INFLUENCE OF BIODIESEL ON INJECTION, FUEL SPRAY, AND ENGINE CHARACTERISTICS

by

Breda KEGL and Stanislav PEHAN

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This paper discusses the influence of biodiesel on the injection, spray, and engine characteristics with the aim to reduce harmful emissions. The considered engine is a bus diesel engine with injection M system. The injection, fuel spray, and engine characteristics, obtained with biodiesel, are compared to those obtained with mineral diesel under peak torque and rated conditions. The considered fuel is neat biodiesel from rapeseed oil. Its density, viscosity, surface tension, and sound velocity are determined experimentally and compared to those of mineral diesel. The experimentally obtained results are used to analyze the most important injection, fuel spray, and engine characteristics. Furthermore, the influence of biodiesel usage on lubrication is presented briefly. The results indicate that, by using biodiesel, harmful emissions (NO_x, CO, HC, smoke, and PM) can be reduced to some extent by adjusting the injection pump timing properly while keeping other engine characteristics within acceptable limits. Furthermore, the results indicate better lubrication conditions when biodiesel is used.

Key words: *biodiesel, diesel engine, injection characteristics, fuel spray, emission, lubrication*

Introduction

Care of environment, increasing prices and uncertainties concerning mineral fuel availability necessitate the search for alternative fuels. In near future, biodiesel fuels such as ethyl or methyl esters from soybean oil, rapeseed oil, sunflower oil, *etc*. offer a potentially very interesting alternative regarding harmful emissions, engine wear, cost, and availability [1, 2]. Furthermore, biodiesel does not contain carcinogens, such as poly aromatic hydrocarbons and nitrous poly aromatic hydrocarbons. When burned, it produces pollutants that are less detrimental to human health [3].

The actual injection, fuel spray, and engine characteristics, however, vary significantly in dependence on the used fuel, employed engine, and engine operating regimes [1-7]. It is known that higher density, sound velocity, and bulk modulus of biodiesel cause advanced injection timing in injection systems. Generally, this is one of the reasons for increased NO_x emission. To moderate the NO_x emission in case of biodiesel usage, several strategies are possible, depending on the injection system type [8-10].

Most of the currently working diesel engines have been developed for operation with mineral diesel fuels. For these engines biodiesel can obviously not be used without any precautions. Therefore, many investigations are still necessary to prevent or at least mitigate various engine or environmental problems. Regarding the environmental problems, both the injection system and the fuel play an important role. This is because they influence the injection – fuelling, injection rate, injection pressure, injection timing (start of injection), fuel spray – spray tip penetration, spray angle, and mean droplet size (SMD), and consequently the engine characteristics – emissions, fuel consumption, and engine performance [9, 11-17].

This paper focuses on a diesel engine with mechanical inline fuel injection M system. More precisely, the influence of properties of rapeseed oil biodiesel on the injection, fuel spray, and engine characteristics is considered using the experimental work at peak torque and rated conditions. Furthermore, on the basis of experiments this paper deals briefly with the lubrication phenomena when biodiesel is used.

In the first section the properties of tested biodiesel and mineral diesel are discussed briefly. The next section presents experimental setup and procedures. In the following sections, injection, spray, and engine characteristics are addressed. Furthermore, the influence of biodiesel usage on fuel pump lubrication is discussed. Finally, in the last section, the influence of fuel properties, injection and spray characteristics is analyzed briefly in the context of harmful emissions reduction.

Tested fuels

Two fuels are tested: (1) neat diesel fuel D2, conforming to standard EN 590 and (2) neat biodiesel fuel B100, conforming to European standard EN 14214. Some measured properties of these fuels are given in tab. 1. The biodiesel fuel is produced from rapeseed by Pinus, Slovenia. Some of its specifications are given in tab. 2.

Table 1. Biodiesel and diesel properties

Fuel	D2	B100
Density at 30 ºC [kg/m^3]	827.4	878.4
Kinematic viscosity at 30 ºC [mm^2/s]	3.34	5.51
Surface tension at 30 ºC [N/m]	0.0255	0.028
Sound of velocity at 20 ºC, 100 bar [m/s]	1347.6	1383.6
Calorific value [J/kg]	43800	38177
Cetane number	45-55	51

The fuel properties have a noticeable influence on engine characteristics. For this reason the most important properties of tested fuels have been determined experimentally.

The fuel density is measured with density meter DMA 35 PAAR. The fuel density, obtained by our experiment at ambient pressure, is presented in fig. 1. One can see that the density increases by decreasing the fuel temperature. The measurement of sound velocity in fuel was based on the principle of pressure wave propagation on a specified length of the high pressure (HP) tube, instrumented by two piezoelectric based pressure transducers. A small plunger-type pump was used to induce a pressure wave which was registered by both transducers and simultaneously acquired by a computer aided measuring system [5].

Experimental set-up and procedures

The fuel injection system used in this research is the mechanically controlled fuel injection M system, which consists of a jerk pump, a HP tube and an injector. Some specifications

Table 2. Biodiesel analysis

	Biodiesel – Pinus	Standard EN 14214
Ester content [%/mm]	96.9	>96.5
Sulfur content [mg/kg]	<10	<10
Carbon residue on 10% distillation residue [%/mm]	<0.3	<0.3
Water content [mg/kg]	208	<500
Oxidation stability, 110 °C [hours]	14.8	>6
Acid value [mg of KOH/g]	0.24	<0.50
Iodine value [g of I_2/100 g]	117	<120
Linolenic acid methyl ester [%/mm]	8.5	<12
Methanol content [%/mm]	0.01	<0.20

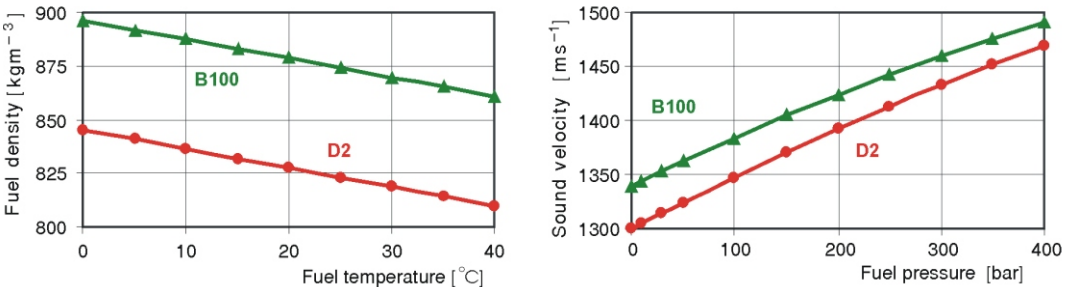


Figure 1. Density and sound velocity of fuel at different conditions

of this system are given in tab. 3. The test bed of the fuel injection system is presented schematically in fig. 2.

This system was fully instrumented in order to measure the basic parameters, characteristic for system operation [5, 18]. A diaphragm-type pressure transducer AVL 31DP 1200E was applied for measurement of pressure traces p_I at the high pressure pipe inflow just behind

Table 3. Test injection system main specifications

Injection system type	Direct injection M system (with wall distribution)
Fuel injection pump type	Bosch PES 6A 95D 410 LS 2542
Pump plunger (diameter, lift)	9.5 mm, 8 mm
Fuel pipe (length, diameter)	1024 mm, 1.8 mm
Injection nozzle (number, nozzle hole diameter)	1, 0.68 mm
Needle lift (maximal)	0.3 mm
Start of delivery (pump injection timing)	17 °CA BTDC and 18 °CA BTDC
Needle opening pressure	175 bar

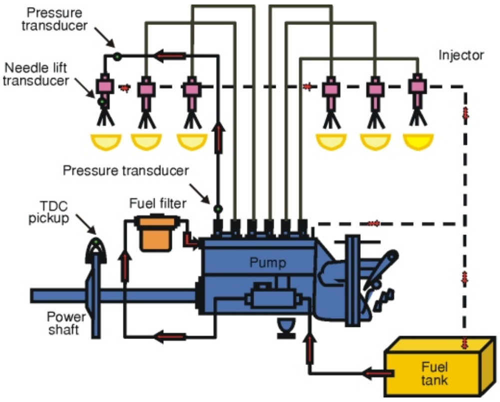


Figure 2. Fuel injection system test bed

the injection pump. A piezoelectric-type pressure transducer Kistler 6227 with charge amplifier Kistler was applied for measurement of pressure traces p_{II} within high pressure tube just before the injector. A specially designed variable-inductance sensor was applied for the needle lift h_n pickup. The position of top dead center (TDC) was measured by an optic sensor. The fuel temperature was measured at the inflow into and behind the delivery pump. The injected fuel quantity was measured by collecting the injected fuel over 500 cycles in a test glass.

Using the fuel spray injection system the fuel was injected into the glass chamber and the spray was filmed with a high speed digital camera Phantom v4.1. Inside the chamber there was atmospheric pressure. The camera was placed at a distance of 2.5 m from the spray, about 20 cm below the nozzle hole. Due to the nature of spray characteristics, the frame rate of 2500 fps at the resolution 128×512 was chosen. The camera was triggered with falling electric pulse which was recorded together with the signal of TDC.

The schematic diagram of the engine test bed is presented in fig. 3. The engine test bed consists of an engine and electro-dynamometer Zöllner A-350AC, 300 kW, air flow rate meter RMG, fuel consumption dynamic measuring system AVL, UHC analyzer Ratfisch, NO_x chemoluminiscent analyzer Thermoelectron, O_2 analyzer Programmelectronic, CO analyzer Maihak, and smoke meter AVL. Using a data acquisition system the instantaneous pressure in the fuel high pressure tube, the instantaneous pressure in the cylinder, the temperatures of fuel, ambient air, intake air, cooling water at inflow and outflow of the engine, oil and the temperature exhaust gases are measured also, fig. 3 [13].

The measurements of injection, fuel spray, and engine characteristics were performed at peak torque and rated conditions. Three categories of analyses are presented to study the following:

– influence of fuels on injection, fuel spray, and engine characteristics,

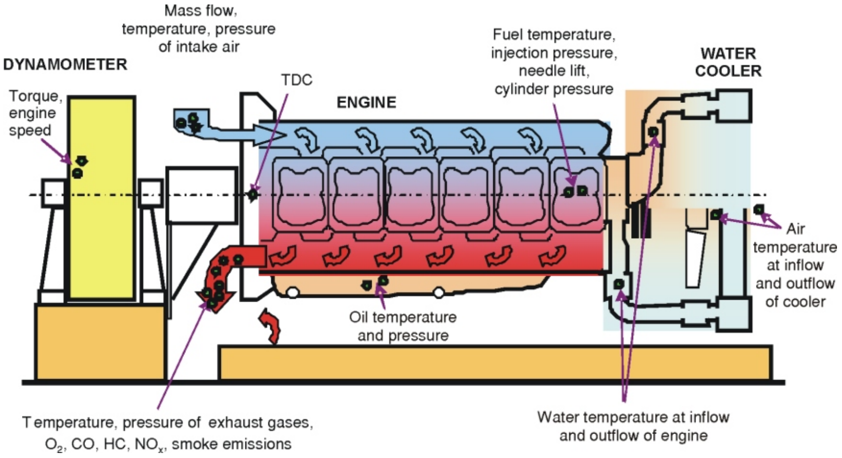


Figure 3. The engine test bed scheme

– influence of biodiesel on fuel pump lubrication, and
– a possibility to reduce harmful emissions by adjusting properly the injection pump timing for B100.

It should be noted that throughout this paper it is assumed that the load is determined by the rack position. This means that at the same load (and speed) the fueling for D2 will be somewhat different than that for B100.

Injection, fuel spray, and engine characteristics

Injection, fuel spray, and engine characteristics are measured in laboratory at ambient temperature of about 20 ºC. Both tested fuels have been used to run the engine with injection pump timing (start of injection pump delivery) of α_i = 23 °CA BTDC (crankshaft angle before top dead centre), which is prescribed by the engine producer (for use with D2).

Injection characteristics

Injection characteristics using D2 and B100 at fuel temperature of 20 ºC at peak torque condition are presented in fig. 4. Injection characteristics using D2 and B100 at fuel temperature of 20 ºC at rated condition are presented in fig. 5. The most important injection characteristics are given in tab. 4.

On the basis of analysis of injection characteristics from figs. 4 and 5 and tab. 4 it is evident that the fuelling Q for D2 and B100 is practically the same. Furthermore, the mean and maximal values of injection pressures p_I and p_II, measured before injector, are higher when biodiesel is used. The difference between the injection pressures p_I and p_II arises due to different fuel density, viscosity, bulk modulus of elasticity (product of fuel density and square of sound velocity), and sound velocity. The diagrams on figs. 4 and 5 show, that the injection delay (time between start of delivery and start of injection) decreases when using B100. That means that by using B100 the injection timing $t_{\mathrm{in\,t}}$ is advanced. For the difference of injection timing, the differences in viscosity and in bulk modulus, which affect the speed of

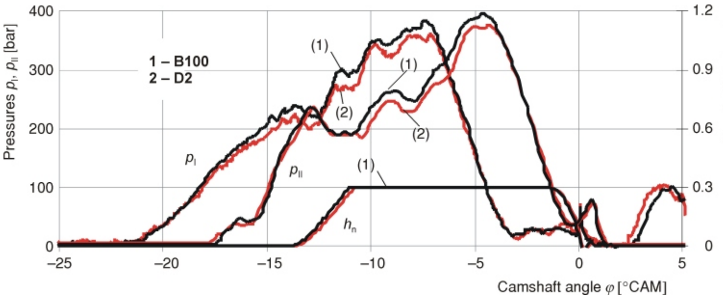


Figure 4. Injection characteristics at peak torque condition (color image see on our web site)

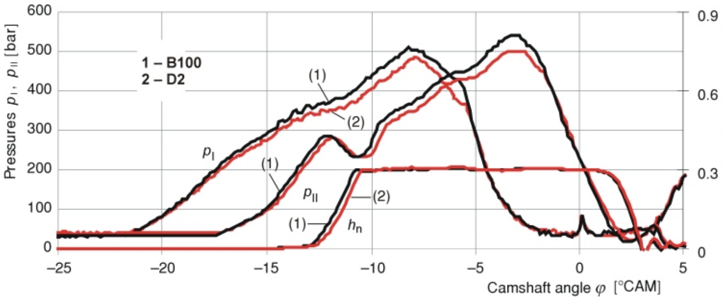


Figure 5. Injection characteristics at rated condition (color image see on our web site)

Table 4. Injection characteristics

Condition	Peak torque		Rated	
Fuel	D2	B100	D2	B100
Q [mm^3/st]	138.5	138	136.5	136
$Q_{\text{n l}}$ [mm^3]	20.2	19.95	14.82	14.55
$Q_{\text{n c}}$ [mm^3]	4.9	4.36	4.3	3.96
$t_{\text{inj t}}$ [ms]	2.8	2.89	1.94	1.98
$p_{\text{I mean}}$ [bar]	194.8	205.3	238.3	255.7
$p_{\text{I max}}$ [bar]	359.9	382.9	483.4	509.5
$p_{\text{II mean}}$ [bar]	232.9	241.7	315.1	329.2
$p_{\text{II max}}$ [bar]	374.6	393.6	502.6	540.8

sound, are responsible. A higher sound velocity and density leads to higher bulk modulus of B100, which leads to a more rapid pressure wave propagation from the pump to the needle nozzle and an earlier needle lift. Higher viscosity of B100 leads to reduced fuel losses during injection process, to faster evolution of pressure and thus to advanced injection timing. Table 4 shows that when using B100 the fuel quantities during needle lifting, $Q_{\text{n l}}$, and during needle closing phase, $Q_{\text{n c}}$, are smaller. Because of the smaller $Q_{\text{n l}}$ B100 offers a potential to reduce the harmful NO$_x$ emissions meanwhile smaller $Q_{\text{n c}}$ may be utilized to reduce smoke and particulate matters (PM) emissions.

Fuel spray characteristics

The different properties of D2 and B100 lead to different injection characteristics and consequently to different fuel spray. As an example, fig. 6 shows the spray comparison for D2 and B100 at peak torque condition. At rated condition the fuel spray comparison for both fuels is presented in fig. 7.

On the basis of experimental results it can be concluded, the biodiesel spray angle is narrower and the penetration length is larger. Some of the most important reasons for that are low fuel vaporization, worse atomization, and higher injection pressure of B100. Worse atomization is a consequence high surface tension and viscosity of B100. This leads to higher spray tip penetration, tab. 5.

Engine characteristics

Fuel properties like density, viscosity, sound velocity, bulk modulus, cetane number, oxygen content, and so on, have also significant effects on start of combustion and premixed and diffusion burn peak and over these on the emission and other engine performances.

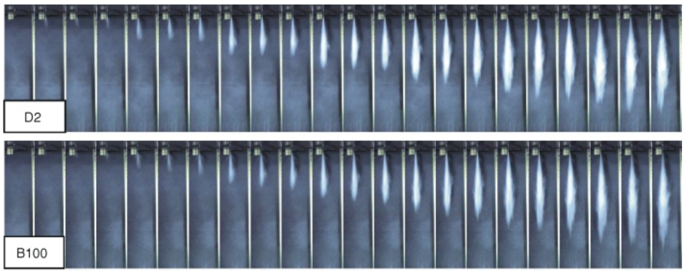


Figure 6. Fuel spray characteristics at peak torque condition (color image see on our web site)

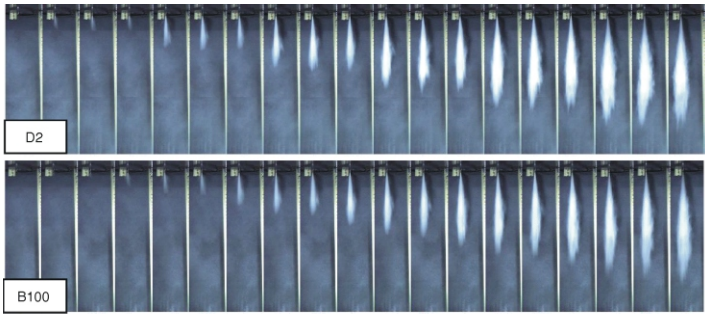


Figure 7. Fuel spray characteristics at rated condition (color image see on our web site)

Table 5. Spray penetration

Operating condition	D2	B100
Peak torque	31.9 cm	32.8 cm
Rated	32.5 cm	33.8 cm

The influence of fuel on engine characteristics is tested by running the engine with injection pump timing prescribed for D2. The comparison of some engine characteristics of D2 and B100 at peak torque and rated conditions is shown in fig. 8 and in fig. 9, separately. At both operating regimes, the engine effective torque M_e and power P_e decreases by about 5% using B100 while the effective specific fuel consumption g_e (for the actual fuel mass) increases by about 10%. On the other hand, the temperatures of exhaust gases $T_{g\,e}$ are lower by about 30 ºC, which may be due to the lower calorific value of B100. To compare the fuels which have different calorific values, the brake thermal efficiency is presented also. This quantity is defined as the actual effective power divided by the amount of fuel chemical energy (fuel consumption rate multiplied by calorific value). In spite of higher effective specific fuel consumption g_e for B100 at both operating regimes, the brake thermal efficiency is practically the same for both fuels.

By comparing the emissions of NO_x, smoke, CO, and unburned HC, it is evident that the NO_x emission increases at rated condition a little more then at peak torque condition when using B100. An opposite effect is observed for the smoke. The CO and HC emissions are lower when using B100 almost at all engine speeds, except the HC emission at peak torque. The lower CO, HC, and smoke emissions, when using B100, are likely due to the fact that biodiesel contains more oxygen, which helps to oxidize these combustion products in the cylinder.

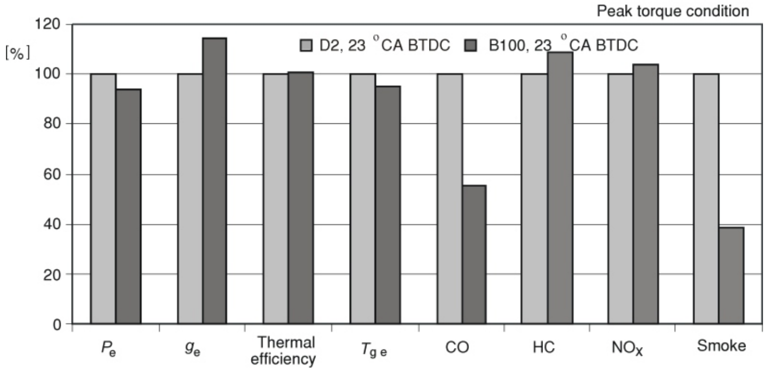


Figure 8. Engine characteristics at peak torque condition

From the obtained results, it is evident that the lowest CO emissions are obtained at peak torque with B100. The lowest HC emissions are obtained at rated condition with B100. Regarding the smoke and NO_x emissions, it can be concluded that B100 reduces smoke to a great extent, meanwhile it increases the NO_x emission by about 5%.

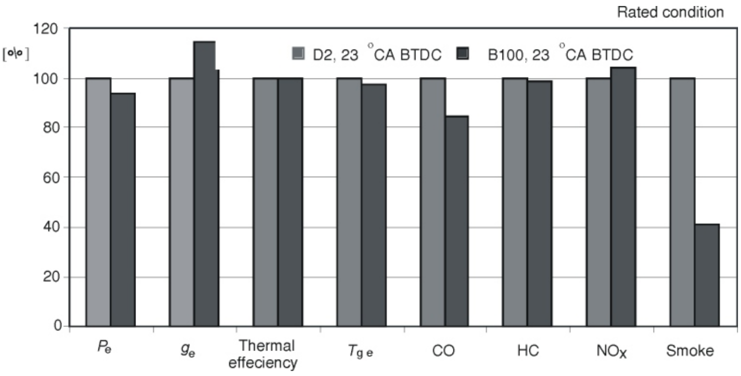
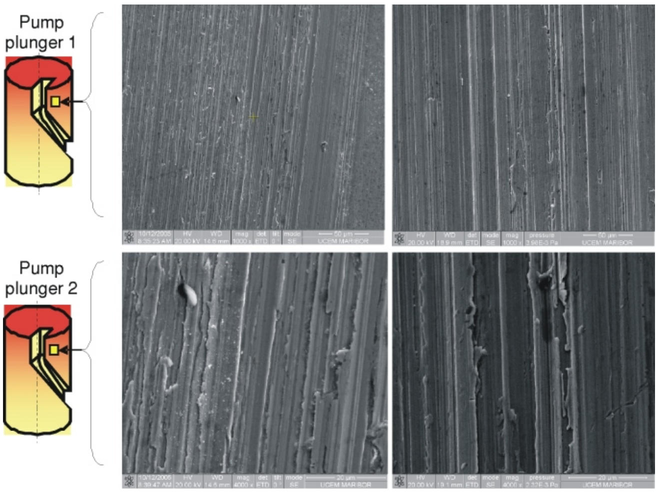


Figure 9. Engine characteristics at rated condition

Biodiesel influence on fuel pump lubrication

To determine the differences in pump plunger surface due to the usage of different fuels, the electronic microscope is used. For this reason the examination of the surfaces before the usage of biodiesel (after 500 000 km and after complete refit) and after its use (for a period of 110 hours of testing) has been done.

The influence of biodiesel on the pump plunger surface is presented in fig. 10 (magnification 1000 , 50 μm). For the decisional parameter the surface area positioned close to the top of the pump plunger has been selected. This is because this surface has a critical influence on the injection pressure. It turned out that under the microscope the surface looked always pretty the same, regardless of the fuel used.



(a) Before biodiesel usage (b) After biodiesel usage

Figure 10. Pump plunger surface before and after biodiesel usage – (color image see on our web site)

To determine the difference in the roughness of the pump plunger surface due to biodiesel usage, some roughness parameters are determined. The arithmetic roughness average R_a, quadratic roughness average R_q, maximum peak to valley height R_y, and average peak to valley height R_z are determined on the pump plunger wall and the head.

Biodiesel usage influences the surface roughness parameters at the pump plunger wall to a small extent, fig. 11. On the contrary, biodiesel influence is rather significant at the pump plunger head, fig. 12. One can see that the surface roughness at the pump plunger head increased by a factor of two when biodiesel was used for about 110 hours. Luckily, for fuel leakage in the HP pump, the surface roughness at the pump plunger head is not as important as the roughness at the pump plunger wall. For this reason, the obtained results are not alarming, although some further tribology investigations would be necessary to evaluate the situation more precisely.

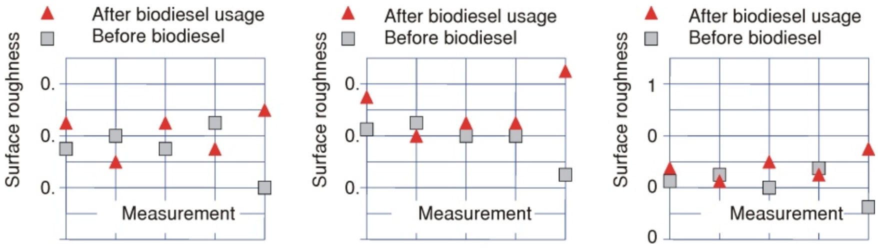


Figure 11. Biodiesel influence on surface roughness at pump plunger wall

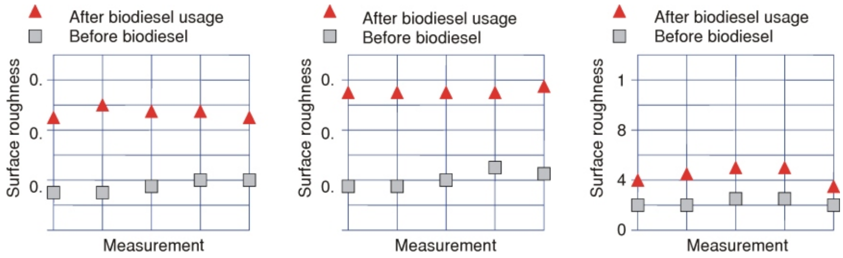


Figure 12. Biodiesel influence on surface roughness at pump plunger head

A good pump plunger surface, illustrated schematically in fig. 13, in fact approximates the most worn surfaces, where lubrication is effective. Such surfaces tend to exhibit the favorable surface profile, *i. e*., quasy-planar plateau separated by randomly spaced narrow grooves.

From fig. 13 and tab. 6 it can be concluded that greater roughness, obtained after biodiesel usage, will not worsen the sliding condition at pump plunger walls. After biodiesel usage the average value of the root mean square roughness becomes relatively lower; in fact it falls 0.45a to 0.40a, which could be an indication for improved lubrication conditions.

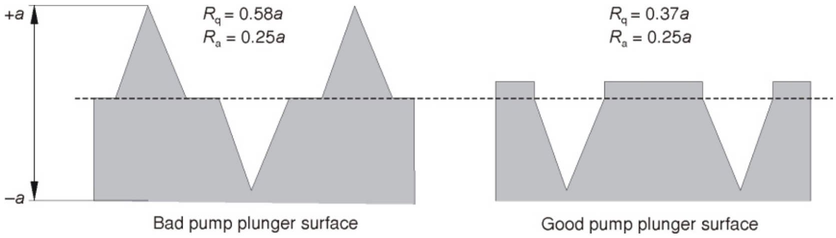


Figure 13. The difference between bad and good pump plunger surface

Emissions reduction by engine modification

The experimental results of injection, fuel spray and engine characteristics lead to the fact that the pump injection timing has to be retarded by using biodiesel in the diesel engine. The tested values of pump injection timing were 23, 22, 21, 19, and 18 °CA TDC. The obtained results show that for B100 the minimal specific fuel consumption g_e is obtained with a_i = 19 °CA TDC. This can be explained with the nature of fuel injection of the employed engine. The M injection system with its single-hole injection nozzle, is oriented so that most of the fuel is depos-

Table 6. Biodiesel influence on surface roughness at pump plunger wall

	R_a [μm] Roughness average	R_q [μm] Root mean square roughness	R_z [μm] Ten-point height	$a = 0.5\ R_z$ [μm]
Before biodiesel	0.065 = 0.325a	0.09 = 0.45a	0.400	0.200
After biodiesel	0.075 = 0.300a	0.10 = 0.40a	0.500	0.250

ited on the piston bowl walls. The use of a bowl-in-piston combustion chamber results in a substantial swirl amplification at the end of the compression process. The air swirl increases as the piston approaches top dead center, influencing significantly the fuel-air mixing rate. It is known, however, that optimum (and not maximum) swirl level gives minimum specific fuel consumption. Obviously, the optimum swirl for B100 fuel was obtained at a_i = 19 °CA TDC. At that setting the maximum cylinder pressure is lower by about 15 bar compared to D2 with standard a_i = = 23 °CA TDC. The temperatures of exhaust gases are also at low levels.

On the basis of extensive analysis, the injection pump timing a_i = 19 °CA TDC was determined as the optimal pump injection timing for the employed engine and tested biodiesel fuel. This setting offers good compromise between all engine characteristics at several engine load and speed regimes.

Figure 14 shows the comparison of the most interesting engine characteristics when D2 and B100 are used at peak torque condition. Compared quantities are the effective power P_e, effective specific fuel consumption g_e, thermal efficiency, temperature of exhaust emissions $T_{g\,e}$ as well as emissions of CO, HC, NO_x, and smoke. At rated condition the comparison between optimal pump injection timing for B100 with prescribed pump injection timing for D2 is presented in fig. 15.

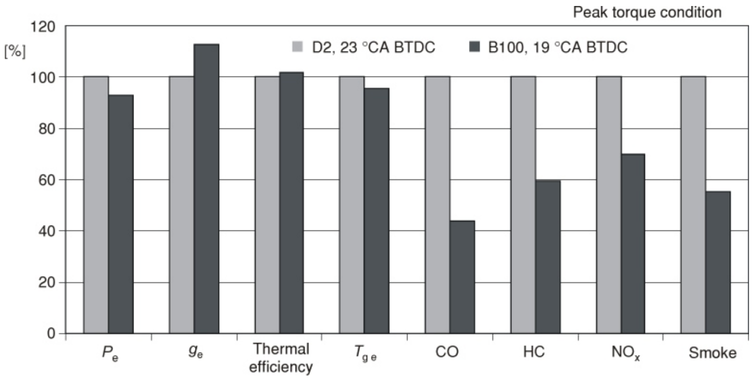


Figure 14. Engine characteristics at peak torque condition by optimized pump injection timing

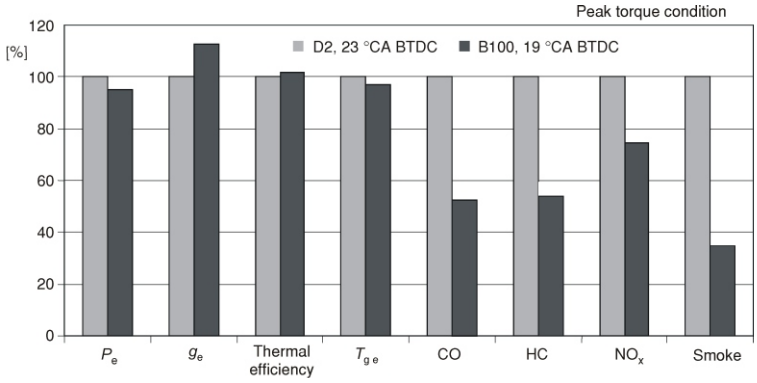


Figure 15. Engine characteristics at rated condition by optimized pump injection timing

The obtained results show that the compromise with respect to harmful emissions, engine power, specific fuel consumption, and exhaust gas temperature may be searched for by optimization of the pump injection timing.

Conclusions

The paper discusses the effects of biodiesel usage on emissions of bus diesel engine MAN D 2566 with mechanically controlled fuel injection M system. The used biodiesel is produced from rapeseed oil. The injection, fuel spray and engine characteristics of biodiesel B100 are compared to those of mineral diesel D2. The lubrication phenomena are also briefly addressed. On the basis of the analysis of experimentally obtained results, the following conclusions can be made.

By using the engine without any modifications, biodiesel has a positive effect on CO and smoke emissions and on exhaust gas temperature at rated and peak torque conditions. The HC emission is increased at peak torque condition only. The thermal efficiency is practically unaffected, meanwhile the specific fuel consumption increases. Regarding the smoke and NO_x emissions it can be concluded that B100 reduces smoke to a great extent, but increases the NO_x emission by about 5% at both tested regimes.

Compared to D2, biodiesel forms a narrower and longer spray under most tested operating regimes. The SMD is not as high as it could be expected due to the physical properties of B100. This is due to higher mean injection pressure of B100 (compared to D2).

The analysis of injection characteristics shows that the injection duration, injection timing, and injection pressure of B100 increase at both considered operating regimes. The higher sound velocity and bulk modulus of B100 lead to reduced injection delay and advanced injection timing. By B100 the fuel quantities during needle lifting and during needle closing phase are smaller. Because of the smaller $Q_{\mathrm{n\,l}}$ B100 offers a potential to reduce the harmful NO_x emissions meanwhile smaller $Q_{\mathrm{n\,c}}$ may be utilized to reduce smoke and particulate matters (PM) emissions.

The use of B100 increased the pump plunger surface roughness. However, this should not worsen the sliding conditions at the pump plunger walls. After biodiesel usage the average value of root mean square roughness decreased which could be an indicator for even better lubrication conditions.

In order to reduce all harmful emissions (of the considered engine), the injection pump timing has to be retarded from 23 to 19 °CA BTDC. It has to be pointed out that by this modification the specific fuel consumption and other engine performances remained within acceptable limits.

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Authors' addresses:

B. Kegl
Engine Research Laboratory, Faculty of Mechanical Engineering,
University of Maribor
17, Smetanova, SI-2000 Maribor, Slovenia

S. Pehan
Faculty of Mechanical Engineering, University of Maribor,
17, Smetanova, , SI-20000 Maribor, Slovenia

Corresponding author B. Kegl
E-mail: breda.kegl@uni-mb.si

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