NO_X EMISSION USING BIODIESEL

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Abstract

Most investigations show that the use of biodiesel results in lower emissions of HC, CO and smoke whereas the emission of NO_x increases. For this reason attention in this paper is focused on the possibility to reduce NO_x emission when using biodiesel fuel. The experiments are performed on an NA diesel bus engine with direct injection M system. The tested fuels are mineral diesel and domestic biodiesel fuel produced from rapeseed.

At first the influences of different fuels on NO_x emission are investigated. The analysis of experimentally obtained results is performed at different engine operating regimes with the injection timing prescribed by the engine producer for mineral diesel fuel. The NO_x emissions and other engine characteristics with biodiesel are compared against those obtained using mineral diesel. In this way the influences of fuel properties on engine harmful emissions, specific fuel consumption, brake thermal efficiency and engine power are investigated.

Furthermore the possibility for reduction of NO_x emission without expensive engine modifications is investigated. Keeping this in mind, the optimal injection pump timing is determined. The experimental results show that the retarded injection pump timing is necessary when using biodiesel in order to reduce harmful NO_x emission without worsening other engine characteristics. During the experiments, the engine was monitored for possible operation problems and carefully examined after the tests.

Keywords: biodiesel, NO_x emission, injection pump timing

1. Introduction

In order to avoid world petroleum crisis and to reduce harmful diesel engine emissions, attention has been directed to find out alternative sources of fuels for diesel engines. 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 [Dorado et al, 2003; Senda et al, 2004]. Compared to mineral diesel, biodiesel fuels have comparable energy density and cetane number, they have little sulfur and much oxygen. However, high viscosity, high molecular weight, low volatility etc. of biodiesel fuels may in some cases lead to problems like severe engine deposits, injector cooking and piston ring sticking.

At this time, most working diesel engines have been developed for operation with mineral diesel fuels. For these engines biodiesel fuels can obviously not be used without any precautions. For this reason, many investigations are necessary to prevent or at least mitigate different engine or environmental problems.

Compared to mineral diesel, biodiesel and biodiesel blends in general show lower CO, smoke and HC emissions but higher NO_x emission and higher specific fuel consumption [Senda et al, 2004; Nabi et al, 2006, Alam et al, 2004, Porai et al, 2004, Senatore et al, 2000].

In some cases biodiesel showed improved engine performance with lower emissions. Thus, biodiesel could potentially meet future emission norms by tuning the engine optimally for these fuels and by using appropriate exhaust post-treatment technology to offset disadvantage of higher

HC and NO_x emissions, without any change in engine hardware [Sinha & Agarwal, 2005]. Another way to reduce NO_x slightly is to apply EGR [Nabi et al, 2006]. Combustion analysis of soy-derived biodiesel also revealed that NO_x emissions were sensitive to the timing or crank angle at which the maximum cylinder temperature and the maximum rate of heat release occurred [Szibist et al, 2005]. A very important factor in engine-out NO_x emission has the injection timing [Kegl, 2006].

In this paper attention is focused on the possibility to reduce NO_x emission when biodiesel from rapeseed is used. At first the physical properties of biodiesel are determined and compared to those of mineral diesel. Furthermore, the difference among experimentally obtained engine characteristics of biodiesel and mineral diesel is investigated considering fuel properties. At the end it is shown that the NO_x emission of tested bus diesel engine using tested biodiesel can be reduced essentially with inexpensive engine modifications.

2 Experiment set-up

The experimental system consists of an engine and electro-dynamometer Zöllner A-350AC, 300kW, air flow rate meter RMG, fuel consumption dynamic measuring system AVL, UHC analyser Ratfisch, NO_x chemoluminiscent analyzer Thermoelectron, O_2 analyzer Programmelectronic, CO analyzer Maihak and smoke meter AVL. The main engine specifications are given in Table 1. This engine is used from exploitation after 500000km and after general renovation. Using a data acquisition system instantaneous pressure in the fuel high pressure tube, instantaneous pressure in the cylinder, the temperatures of fuel, ambient air, intake air, cooling water in and out of engine, oil and the temperature exhaust gasses are measured also.

Table 1. Test engine main specifications

Engine model	MAN D 2566 MUM
Engine type	4 stroke, 6 cylinder in line, water cooled
Injection	Direct injection system with wall distribution (M system)
Fuel injection pump	Bosch PES 6A 95D 410 LS 2542
Displacement	11 413 cm^3
Compression ratio	17.5 : 1
Bore and stroke	125 mm x 155 mm
Max Power	162kW at 2200 rpm

3. Fuel properties

The tested fuels are neat diesel fuel D2, conforming to European standard EN 590 (Slovenian standard SIST EN 590) and neat biodiesel fuel B100, conforming to European standard EN 14214 (Slovenian standard SIST EN 14214). Some measured properties of these fuels are given in Table 2. The biodiesel fuel is produced from rapeseed by Pinus, Slovenia. Some of its specifications are given in Table 3, along with the corresponding EN 14214 standard specifications.

Table 2. Diesel and biodiesel properties

Fuel	**D2**	**B100**
Kinematic viscosity @ 30 ^oC (mm^2/s)	3.34	5.51
Surface tension @ 30 ^oC (N/m)	0.0255	0.028
Calorific value (J/kg)	43800	38177
Cetane number	45-55	> 51

Table 3. Biodiesel analysis

	Biodiesel - Pinus	European standard for Biodiesel, EN 14214
Cetane number	> 51	> 51
Ester content (% m/m)	96.9	> 96.5
Sulfur content (mg/kg)	< 10	< 10
Carbon residue on 10% distillation residue (% m/m)	< 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 (% m/m)	8.5	< 12
Methanol content (% m/m)	0.01	< 0.20

The fuel density is measured with Density meter DMA 35 PAAR. The comparison of fuel density obtained by our experiment at ambient pressure is presented in Figure 1. One can see that the density increases by increasing the content of biodiesel and by decreasing fuel temperatures.

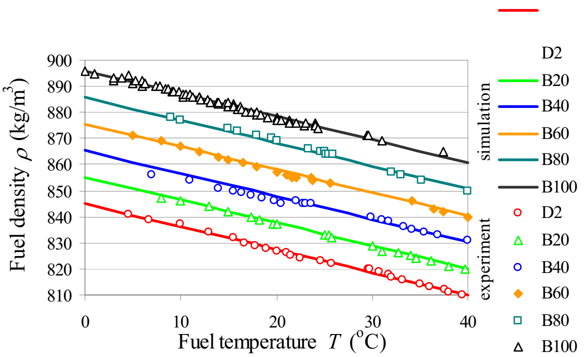

Figure 1. Fuel density at different conditions

The measurement of sound velocity in fuel is based on the principle of pressure wave propagation on a specified length of the HP tube, instrumented by two piezoelectric based pressure transducers located at the opposite sides of the tube. The sound velocity was measured at different pressures up to 400 bar using different fuels. Figure 2 shows the dependence of fuel sound velocity and bulk modulus. They increase with both the fuel pressure and biodiesel content.

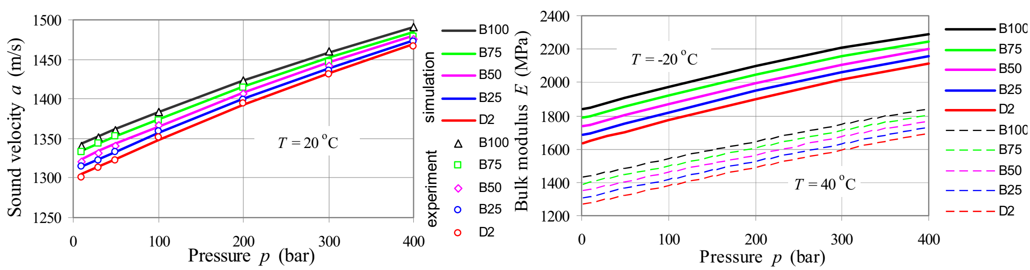

Figure 2 . Sound velocity and bulk modulus of fuels at different conditions

4. Engine characteristics using biodiesel and diesel fuels

Fuel properties, like density, viscosity, sound velocity, bulk modulus, cetane number, oxygen content and so on, have significant effects on start of injection and other injection characteristics.

By considering the weighting factors of the 13 modes of ESC test, the parts of fuelling of different injection phases with respect to fuelling per stroke, are presented in Figure **3**. This figure shows the injection phases as

- needle opening phase (A)
  - during first 10% of injection duration (A1)
  - from end of A1 till the end of the opening phase (A2)
- open needle phase (B)
- needle closing phase(C)
  - from start of closing phase till the begin of C2 (C1)
  - during the last 10% of injection duration (C2).

The presented results show, that the fuelling A1 is the highest with D2, meanwhile the fuelling C2 is the smallest with B25 and B75. The fuelling during needle lifting as well as needle closing decreases with increasing content of biodiesel.

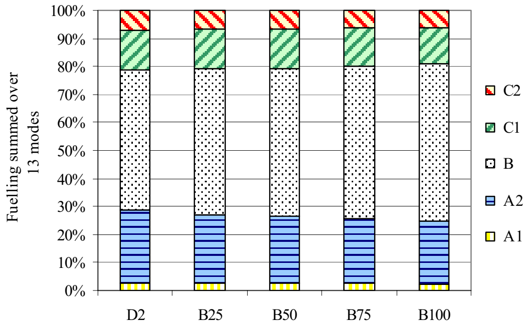

Figure 3. Fuelling in different phases of injection summed over all 13 ESC modes

In order to be able to compare the behavior of different fuels, the relative fuellings at several phases of injection, summed over all 13 ESC modes, are calculated. The most interesting phases (A, A1, C, and C2) are compared in Figure **4**. One can see that by increasing biodiesel content all of the compared quantities decrease. This offers a good opportunity to reduce NO_x as well as smoke and PM emissions.

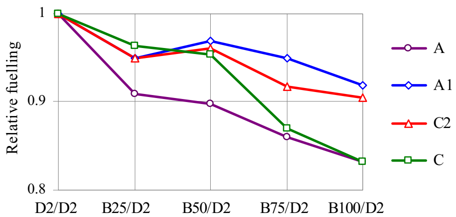

Figure 4. Relative fuelling of injection summed over all 13 ESC modes

Besides of good behavior of biodiesel with regard to fuelling in individual phases of injection process, the mean injection pressure as well as the mean injection rate, summed over all 13 modes, is presented in Figure **5**. By considering the weighting factors of the 13 modes of ESC test, it is evident that the mean injection rate and pressure increase almost linearly with higher content of biodiesel. The higher bulk modulus and kinematic viscosity of biodiesel result in higher mean injection pressure for B100 with respect to D2 fuel.

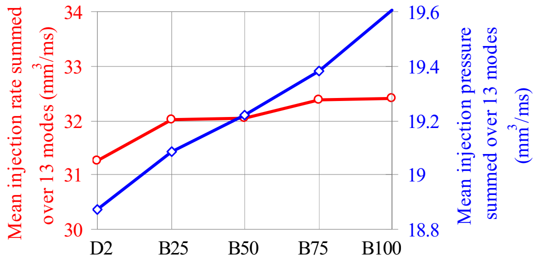

Figure 5. Mean injection pressure and mean injection rate summed over all 13 ESC modes

From Figures **4** and **5** it seems that a suitable fuel regarding the harmful NO_x and smoke emissions is the employed neat B100 fuel, because of the smallest fuel quantity at the start as well as at the end of injection and because of higher mean injection pressure as well as higher mean injection rate. It has to be noted that injection delay reduces with B100 at practically all operating modes because of higher values of sound velocities. For this reason the time between the start of fuel delivery and the start of fuel injection is reduced. Therefore, the injection timing increases. This leads to the fact that the injection timing has to be retarded by using biodiesel blends in the diesel engine.

Fuel properties have significant effects on start of combustion and premixed and diffusion burn peak and over these on the emission and engine performances also.

The influence of fuel on engine characteristics is tested by running the engine with prescribed injection pump timing for D2 fuel. The comparison of some engine characteristics of D2 and B100 on idle and full load conditions (EC characteristics) is shown on Figure 6. At full load 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% in the whole engine speed regime. On the other hand, the temperatures of exhaust gases $T_{g,e}$ are lower by about 30°C, which may be due to the lower calorific value of B100.

For comparing the fuels having different calorific values, the brake thermal efficiency is presented on Figure 6 also. This efficiency is defined as the actual effective power divided by the amount of fuel chemical energy (fuel consumption rate x calorific value). In spite of higher effective specific fuel consumption g_e for B100 fuel at all engine speeds, the brake thermal efficiency is practically the same for both fuels because of different calorific values.

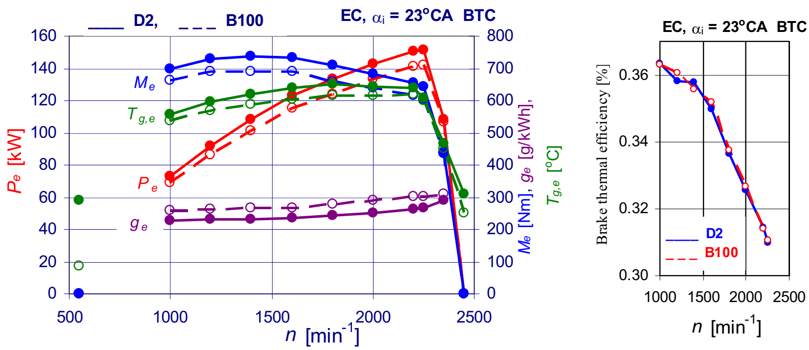

Figure 6. Influence of fuel on engine performance at idle and full load conditions

By comparing the emissions of NO_x, smoke, CO and unburned HC, it is evident from Figure 7 that the NO_x emission increases at full load when using B100, meanwhile it decreases at idle. An opposite effect is observed for the smoke. The CO and HC emissions are lower when using B100 almost at all engine speeds, except at low ones. With respect to increasing engine speed, the CO emission slightly decreases, meanwhile the HC emission is practically the same. At idle, the CO emission is much higher that at full load. The lower CO, HC and smoke emissions when using B100 are likely due primarily to the fact that biodiesel contains more oxygen, which helps to oxidize these combustion products in the cylinder.

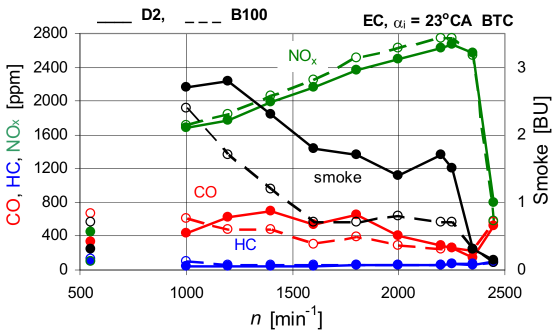

Figure 7. Influence of fuel on engine emissions at idle and full load conditions

When using B100 the NO_x emission is higher at all loads, except at 50% load, where the NO_x is practically the same for both fuels, Figure 8. The larger NO_x formation for B100 resulted because of higher oxygen content available in B100 to react with the nitrogen component in the surrounding air. As already is discussed, by considering the fuel consumption rate, the NO_x emission index decreases by increasing the engine speed almost at all loads. At 50% partial load the NO_x emission index is higher when using D2 at several engine speeds, meanwhile at all other loads the differences between both fuels are lower.

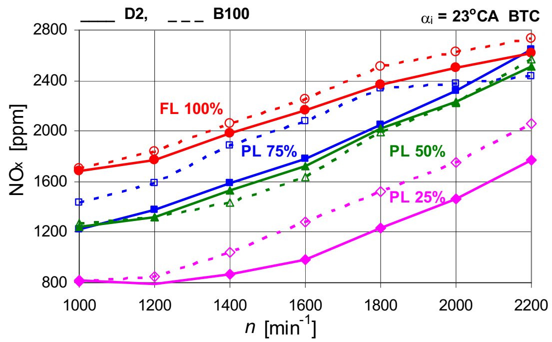

Figure 8. Influence of fuel on NO_x emission at partial loads

5. Engine characteristics at different injection timing

The influence of injection pump timing on engine characteristics is tested for B100 fuel. The tested values of pump timing $\alpha_i\,(^{\circ}\mathrm{CA\ BTC})$ in degree of cranckshaft angle before top center are

23, 21, 20, 19, 18 and 17. As an example, the effect of these pump timings on the pressure in cylinder is presented on Figure 9. By the retarded pump injection timing the injection occurs closer to the end of compression stroke. Therefore, the peak in-cylinder pressure decreases with retarded injection pump timing and the peak moves away from the top center. As it is evident, the maximum in-cylinder pressure decreases by about 20 bar when pump injection timing changes from 23 °CA BTC to 17 °CA BTC.

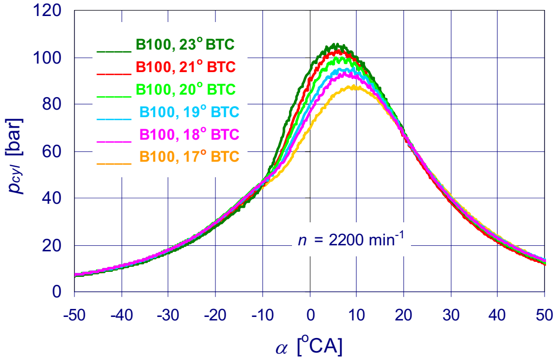

Figure 9. Influence of injection pump timing on cylinder pressure at rated conditions

Retarding the pump injection timing reduces the NO_x emissions, Figure 10, since later injection leads to lower combustion temperatures, and the strong temperature dependence of the NO_x formation ensures a reduction in NO_x, despite the increase in combustion duration associated with the retarded injection. Figure 10 shows, that NO_x emission decreases significantly till $\alpha_i = 19^\circ \text{CA BTC}$ while further retarding has a minor influence.

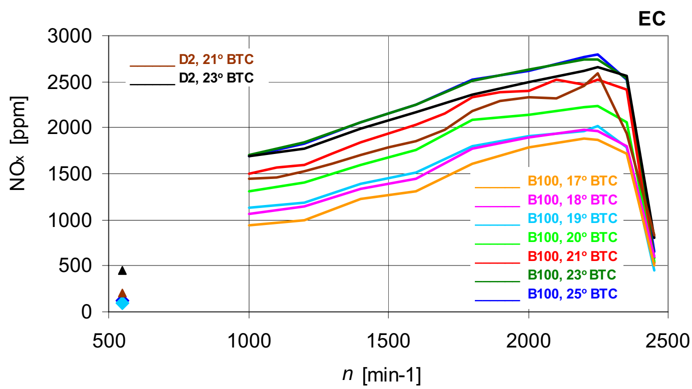

Figure 10. Influence of injection pump timing on NO_x emission at idle and full load condition

Figure 11 presents a comparison of D2 at prescribed pump timing with B100 at different pump timing values at rated conditions. 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.

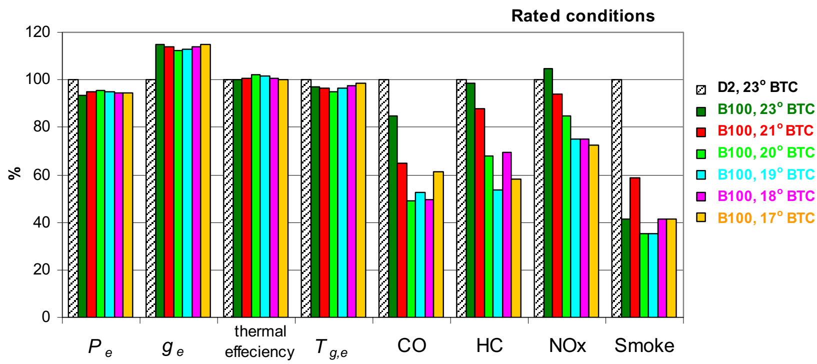

Figure 11. *Influence of injection pump timing and fuel on engine characteristics at rated condition*

Figure 12 shows that in all 13 characteristic ESC points NO_x emission of B100 is lower as of D2.

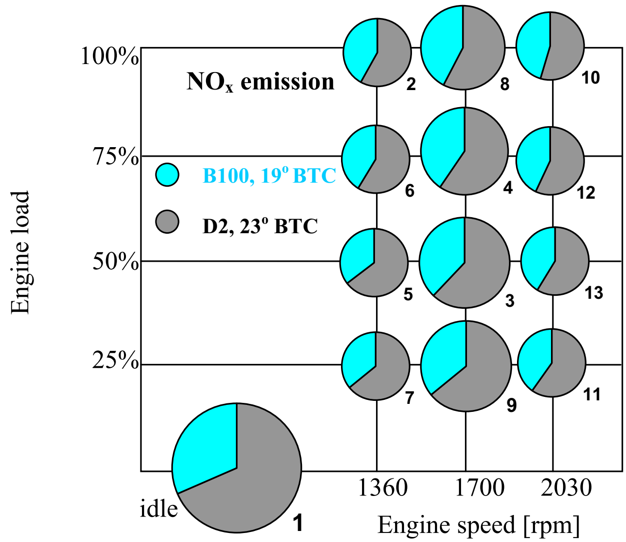

Figure 12. *NO_x emissions index of B100 and D2 at ESC points*

According to the ESC test the individual characteristic points are weighted by corresponding factors that take into account the importance of individual engine regimes. By considering the ESC weighting factors, the reduction of emissions of B100 with optimized injection pump timing $\alpha_i = 19^{\circ}\,\mathrm{CA\ BTC}$ compared to D2 with standard $\alpha_i = 23^{\circ}\,\mathrm{CA\ TDC}$ is shown on Figure 13.

Evidently all of the emissions as well as emission indexes reduced essentially. The results obtained indicate that the employed biodiesel could represent a very attractive fuel, at least for engines similar to the one used on the test.

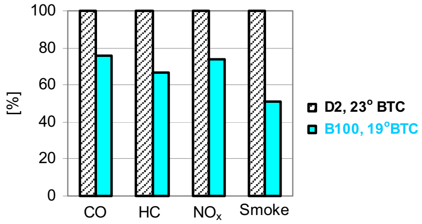

Figure 13. *Emissions of D2 and B100 considering ESC test weighting factors*

Finally, it is worth to make some notes on the behavior during the test. In order to perform all the above described tests, the engine has run on B100 fuel for about 60 hours. During this period the engine performed completely normally. 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.

5. Conclusions

Experiments were performed on bus engine MAN D 2566 with direct injection M system with prescribed injection pump timing of $\alpha_i = 23^{\circ}\,\mathrm{CA\,TDC}$ for D2 fuel. The tested biodiesel was net biodiesel B100 produced from rapeseed oil. In order to find the optimal injection pump timing for B100 attention was focused on harmful emissions while keeping other engine performances at acceptable levels. According to the results, the following conclusions can be made:

- All of the engine characteristics at all engine regimes change significantly when the D2 fuel is replaced by B100. These variations, however, depend significantly on the fuel injection pump timing.
- It is possible to find optimal injection pump timing for B100 so that all harmful emissions are reduced while keeping the effective power, effective specific fuel consumption, temperature of exhaust gases, cylinder pressure and other important engine characteristics at acceptable level.
- The optimized injection pump timing of $\alpha_i = 19^{\circ}\,\mathrm{CA\,BTC}$ for B100 fuel offers a reduction of CO and NO_x emissions by about 25%, a reduction of HC emissions by about 30% and a reduction of smoke emissions by about 50% with respect to ECS test and the corresponding weighting factors.
- Because of the lower heating value of B100 fuel, the engine effective power is reduced by about 5% and the specific fuel consumption is increased by about 10%, while the thermal efficiency is practically the same for both fuels. The temperatures of exhaust gases as well as the in-cylinder pressures were lower than those obtained with D2.
- The engine performed normally during the tests. No problems could be observed on any of the critical components of the engine.

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