for engine torque, engine power, specific fuel consumption, exhaust gas temperature, smoke opacity, HC, CO, CO_2, and

NO_x emissions was collected. According to results of experiment carried out at first stage, it was determined that the most suitable fuel was B25 in terms of performance and NO_x emission. At second stage, the tests were performed at a constant speed (2600 rpm), in the ranges of 25%, 50%, 75%, and 100% engine loads at different injection pressures (160, 180, 200, 220, and 240 bar) to determine optimum injection pressure for the B25 fuel. The original injection pressure of the engine is 200 bar. Prior to the tests, the engine was warmed up. At all the tests, all values were recorded after allowing sufficient time for the engine to stabilize. The engine tests were repeated for each injection pressures and test fuels, and performed under same conditions for comparison.

Experimental results and discussion

At first stage, in order to determine the suitable diesel-biodiesel blend rate in terms of performance and emissions, the test engine was run at a constant speed (2600 rpm) and full load; with B0, B25, B50, B75 and B100 fuels.

The effect of various fuels on engine performance and exhaust emissions

Figure 2 shows the effect of various fuels on power and specific fuel consumption. As can be seen from fig. 2, the power decreases as biodiesel content in the blend increases. Owing to the fact that the heating value of biodiesel is lower than that of diesel fuel, the power decreases. The values of power obtained are about 3.27 kW, 3.17 kW, 3.12 kW, 3.07 kW and 3.04 kW with B0, B25, B50, B75, and B100 fuels, respectively. The power obtained with B100 is about 7-8% lower than that with B0. At same conditions, a decrease of 3% in power is seen with B25 fuel when compared with B0. When fig.2 is examined, it is seen that SFC increases as the biodiesel content in the blend raises. The values of the SFC are about 343.82 g/kWh, 363.40 g/kWh, 377.79 g/kWh, 385.60 g/kWh and 396.74 g/kWh with B0, B25, B50, B75, and B100 fuels, respectively. SFC values obtained with B100 and B25 are about 15% and 5% higher than those with B0, respectively. Owing to the fact that the heating value of biodiesel is lower than that of diesel fuel, the SFC increases as the biodiesel content in blend increases. Similar trends related to power and SFC were reported in [8, 10]. As a result, SFC and power values of B25 were close to those of B0. For B50, B75, and B100, as biodiesel content in blend raises, SFC increases and power decreases.

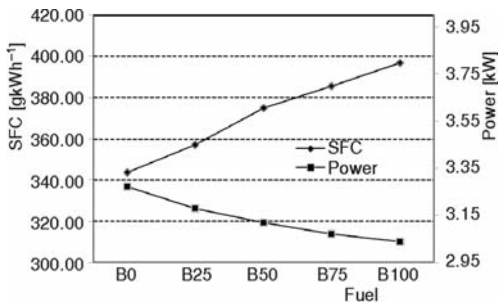

Figure 2. The effect of various fuels on power and specific fuel consumption

The effect of various fuels on HC and CO emissions is given in fig. 3. When fig. 3 is examined, it is seen that HC and CO emissions decrease as the biodiesel content in blend rises. The values of HC and CO emissions are minimum with B100. Since oxygen is present in

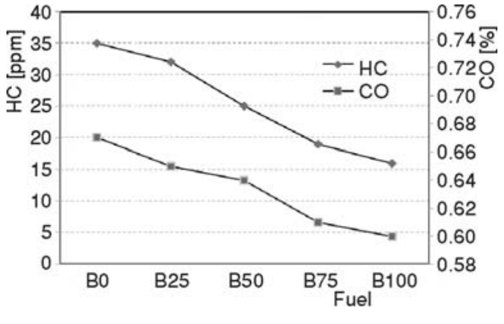

Figure 3. The effect of various fuels on HC and CO emissions

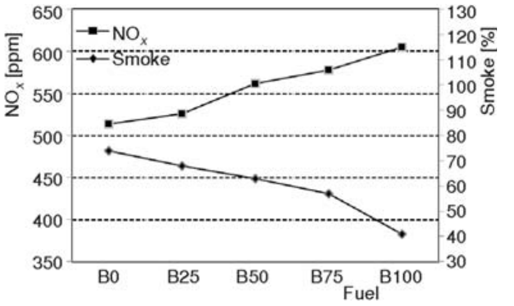

Figure 4. The effect of various fuels on NO$_x$ and smoke emissions

biodiesel and higher H/C ratio of biodiesel than diesel fuel, the combustion becomes better and so the HC and CO emissions decrease. Same observations related to HC and CO were found in [12, 14, 15].

Figure 4 shows the effect of various fuels on NO$_x$ and smoke emissions. As biodiesel rate in blend rises, smoke emission decreases and NO$_x$ increases. NO$_x$ rises at high cylinder temperature and light lean fuel-air mixtures. Since the biodiesel has oxygen, the combustion becomes better and so the NO$_x$ emission increase while smoke emissions decrease. Similar results related to NO$_x$ and smoke emissions were reported in [12-14, 16].

According to the results of the experiment carried out at first stage, it was determined that the most suitable fuel was B25 in terms of performance and NO$_x$. SFC and power values of B25 were close to those of B0. NO$_x$ emission of B25 was lower than that of B50, B75, and B100. CO, HC, and smoke emissions of B50, B75, and B100 were also low. But, the power decreased and the SFC increased further with B50, B75, and B100 when compared with B0 fuel.

The effect of B0 and B25 fuels on performance at different injection pressures

At second stage, the engine was tested at a constant speed (2600 rpm), at different loads, with B25 at different injection pressures (160, 180, 200, 220, and 240 bar) and with B0 at the original injection pressure. The original injection pressure of the engine is 200 bar.

Figure 5 shows the effect of injection pressure on power at different loads. While the obtained maximum power is 3.27 kW with B0 at original injection pressure, it is 3.23 kW with B25 at the same pressure.The obtained power values with B25 are 3.0 kW, 3.13 kW, 3.25 kW, and 3.20 kW at injection pressures of 160, 180, 220, and 240 bar, respectively. For B25, suitable injection pressure is 220 bar in terms of power. There is only 1% power loss with B25 at 220 bar when compared with B0. Since density and viscosity of the biodiesel is higher than those of diesel fuel, with increasing injection pressure from 200 bar to 220 bar, atomization of the blend fuel becomes better and combustion improves. Therefore, the power increases.

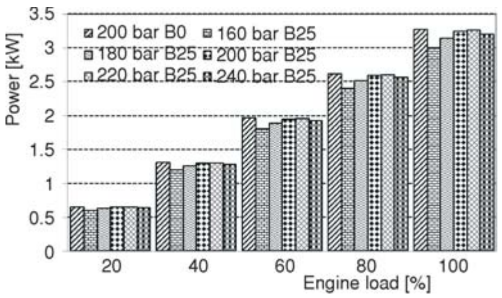

Figure 5. The effect of injection pressure on power at different loads

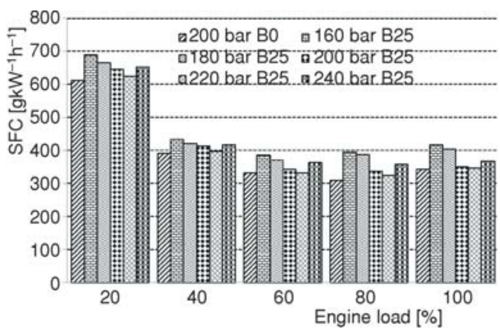

Figure 6. The effect of injection pressure on specific fuel consumption at different loads

The effect of injection pressure on SFC at different loads is given in fig. 6. As seen from fig. 6, as the injection pressure raises SFC decreases at all loads. The value of the SFC is minimum at 220 bar at all the loads. The SFC starts again to increase at 240 bar. At full load the values of SFC are about 418.66 g/kWh, 405.19 g/kWh 351.92 g/kWh, 347.55 g/kWh, and 368.51 g/kWh for 160 bar, 180 bar, 200 bar, 220 bar, and 240 bar, respectively. An increase of only 2% in SFC is seen at injection pressure of 220 bar with B25 when compared to B0 for all the loads. Since the heating value of the biodiesel is lower than that of diesel fuel, SFC increases when using biodiesel.

The effect of B0 and B25 fuels on exhaust emissions at different pressures

Figure 7 shows the effect of injection pressure on HC emission at different loads. For all the injection pressures and fuels HC increases as engine load rises. As seen from fig. 7, HC decreases with B25 as the injection pressure increase. This trend continues up to 220 bar. HC increases again at 240 bar. When compared to B0, a decrease of 33% is obtained with B25 at 220 bar. Since density and viscosity of the biodiesel is higher than that of diesel, the decrease of injection pressure cause worsening of atomization and mixture formation and this, in turn, decreases the combustion efficiency and increases HC. However, further increasing in the injection pressure increases also the penetration depth of fuel and fuel strikes the combustion chamber wall and this, in turn, causes misfire and increases HC. Similar results related to effect of the injection pressure on HC were reported in [14].

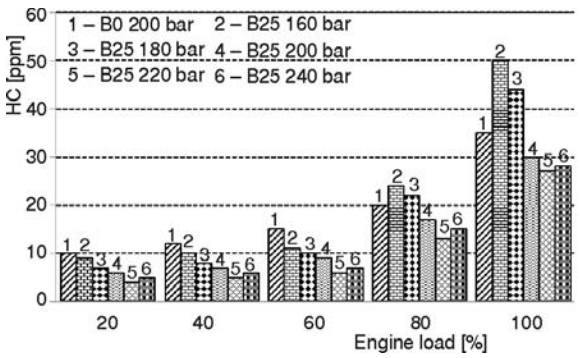

Figure 7. The effect of injection pressure on HC emission at different loads

The effect of injection pressure on CO emission at different loads is given in fig. 8. When fig. 8 is examined, CO increases as the load increases for either fuel. As seen from fig. 8, CO decreases as the injection pressure increase with B25. This trend continues up to 220 bar. CO increases again at 240 bar. At full load, minimum CO is 0.52% at injection pressure of 220 bar. When compared to B0, a decrease of 9% is obtained with B25 at 220 bar. Since biodiesel has oxygen, the combustion becomes better and so the CO decreases. As seen from fig. 8, the effect of variation of the injection pressure on CO is little at medium and low loads.

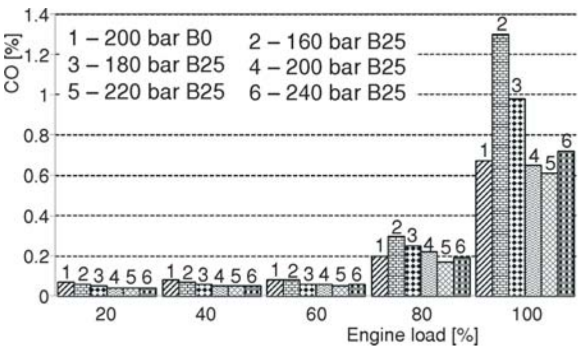

Figure 8. The effect of injection pressure on CO emission at different loads

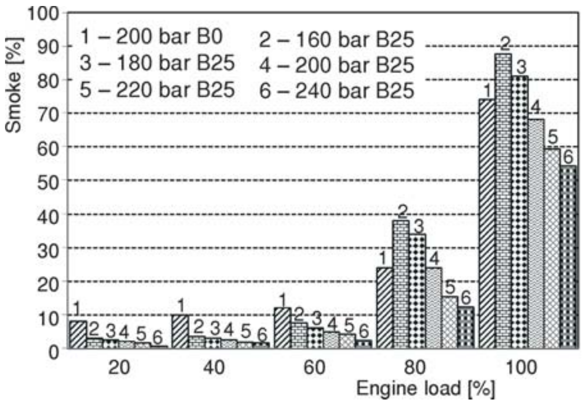

Figure 9. The effect of injection pressure on smoke emission at different loads

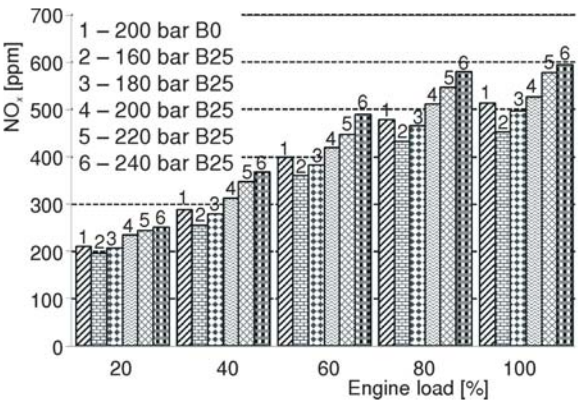

Figure 10. The effect of injection pressure on NO_x emission at different loads

Figure 9 shows the effect of injection pressure on smoke emission at different loads. It is seen that the smoke emission increases by increasing load for all the pressures and fuels. Besides, as the injection pressure increases, smoke emission decreases with B25. At full load, minimum smoke emission is measured as 54.2% at pressure of 240 bar with B25. When compared to B0, a decrease of 20% is obtained with B25 at 220 bar. There are some reasons of decreasing smoke emission at the high injection pressure. The first one is the presence of oxygen in biodiesel. This makes the combustion better and so the smoke emissions decrease. The second one is the high injection pressure that makes the mixture formation and atomization better and this, in turn, decreases smoke emission. Similar observations related to effect of the injection pressure on smoke emission were reported in [10, 14]. As seen from fig. 9, the injection pressure varying does not extremely affect the smoke emission at medium and low loads.

Figure 10 shows the effect of injection pressure on NO_x emission at different loads. As seen from fig. 10 the NO_x emission increases by increasing injection pressure at all the loads. Similar results related to the effect of the injection pressure on NO_x were reported in [14, 18]. As injection pressure rises, atomization of the blend becomes better and the combustion improves and this, in turn, increases the combustion temperature. The high combustion temperature raises the NO_x also. The minimum NO_x emission at the full load is 452 ppm with B25 at 160 bar. An increase of 12% is observed in NO_x with B25 at 220 bar when compared to B0 fuel.

Conclusions

In this study, the effect of the blend rate and injection pressure on the performance and emissions of a diesel engine fuelled with biodiesel (SME)-diesel blend fuel was experimentally investigated. For the tests, a four-stroke, single cylinder, direct injection diesel engine was used. The tests were performed at two stages in order to determine the suitable biodiesel-diesel fuel blend rate and the optimum injection pressure which compensates the negative effect of the high viscosity of biodiesel on atomization and mixture formation.

At first stage, the engine was tested with diesel fuel, B25, B50, B75, and B100 fuels at full load, constant speed and original injection pressure. According to the test results, it was determined that the best suitable fuel was B25 in terms of performance and emission. SFC and power values of B25 were close to those of B0. NO_x emission of B25 was lower than that of other fuels (B50, B75, and B100). It is true that the CO, HC, and smoke emissions were low with B50, B75, and B100 also. But, the power decreased and the SFC increased further with B50, B75, and B100. At second stage, the engine was tested at different loads with diesel fuel at the original injection pressure and with B25 at different injection pressures (160, 180, 200, 220, and 240 bar) in order to determine the optimum injection pressure for B25 fuel. It was determined from the tests that the most suitable injection pressure was 220 bar in terms of performance and emissions. An increase of only 2% in specific fuel consumption without important power loss (%1) was observed with B25 fuel at injection pressure of 220 bar when compared with diesel fuel. In addition, HC, CO, and smoke emissions were reduced by about 33%, 9%, and 20%, respectively. On the other hand, NO_x emission increased by about 12%.

As can be seen from the experimental results, losses in power and SFC were observed when the engine was running with B25, B50, B75, and B100 fuels without varying the engine settings. Still, it was seen that CO, HC, and smoke emission were reduced. The increase in power and decrease in SFC were obtained by varying injection pressure according to biodiesel fuel. Moreover, significant reductions in CO, HC, and smoke emissions were observed when running with optimum injection pressure instead of the original injection pressure. The experimental results showed that biodiesel or biodiesel-diesel blends could be used instead of diesel fuel without important performance loss. In addition, by optimization of the injection pressure according to the used fuel, performance, and emissions can be significantly improved.

The petroleum dependence of the agricultural countries could be reduced by producing and using biodiesel. Besides, the vehicle based air pollution can be decreased by using biodiesel.

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