EXPERIMENTAL INVESTIGATION REVIEW OF BIODIESEL USAGE IN BUS DIESEL ENGINE

by

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This paper assembles and analyses extensive experimental research work conducted for several years in relation to biodiesel usage in a MAN bus Diesel engine with M injection system. At first the most important properties of the actually used neat rapeseed biodiesel fuel and its blends with mineral diesel are discussed and compared to that of mineral diesel. Then the injection, fuel spray, and engine characteristics for various considered fuel blends are compared at various ambient conditions, with special emphasis on the influence of low temperature on fueling. Furthermore, for each tested fuel the optimal injection pump timing is determined. The obtained optimal injection pump timings for individual fuels are then used to determine and discuss the most important injection and combustion characteristics, engine performance, as well as the emission, economy, and tribology characteristics of the engine at all modes of emission test cycles test. The results show that for each tested fuel it is possible to find the optimized injection pump timing, which enables acceptable engine characteristics at all modes of the emission test cycles test.

Key words: *bus Diesel engine, fuel injection, fuel spray, engine performance, tribology characteristics, optimized injection pump timing, combustion, emission*

Introduction

Diesel engine development consists of a wide range of complex processes driven by engine performance, economy, and ecology factors [1, 2]. On top of this the ever stringent ecology regulation and limited petroleum sources make the situation even more sophisticated and it seems that further progress can only be achieved by involving systematic optimization procedures [3-9].

One of the important directions of Diesel engine development is related to alternative fuels, which might often be renewable, available locally, and cleaner than mineral diesel [10, 11]. The development and use of biofuels for the transport sector have attracted especially growing attention worldwide due to their promising benefits including a reduced dependence on fossil fuels and a potential to slow down the effect of global climate change [12-17]. The growing awareness and interest for biofuels led many investigators to work on production, properties, and usage of biodiesel fuels in a Diesel engine [18-24].

In general, biodiesel is a sustainable, non-toxic, biodegradable diesel fuel substitute that can be employed in current diesel car infrastructure without major engine modifications [23]. The most important physical and chemical properties of biodiesel fuels that influence

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Diesel engine performance, ecology, and economy characteristics, are: long time chemical and temperature stability, density, viscosity, sound velocity, bulk modulus, cetane number, cloud point, pour point, cold filter plugging point, flash point, filter plugging tendency, lubricity, corrosiveness, chemical composition, sulphur and aromatic content, contaminants content, and water content [25-27]. Fuel stability is related to many factors like fuel degradation, phase separation, oxidation, and polymerization. Biodiesel exhibits, from the ecological point of view, a rather good and welcome biodegradability. On the other hand, this property implicates a bunch of problems when storing biodiesel, including microbiological growth [28]. Biodiesel fuels have high thermal stability [24] but their oxidative stability is lower than that of mineral diesel. The density and viscosity of biodiesels are generally higher than that of mineral diesel. Higher viscosity values are a consequence of various chain lengths and position, number, and nature of double bonds, as well as the nature of oxygenated moieties [29]. The sound velocity as well as the bulk modulus of biodiesel fuels are also higher than those of mineral diesel [30]. For practically all biodiesels, the average cetane number is larger than 50 [26]. Higher cetane numbers lead to shorter ignition delay and greater efficiency. For biodiesel fuels the cloud point, pour points, and cold filter plugging point are about 15-25 °C higher than those of mineral diesel [18]. The flash points of biodiesel fuels are higher than that of mineral diesel by about 100 °C, which makes storage and handling safer [31]. Filter plugging tendency is worse than that of mineral diesel. Biodiesels exhibit good lubrication properties that reduce wear in the engine [26, 32]. Biodiesel fuels contain more oxygen than mineral diesel, therefore biodiesels produce relatively higher NO_x emission levels during combustion [33]. In general, they have low sulphur and aromatic content, which results in almost no SO_2 emissions. In general, biodiesels are very hygroscopic because of strong polar interactions between esters and water. For example, the water content in rapeseed biodiesel is around 150 mg/kg, while in mineral diesel it is around 50 mg/kg [26, 32]. Further biodiesel benefits are fewer carcinogenic particulate matter (PM) emissions and ease of handling, transport, and storage [24, 33, 34]. Compared to mineral diesel, biodiesels have greater sensitivity to low temperatures [35-37]. There are also problems related to situations when biodiesels are first introduced into equipment that has a long history of neat mineral diesel usage. Mineral diesel fuel typically forms a layer of deposits on the inside of tanks and fuel tubes. Biodiesels may loosen these deposits, causing the clogging of fuel filters. Biodiesel fuels are relatively aggressive toward fuel pipes, sealing, and filters. These elements need to be adapted adequately.

Biodiesel usage influences directly the injection and combustion processes and consequently all engine characteristics. According to most investigations, engine power and torque, PM, CO, and unburned HC in general decrease when mineral diesel is replaced by biodiesel. On the other hand, NO_x typically increase. Of special interest is the variation of PM and NO_x emissions which is attributed both, to the difference in chemical characters of diesel and biodiesel (which affects combustion kinetics) and to different physical properties, which affects fuel spray characteristics [1, 18, 22, 38-40].

Biodiesels obviously come with many advantages but also with many disadvantages. To eliminate the disadvantages of biodiesel usage in Diesel engines, many experimental and numerical investigations of biodiesel influence on all engine characteristics are necessary. Although electronically controlled injection systems gradually replace the mechanically controlled ones, there are still two good reasons to do experimental work on mechanically controlled systems. Firstly, there are still an immense number of mechanically controlled Diesel engines operating worldwide. Secondly, from the experiments on existing mechanical systems, one can also acquire a lot of useful knowledge for the development of electronically controlled systems.

The influence of biodiesel usage depends on the used biodiesel, injection type, engine type, and operating conditions. This paper deals with extensive investigation [1], and contains various experimentally obtained aspects of rapeseed biodiesel influence on injection characteristics of a mechanically controlled M injection system, on combustion process, and consequently on performance, ecology, economy, and tribology characteristics of a MAN bus Diesel engine. In this context five various fuels are extensively tested, namely, neat biodiesel, neat mineral diesel, and their blends.

Experimental equipment

The engine tested in this work is a bus Diesel engine MAN D 2566 MUM with a mechanically controlled fuel injection system [22, 32, 33, 36], tab. 1. The engine has completed 500 000 km and has undergone general renovation. It is equipped with a direct injection (DI) M system which consists of an injection fuel pump, a high pressure (HP) tube and an injector.

The experiments were performed separately on the injection system of the engine, placed on its own test bed, and on the whole engine, mounted onto another test bed. They were related to injection characteristics (such as fueling, injection pressure, injection duration, *etc.*), spray development, and tribology characteristics.

Table 1. Test engine specifications

Engine model	MAN D 2566 MUM
Engine type	4-stroke, 6 cylinder in line, water cooled
Displacement	11 413 cm^3
Compression ratio	17.5:1
Bore and stroke	125 mm × 155 mm
Max power	162 kW at 2200 rpm
Max torque	775 Nm at 1500 rpm
Injection type	DI with wall distribution M system
Pump	Bosch PES 6A 95D 410 LS 2542
Pump plunger diameter/lift	9.5 mm/8 mm
Fuel pipe length	1024 mm
Fuel pipe inner diameter	1.8 mm
Maximal needle lift	0.3 mm
Nozzle hole number/diameter	1/0.68 mm
Needle opening pressure	175 bar
Pump injection timing	23 °CA bTDC

The experiments related to injection characteristics were performed in two ways, depending on the working temperature. At normal operation temperatures, the measurements were done on a single injection assembly (along the fuel path to one cylinder). The observed injection assembly was the one positioned next to the only fuel intake port into the low pressure pump's gallery. On the other hand, to measure the injection characteristics at low fuel temperatures, the set-up of the test bed was modified so that the measurements were done on all injection assemblies and cooling system was attached to the test bed [1, 36].

In order to determine the tribology characteristics, a new device for simultaneous testing of two different fuels was developed, where the low pressure gallery of the HP pump was separated into two parts for two different fuels, fig. 1. After running the fuel injection system on this device for a prescribed time, the surface roughness was investigated.

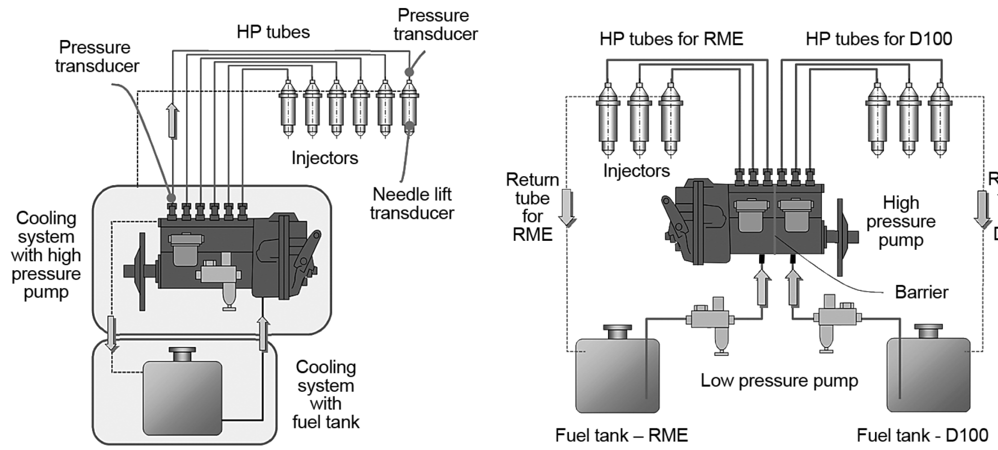

Figure 1. Schemes of injection test bed and device for simultaneous testing of two fuels

In order to measure the fuel spray development, a device consisting of the injection system and a pressure chamber was used, fig. 2. The pressure chamber was filled by the inert gas N_2 at 60 bar. The spray injected into the pressure chamber was recorded by the Fastec HiSpec 4 high-speed digital camera with a resolution of 128 × 332 pixels at a frame-rate of 18 499 fps.

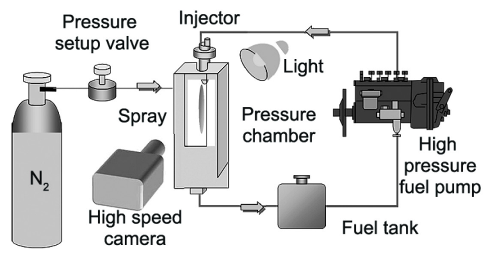

Figure 2. Schemes of fuel spray test beds

The device for surface roughness measurements consists of the pick-up RHT 3/6 and the rotary drive unit PURV 3-100. The tribology characteristics, especially surface characteristics, were estimated on the basis of the roughness parameters R_a (arithmetic roughness average), R_z (average peak-to-valley height), and R_{max} (maximum peak-to-valley height).

The speed of sound in fuel was determined experimentally by utilizing the phenomena of pressure wave propagation. In particular, the time difference between two pressure waves was measured on some specified length of HP tube. Unlike injection characteristics, the engine characteristics obviously have to be measured on the whole engine. The test bed used here consists of the engine and electro-dynamometer Zollner 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 [1]. Furthermore, by using a data acquisition system the instantaneous injection pressure and needle lift, the instantaneous in-cylinder gas pressure, the temperatures of fuel, ambient air, intake air, cooling water at inflow and outflow of the engine, oil pressure and temperature, and the temperature exhaust gases can be measured and recorded.

The injection and engine characteristics were measured at various engine speeds at full and partial loads and well as at the all modes steady-state emission test cycle (ESC) for truck and bus engines. Finally, it should be noted that throughout this paper it is assumed that the pump load is not determined by the actual fueling but by the rack position.

Fuel properties

The tested fuels were neat mineral diesel fuel D100, conforming to European standard EN 590 (Slovenian standard SIST EN 590), neat rapeseed biodiesel fuel rapeseed methyl ester (RME), conforming to European standard EN 14214 (Slovenian standard SIST EN 14214), and their blends BXX, where XX denotes vol.% of biodiesel in fuel (*e. g.* B25 consists of 25 vol.% of biodiesel and 75 vol.% of mineral diesel). The properties of mineral diesel D100 and biodiesel fuel, produced from rapeseed by Bio Goriva, Maribor, Slovenia, are given in tab. 2.

Table 2. Biodiesel and mineral diesel properties

Property	Unit	RME	D100
Density at 15 °C	kgm^{-3}	883	837.3
Kinematic viscosity at 40 °C	mm^2s^{-1}	4.44	2.78
Surface tension	Nm^{-1}	0.0279	0.0263
Cold filter plugging point (CFPP)	°C	–10	–26
Flash point	°C	>120	66.0
Sulphur content	$mgkg^{-1}$	5.8	31.0
Carbon residue (on 10% distillation residue)	% (m/m)	<0.3	0.01
Cetane number	–	51.0	51.8
Water content	$mgkg^{-1}$	208	50
Total contamination	$mgkg^{-1}$	14	2
Capper strip corrosion (3 h at 50 °C)	rating	1a	1a
Ester content	% (m/m)	96.9	–
Oxidation stability, 100 °C	hours	14.8	–
Acid value	$mgKOHg^{-1}$	0.24	–
Iodine value	gI_2/100 g	117	–
Linolenic acid methyl ester	% (m/m)	8.5	–
Polyunsaturated (>4 double bonds) methyl ester	% (m/m)	<1	–
Phosphorus content	$mgkg^{-1}$	<5.0	–
Methanol content	% (m/m)	0.01	–
Monoglyceride content	% (m/m)	0.59	–
Diglyceride content	% (m/m)	0.14	–
Triglyceride	% (m/m)	<0.05	–
Free glycerol	% (m/m)	0.006	–
Total glycerol	% (m/m)	0.176	–

Besides of the fuel properties, given in tab. 2, the density, kinematic viscosity, CFPP, surface tension, and speed of sound influence the injection characteristics significantly. For all tested fuels (RME, B75, B50, B25, and D100) these properties were determined experimentally. The fuel densities were measured at ambient pressure at various temperatures. In general, the density increases by increasing the content of RME and by decreasing temperature. The kinematic viscosities of all fuels increase by increasing the part of biodiesel. The CFPP and surface tension generally decrease with the content of biodiesel in the blend. The measured speed of sound increases by increasing the content of biodiesel in the blend and for neat RME it is higher up to 50 m/s, compared to D100 at all tested pressures. The bulk modulus of elasticity of various fuels varies in accordance with the speed of sound.

Obviously, biodiesel addition causes significant variations in physical and chemical properties of the fuel. This has a significant influence on the injection characteristics.

Main biodiesel effects

The influence of physical and chemical properties of fuels is here investigated in relation to (a) injection characteristics at various fuel temperatures, (b) fuel spray characteristics at ambient conditions, and (c) engine characteristics at various engine regimes. For all fuels the experiments have been done under the same operating conditions.

Injection characteristics

At first, the injection characteristics for RME and D100 are experimentally determined at fuel temperature of 22 °C at various speeds at full and partial loads as well as at all modes of the ECS test. For RME and D100, the injection pressure and needle lift histories at peak torque are presented. It can be seen that the injection pressure and needle lift increase faster when using RME. This means that by keeping the injection pump timing fixed, the injection process will be advanced when RME replaces D100. An analysis of experimental results obtained at various engine regimes by using all tested fuels shows that the maximum injection pressure increases with increasing biodiesel content. By increasing the pump speed at higher load, the influence of biodiesel content is even more evident. Along with the increased injection pressure, the injection timing is also advanced by increasing the content of biodiesel. The largest difference in injection pressure is about 40 bar for RME with respect to D100. The deviations in viscosity and consequently in bulk modulus, which affect the speed of sound, are responsible for the difference in injection timing. A higher bulk modulus, caused by increasing the content of biodiesel, leads to a more rapid pressure wave propagation from the pump to the nozzle and an earlier needle lift. The higher viscosity of biodiesel leads to reduced fuel leakage during the injection process, to a faster evolution of pressure rise and thus to advanced injection timing. To get a better comparison between injection characteristics of D100, B25, B50, B75, and RME fuels, a comparison of some important injection characteristics at different operating regimes was performed. At constant pump injection timing and at a constant rack position, one can observe a gradual increase of fueling with increased biodiesel content at lower speeds regimes and at low partial loads. The injection duration of biodiesel blends deviates from that of mineral diesel, especially at low load regimes. For almost all tested regimes, the largest difference is obtained at 50% partial load when using RME. Only at the low speed regime (irrespective of load) the injection duration of biodiesel and its blends is shorter than that of mineral diesel. A shorter injection duration at relative high fueling leads to a higher mean injection rate, as can be seen at lower speed regimes for all tested loads. The difference between the injection pressures of different fuels is due to variations in fuel density, viscosity, bulk modulus, and speed of sound. The maximum injection pressure for RME and all its blends is higher than that for D100 at all tested operating regimes. The maximum differences are observed at lower speed regimes at full load. The experimental results show that the injection timing advances with a higher content of biodiesel for the already mentioned reasons. This means that the injection delay (time interval between the start of delivery and the start of injection) becomes gradually smaller.

On the basis of all experimentally obtained injection characteristics at all tested operating regimes at fuel temperature of 22 °C, the measured injection characteristics have shown that with increasing biodiesel content the injection delay decreases. Meanwhile, the injection timing, the mean injection rate, and the maximal injection pressure increase. It is known that with the advanced injection timing the pressure in the cylinder increases and the NO_x emissions increase also. For this reason, the NO_x emissions will increase by increasing the content of biodiesel if the injection timing remains unchanged.

The influence of fuel temperatures on fueling was investigated experimentally for one injection assembly and, separately, for the whole injection system, including all six injection assemblies. Fifteen experiments were performed at full load operating regimes for various fuels.

For one injection assembly it can be seen that when using D100, the fueling was practically independent of fuel temperature at practically all engine speeds. On the other hand, during RME usage, the fueling decreased by lowering the temperature, especially at higher engine speeds. At rated condition, the fueling at –15 °C was lower up to 45%, compared to the one at 15 °C. The reason lies in the fact that at temperatures below 0 °C, the viscosity of RME rises steeply because of the precipitation of crystalline saturated methyl esters. This is mainly due to the formation of crystals which ultimately impairs the flow of the fuel [29, 36].

In the case of D100 and RME flow through all injection assemblies, experimental data revealed that the pressure drop through the fuel filter for D100 was practically unaffected by temperature changes. At all tested temperatures it was small and constant. For D100 it was observed that this temperature has no influence on the fueling at any tested operating condition. The differences in fueling with respect to individual injection assemblies were about 5-10% at the same operating regime. For RME at fuel temperature of 15 °C variations with respect to individual injection assemblies are rather small and within the range of 5-10% at the same operating regime. Experimental results show that this observation holds true for temperatures above –7 °C. However, at temperatures lower than –7 °C, these variations raise unacceptably. Especially at higher speeds, the variations between individual assemblies for RME at fuel temperature of –15 °C may reach as much as 80%, fig. 3.

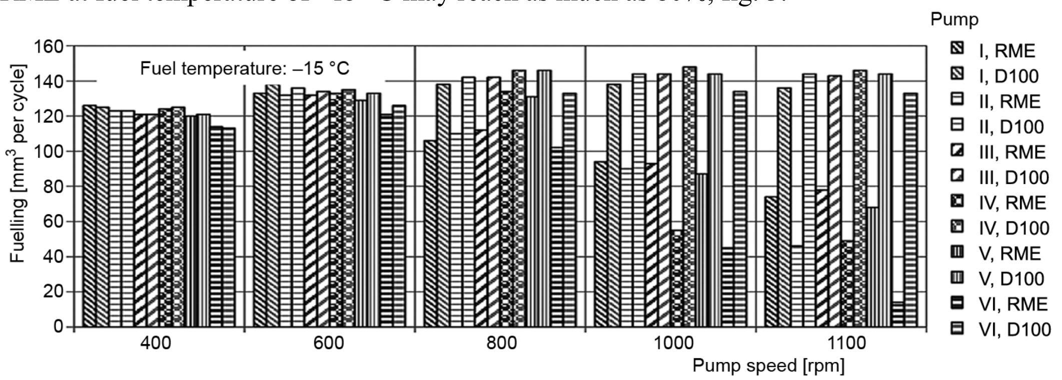

Figure 3. Fuel spray at the same conditions for D100 and RME

Only for the first injection assembly, being located the closest to the fuel inlet into the low pressure pump's gallery, the fueling remains more or less acceptable. For other assemblies, the situation becomes worse, as the distance between the gallery inlet and assembly inlet becomes larger. This observation can probably be explained by the increased pressure drop through the fuel filter. This may result in insufficient fuel supply into the low pressure pump's gallery. The increased pressure drop through the filter is a consequence of steeply increasing viscosity and gradual appearance of solidification of RME at lower temperatures.

Fuel spray characteristics

Various properties of D100 and RME lead to different injection characteristics and consequently to different fuel spray. Experimental fuel injection into an ambient pressure chamber shows that in general the biodiesel spray angle is narrower and the penetration length is larger [22, 38]. In fact, RME spray forms a narrower and longer spray tip penetration in comparison to D100 at most tested operating regimes. Some of the most important reasons for that are low fuel vaporization, worse atomization, and higher injection pressure of RME. Worse atomization is a consequence of RME's high surface tension and viscosity. This leads to higher spray tip penetration and to higher Sauter mean diameter, d_{32}, of biodiesel spray. Higher injection pressure causes higher injection rates, contributing also to higher spray velocities of RME. This also contributes to a narrow spray and longer spray tip penetration.

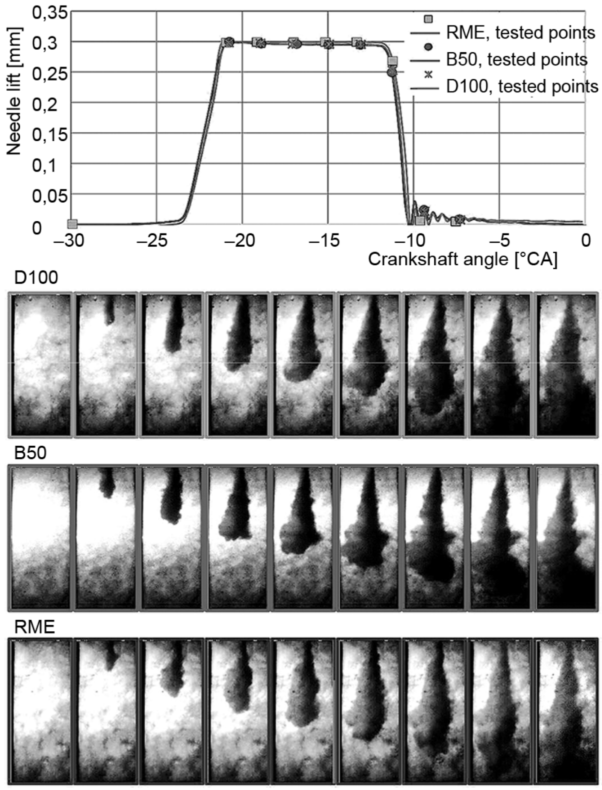

Figure 4. Fuel spray at the same conditions for D100, B50, and RME

Sprays of fuel injection into a HP chamber were compared for D100, B50, and RME at peak torque condition, fig. 4, the markers in the diagram denote time moments at which the pictures were taken.

The results at other regimes are quite similar. Higher injection pressure annihilates the effect of increased friction between the biodiesel and nozzle surface due to higher viscosity of RME. This means that higher injection pressure is a necessity in the case of a D100 designed Diesel engine fueled with RME, if one wants to achieve good combustion performance. For our tested injection system, the injection pressure of RME is higher than that of D100 at the same operating regime. The higher injection pressure of RME has a positive effect on the d_{32} and consequently on the combustion process.

Engine performance, harmful emissions, and economy characteristics

The influence of fuel on engine characteristics was tested by running the engine without any engine modifications (at the injection pump timing, α_i, prescribed for D100) [32]. At all modes of ESC test, the effective power, P_e, is almost the same. The effective specific fuel consumption, g_e, (for the actual fuel mass) increases by about 15% at all 13 modes when using RME. The reason for that lies in lower calorific value of RME. Since the calorific values of D100 and RME are quite different, it is convenient to compare the brake thermal efficiency, η_t. This quantity is defined as the actual effective power, divided by the amount of fuel chemical energy (fuel consumption rate, multiplied by the calorific value). It is evident that is practically the same for both fuels. The lower calorific value of RME is probably also the reason for lower temperatures of exhaust gases at high load modes.

Regarding harmful emissions, one can see that the HC emission is always lower when using RME. Interesting observations can be made for the NO_x and smoke. Except at idle, the NO_x emission is always higher when using RME, while exactly the opposite is true for the smoke. The use of RME leads also to lower CO emission, except at moderate loads and moderate to higher speed regimes, as well as at idle. In case of RME, the larger NO_x formation is partially a consequence of higher content of oxygen, which reacts with the nitrogen component in the surrounding air. On the other side, more oxygen helps to oxidize the combustion products in the cylinder, which leads to lower HC, CO, and smoke emissions.

It may also be worth to compare some engine characteristics at the same injection pump timing by considering the ESC test weighting factors. It is shown that when RME replaces D100, the CO, HC, and smoke emissions decrease and the NO_x emission raises, fig. 5. This is in accordance with the expected advanced injection timing, which is due to higher speed of sound, bulk modulus, and density of RME.

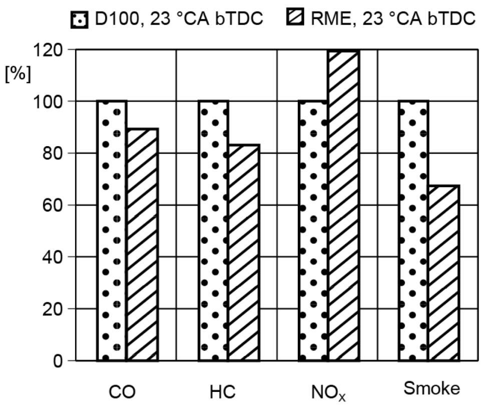

Figure 5. Relative emissions of D100 and RME at the same pump injection timing by considering the ESC test weighting factors

Injection pump timing effects

It is well known that injection timing or start of injection is a very important parameter that significantly influences all engine characteristics [33, 36, 38]. This is mainly due to the fact that injection timing influences the mixing quality of the air-fuel mixture and, consequently, the combustion process, including harmful emissions. It is generally known that retarded injection decreases maximal pressure in the cylinder and leads to a lower peak rate of heat transfer and consequently to lower combustion noise. Because the delayed injection leads to lower temperatures, the NO_x emissions are also reduced. On the other hand, retarded injection leads to an increase in fuel consumption. Smoke emission may also increase, though trends vary significantly between different types and design of engines. For a DI Diesel engine at high load, HC emissions are low and vary only modestly with injection timing. At partial loads, HC emissions are higher and increase as the injection start is shifted significantly from the optimum. This trend is especially evident at idle.

In mechanically controlled injection systems, the start of injection can hardly be controlled directly, because it depends on sophisticated transport phenomena in the pump, HP tubes, and the injector. However, the start of injection is closely related to the start of injection pump delivery, which can be set easily to any desired value, and throughout the paper, it will be called the injection pump timing. In order to determine the optimal start of injection pump timing for each tested fuel, the experiments were performed at various engine operating regimes, like the 13 modes of the ESC test as well as at various engine speeds at full and at partial loads. The experiments were performed at various injection pump timings and the most important engine characteristics were analyzed. As an example, fig. 6 shows some of the most important injection and combustion characteristics at various injection pump timings at mode 8 of the ESC test.

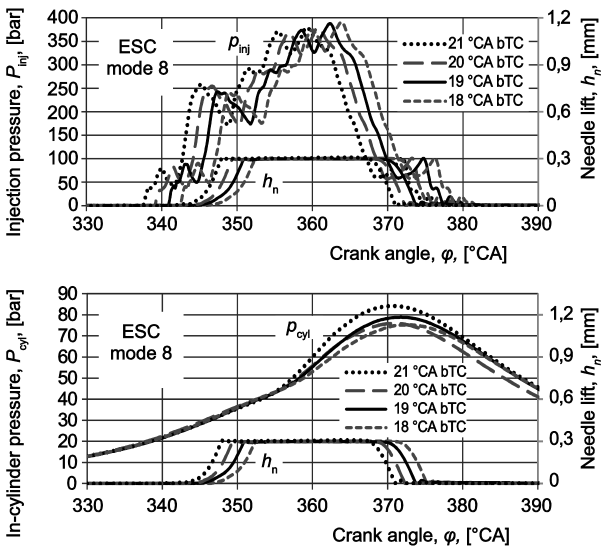

Figure 6. Influence of injection pump timing on injection and combustion characteristics obtained with RME

It can be seen that the retarded injection pump timing leads to retarded injection timing and combustion start. It can be observed, however, that the ignition delay becomes shorter as the injection pump timing is retarded. In general, this leads to lower exhaust gas temperatures.

Once the experimental data for all operating regimes and all injection pump timings were acquired, the most important engine parameters were weighted by corresponding factors that take into account the importance of individual engine regimes (ESC test weighting factors) and summed over all operating regimes. Figure 7 illustrates the results obtained with RME in dependence on various injection pump timings. The numbers given are relative to those obtained with D100 at standard injection pump timing of 23 °CA bTDC.

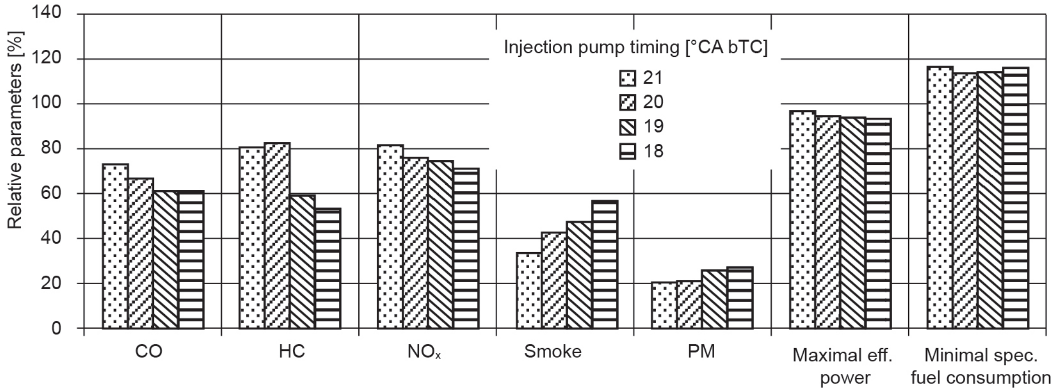

Figure 7. Cumulative influence of injection pump timing on engine characteristics, obtained with RME and ESC test weighting factors

The presented results show that the minimal specific fuel consumption is obtained at 19 °CA bTDC. This can be explained by the fuel injection type of the employed engine. Namely, the M injection system has its single hole injection nozzle oriented so that most of the fuel is deposited 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 TDC, significantly influencing the air-fuel mixing rate. It is known, however, that the optimum (and not maximum) swirl level gives the minimum specific fuel consumption. Obviously, the optimum swirl for RME fuel was obtained at 19 °CA bTDC. At this setting, the maximum cylinder pressure is lower by about 15 bar, compared to that obtained with D100 at standard injection pump timing of 23 °CA bTDC. The temperatures of exhaust gases are also at low levels. On the basis of extensive analysis, the injection pump timing of 19 °CA bTDC seems to be the optimal pump timing for the employed engine and fuel. This setting offers a good compromise between all engine characteristics like effective power, specific fuel consumption, CO, HC, NO_x, smoke, and PM emissions, at several engine operating regimes.

In a similar manner as for neat RME, the optimal injection pump timings for B25, B50, and B75 fuels were determined as 22, 21, and 20 °CA bTDC, respectively. With the optimal injection pumps timing for all tested fuels, the injection, combustion, emission, and economy characteristics, and engine performance were compared and analyzed.

Main biodiesel effects at optimized injection pump timing

It is known that at constant injection pump timing, the needle lift opens earlier by higher content of biodiesel in mineral/biodiesel fuel mixtures [36, 38]. The differences in pressure, when RME and D100 are used, are almost negligible. However, differences are observed for in cylinder gas temperature and in heat release rate. The in cylinder gas temperature and heat release rate of RME are considerably lower and their peak values are advanced with respect to D100. As example, only for mode 8, the experimentally obtained injection pressure, needle lift, numerically determined in-cylinder gas pressure, temperature, heat release rate obtained by using BOOST AVL software, are shown in fig. 8.

The advanced injection timing for RME leads to an earlier increase of heat release rate, in cylinder gas pressure, and temperature. As it is evident from fig. 8, the maximum of the in-cylinder gas pressure, in-cylinder gas temperature, and heat release rate appear

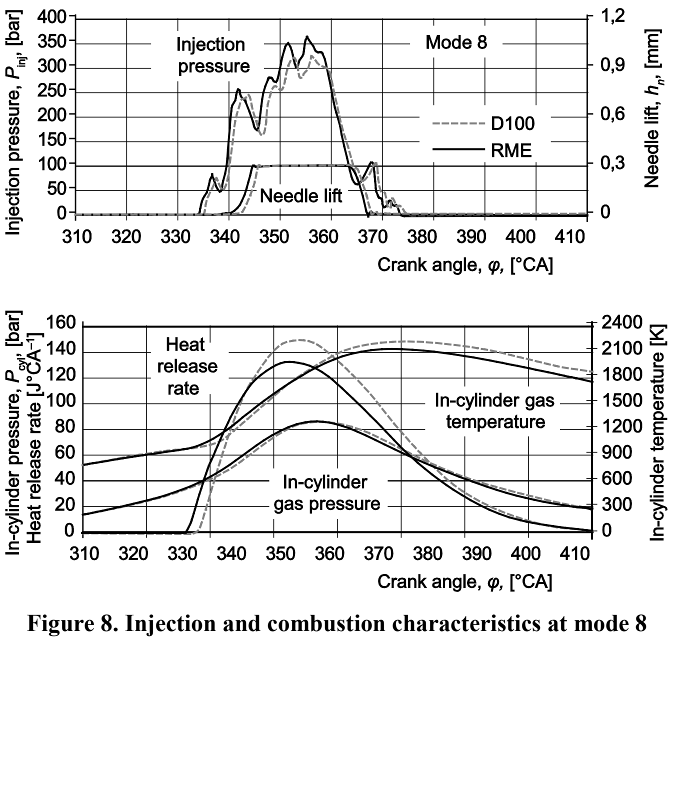

Figure 8. Injection and combustion characteristics at mode 8

earlier for RME. The lower in-cylinder gas temperature of RME can be attributed to two reasons. Firstly, evaporation of RME in the intake system lowers the intake mixture temperature. Secondly, the latent heat of vaporization of RME is higher than of D100, but the heating value is lower than of D100. Thus, more heat is needed for RME than for D100 for fuel vaporization, while the energy released by RME is lower than that from the same mass of D100. So, the in-cylinder gas temperature can be lower for RME.

By taking into account the calculated maximum heat release rate and maximum in-cylinder temperature, the NO_x emission should be lower for RME. On the contrary, the NO_x emission is higher when RME is used at all tested operating regimes at full load. Combustion analysis shows that the formation of NO_x is insensitive to the maximum in-cylinder gas temperature and the maximum heat release rate. A more important factor in the engine-out NO_x emissions was an advance in the start of injection timing caused by the higher bulk modulus of compressibility of RME. This advance initiated a phase shift in the timing of the combustion process, as evidenced by the timing of the maximum heat release rate and the maximum in-cylinder gas temperature. To explain the higher NO_x emission for the tested RME, the advanced injection and combustion process and therefore the higher in-cylinder gas temperature at the beginning of combustion has to be considered. The conditions in the cylinder during the first part of injection and combustion process influence to a great extent the NO_x formation. The moments, at which the maximum in-cylinder gas temperature and heat release rate (in-cylinder gas temperature and heat release peak timing) occur, proved to be more important than the maximum values of the in-cylinder gas temperature and heat release rate. Earlier peaks prolong the period with conditions favorable for NO_x formation.

Injection and combustion characteristics

In our cases the experimentally obtained injection pressure, needle lift history, and in-cylinder pressure were compared at optimized injection pump timing for each tested fuel at some modes. Figure 9 shows the injection pressures, needle lift histories, and in-cylinder gas pressures at 100% load and 1700 rpm (mode 8 of ESC test) by using D100, B25, B50, B75, and RME fuels at 23, 22, 21, 20, and 19 °CA bTDC, respectively.

A comparison of the given results shows that the injection characteristics are very close for D100 and B25 as well as for B75 and RME. It seems that the retarded injection pump timing of B25 with respect to D100 compensates the higher density, speed of sound, and bulk modulus of B25. A similar conclusion can be made for RME and B75. It can be seen that the starts of combustion are very similar for all fuels at the optimized injection pump timing.

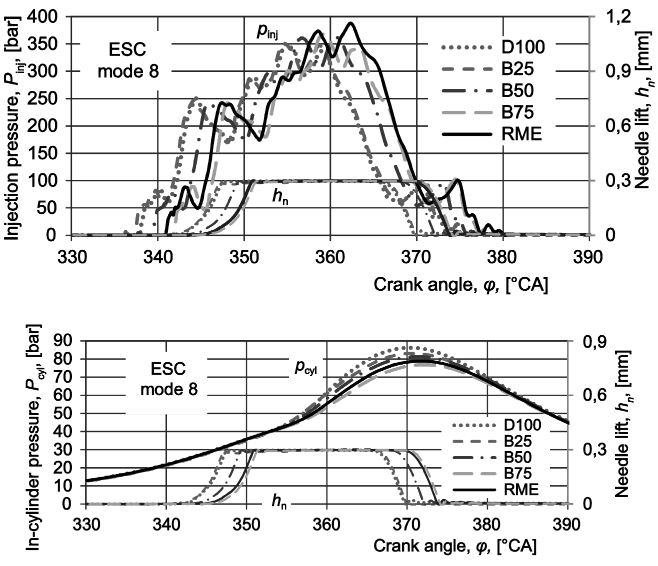

Figure 9. Injection characteristics and in-cylinder pressure at mode 8

Engine characteristics

In the most modes of the ESC test, the effective engine power decreases by increasing the content of biodiesel. The highest effective engine power is achieved with neat mineral diesel because of its high energy content. By using RME the effective power at mode 10 is about 3% lower than the one obtained with D100. On the other hand, at this mode, the specific fuel consumption of RME is higher by about 10% with respect to D100. Practically at all modes of the ESC test, the effective engine specific fuel consumption of D100 is lower than the one obtained with B25, B50, B75, and RME at optimized injection pump timings.

The differences in exhaust gas temperature of D100 and RME are lower than 50 °C at practical all modes of the ESC test. It is known, that the amount of injected fuel increases with the engine speed. Hence, the temperature of exhaust gas rises. The relative low values of exhaust gas temperature at various operating regimes are probably a consequence of a good quality of combustion. One can see, that the variations of the exhaust temperature are not proportional to biodiesel content, an increase in biodiesel content may result in higher temperature at some modes and in lower temperature at other modes. The reason for that is probably due to the fact that fueling is not the same for various fuels at constant rack position.

The measurements of harmful emissions at all modes of the ESC test show that the NO_x, CO, HC, and smoke emissions may generally decrease with higher content of biodiesel, if the injection pump timing is optimized [30]. But it should be noted that at some modes the highest NO_x and CO emissions were obtained with B25. The unpleasant harmful emissions for fuel B25 show that the optimized injection pump timing for fuel B25 is good enough in respect to engine power, torque, fuel consumption but not enough in respect to harmful emissions.

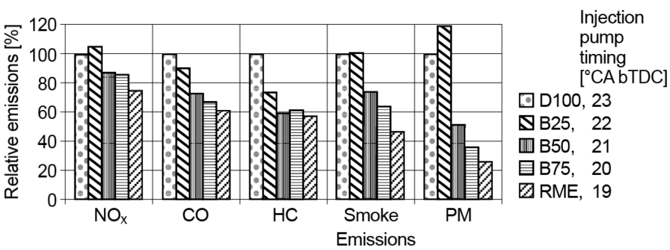

Figure 10. Relative emissions of fuels at optimized pump injection timing, ESC test

By considering the ESC test weighting factors, a comparison of relative emissions of all tested fuels shows that increased biodiesel content may result in significant reduction of all harmful emissions – an exception are the NO_x, smoke, and PM emissions of B25, fig. 10. The smallest harmful emissions were obtained with RME at injection pump timing of 19 °CA bTDC.

Engine tribology characteristics

Finally, it is worthwhile to make some notes on the engine behavior during the test. To perform all the previously described tests, the engine was run on each tested fuel for about 500 hours. During this period, the engine performed completely normally and there were no difficulties regarding engine starting. After the tests, the critical components of the engine were carefully examined. All of them were in a normal condition.

The changes of the most important surface roughness parameters R_a, R_z, and $R_{\max}$ on the pump plunger, pump plunger sleeve, injector nozzle, and injector nozzle sleeve were investigated in the circular and longitudinal direction. The averaged values of these parameters for the first three elements (I-III) were determined before (new elements) and then after

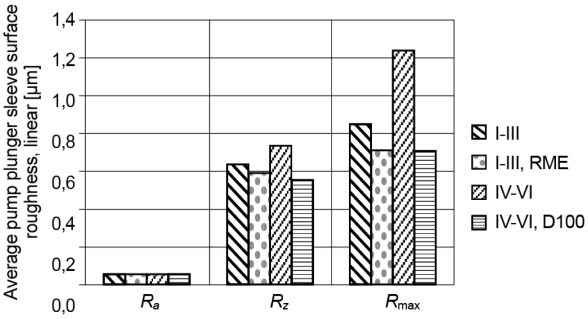

Figure 11. Average pump plunger sleeve surface roughness parameters

500 hours of their usage with RME. The last three elements (IV-VI) were used to make the same measurements, but for the D100 fuel. As an example, the average pump plunger sleeve roughness parameters in the longitudinal direction are presented in fig. 11.

In general one can say that on average RME results in somewhat larger variations of the surface roughness parameters, compared to D100. The differences, however, do not seem to be dramatic.

Conclusions

According to the presented results one can conclude that biodiesel may well be used in mechanically controlled Diesel engines. Of course, the engine needs some adjustments but the required modifications can be done relatively easily and with low costs. If done properly, the engine may exhibit satisfactory performance and good economic and ecological parameters.

Obviously, a Diesel engine may satisfactory be adapted for a particular biodiesel, but the problem is that biodiesels are produced from many different sources, which results in large variations of their properties although all biodiesel fuels fulfill the EN 14214 standard. Even the properties of a single biodiesel type can vary notably in dependence on the region where the plants are grown or on the weather conditions in a particular year. From the experimental results obtained it is evident that good engine set-up requires quite precisely defined fuel properties. Thus, changing one biodiesel for another (similar) one may still cause problems like increased smoke formation, damaged sealing, filter clogging, and so on. A change from diesel to biodiesel therefore has to be done with great care and only if a stable source of some biodiesel with constant properties is available.

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