Engine and Road Tests of Blends of Biodiesel and Diesel Fuel

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The utilization of alternative fuels in transport is very important due to dependence on petroleum, increaseasing in number of vehicles and as consequence high CO_2 emission. The investigations of biodiesel as an alternative fuels include raw materials, production, quality (pure or in mixture with diesel), engine and vehicle tests and determining compliance with sustainability criteria. In this paper, the investigations were performed with the biodiesel prepared from damaged sunflower seed and used cooking oils using the latest technology for the purification of biodiesel from methanol based on ion exchange principle. The main target was to examine the possibility of utilisation of different biodiesel and diesel blends in Compression Ignition (CI) engines and their influence on engine power, torque, fuel consumption and exhaust emission. The results of standard and non-standard investigations and engine and vehicle tests of biodiesel and diesel blends are presented.

Keywords: *biodiesel, diesel, mixture, engine tests, road tests, exhaust emission*

1. INTRODUCTION

Transport is an important sector of energy consumption. This sector is completely depended on petroleum derived supply and, at the same time it is significant source of CO_2 emission. Accordingly, in recent years, the efforts to more broadly apply alternative energy sources for transportation are made in the world that will contribute to the reduction of dependency of transport of petroleum products and reduction of CO_2 emissions.

Possibilities of alternative energy sources application were predicted at the beginning of the last century by motor designers, Ford for alcohol and Diesel for vegetable oil. Over the last twenty years, investigations of the possibilities of application of biodiesel as an alternative fuel have started, primarily due to limited oil reserves, periodical reductions in oil supplies by OPEC countries and rise of oil prices on the world market [1,2], as well as because of large agricultural surpluses in some European countries. In addition, in recent years the application of biodiesel as an alternative fuel for IC engines is more important because of CO_2 emissions reduction. All this resulted in the adoption of Directive 2003/30/EC [3] which has, for the first time in the form of an official document, defined the use of biofuels and other fuels that originate from renewable energy sources for traffic. According to this Directive, it was scheduled for the end of 2005 to ensure the replacement of 2% of fossil fuels in traffic, and by the end of 2010, 5.75%, measured on energy content. During 2009, two important documents: Directive and Directive 2009/28/EC 2009/30/EC [4,5] were adopted. These directives were made based on monitoring the situation in the entire sector of energy and environment in the EU, as well as in the traffic. According to the Directive 2009/28/EC it is scheduled that by the end of the 2020 the use of renewable energy in transport (biofuels, electricity and hydrogen produced from renewable sources) is at least 10% of the total fuel consumption in the EU. The goal defined in this way has influenced the changes in the quality of diesel fuel, so that according to the Directive 2009/30/EC maximum content of biodiesel was increased to 7% by volume compared to 5% *V/V* as it was defined by previous Directive 2003/30/EC [5], which led to amendments of the European standard for diesel fuel EN 590:2009. According to EN 590:2009 diesel fuel with biodiesel content to 7 % *V/V* does not need to be specifically marked, while in the case of higher content than specified it must be clearly stated (highlighted). In addition, according to the Directive 2009/30/EC, additional requirements are introduced such as meeting the criteria of sustainability in the process of biofuel production and methods for determining the CO_2 emissions, and CO_2 emission reduction that is accomplished by their use. Biodisel is produced by the transesterification process from vegetable oils, animal fats and used edible oil. According to FAO classification, worldwide there are 22 plant species in agricultural production that are used for production of biodiesel oilseed plants, pulses, textile plants, woody and tropical plants [6-8]. Of all listed plant species, in Europe and the U.S. oil seed plants - canola, soybeans and sunflowers are mostly used, while in Asia Jatropha and palm oil are used [9]. Most modern technologies for producing biodiesel from herbal oils (in composition that are triglycerides of higher fatty acids) is based on transesterification by alcohols of short sequence (usually methanol, ethanol or isopropanol), with methyl esters of fatty acids as the final product that are very similar to diesel fuel by their characteristics. Raw

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materials for production, and biodiesel production processes significantly affect the final quality of this fuel that must be in accordance with the requirements of standards (EN 14214, ASTM 6571-3). It is particularly important to emphasize that all experimental research on engines with biodiesel (pure or mixed with diesel fuel) must satisfy the requirements of these standards, so that the results would be applicable in practice [10]. The application of biodiesel as an alternative fuel in the engines is the subject of many investigations in order to ensure reliable operation while meeting the appropriate requirements in terms of emission [11,12]. All previous investigations indicate that it is possible to use biodiesel in quantities up to 30% *V/V* mixed with diesel fuel without any modifications to the engine, and the higher content requires some modifications [5]. Research of biodiesel includes testing of:

1. biodiesel characteristics
   a. viscosity and impact on quality of atomization,
   b. lubricity and reduced wear and tear effect on the material of injectors and high pressure pump,
   c. low temperature characteristics of fuel and reliable operation in low temperature conditions, selection of appropriate additives
   d. stability during storage and possibilities for improvement
2. engine and vehicle tests
   a. vehicle acceleration,
   b. vehicle elasticity,
   c. maximum speed,
   d. fuel consumption and driveability check-out and behaviour of the vehicle on the road.

This paper presents the results obtained during the research of possibilities of using different diesel and biodiesel blends in CI engines. The aim of the research is to determine the influence of different fuel blends on engine characteristics and materials used for vehicles produced in Zastava Vehicles. During the past decade in EU there is a practice to use diesel and biodiesel mixture in the transport sector. This practice is guided by EU Directive 2009/28/EC for the promotion of using biofuels or other renewable fuels for transportation. Also the EU standards for diesel fuel quality allowed adding 7-10% (*V/V*) of biodiesel without any labeling. The Republic of Serbia is on the begging of that practice, and diesel fuel produced in domestic refineries is not a blend with biodiesel yet. Investigations presented in this paper are important because they make possibilities to evaluate the influence of blends made of diesel and biodiesel fuel from Serbia market on engine characteristics in exploitation.

2. EXPERIMENTAL TESTS

2.1 Fuel

For investigations Euro diesel (ED) and biodiesel (BD) were used. Regarding the applicable regulations in the Republic of Serbia two different qualities of diesel fuel are defined (diesel fuel of the older generation: D2 diesel fuel and a modern fuel – euro diesel). Euro diesel (ED) was selected for the tests as a fuel corresponding to European fuel quality. A sample of biodiesel (BD) was prepared from damaged sunflower seed and used cooking oils using the latest technology for the purification of biodiesel from methanol based on ion exchange principle. Investigations included tests of physical and chemical characteristics of clean fuels (ED and BD) and a mixture of ED with 5, 10, 15 and 20% (*V/V*) BD.

2.2 Engine tests

A single-cylinder diesel engine LDA 450 (manufacturer of 21. Maj, Beograd) was used for engine tests. The engine was tested in the Laboratories of the Faculty of Mechanical Engineering Kragujevac. All tests were performed at full engine load at two different engine speed (1,600 and 2,688 min^{-1}). Investigations of the engine working cycle were carried out with clean fuels (ED and BD). The engine was tested on an electric eddy current engine dynamometer SCHENCK U1-16. Investigations included a recording of in-cylinder pressure diagrams and emission of toxic components. The transducer for pressure recording was positioned on a cylinder head.

2.3 Research of the engine characteristics at the test stand

Research has been performed on the test stand using 188 A9.000 engine with swapped volume 1248 cm^3. Full load characteristics (power, torque and specific fuel consumption) were recorded according to the internal standards for comparative and development research (St. 7.A6400) and flat road load characteristics (St. A.642.). The test engine was equipped with standard equipment (intake and exhaust system, air, fuel and oil filters, etc.). The cooling system already installed on the test stand was used for engine cooling during the tests. Engine oil temperature was controlled by an additional cooling system. Before conducting any test, test engine was run in on the test bench in the period of 6 hours per cycle according to St.7.A6000 and reading and control of basic parameters of the engine were made.

The engine was tested in the Laboratories of Zastava Vehicles, Department for Vehicles Development, Kragujevac. Investigations were carried out on an electric eddy current engine dynamometer SCHENCK W-130. The schematic view of measuring and test installation is shown in Figure 1.

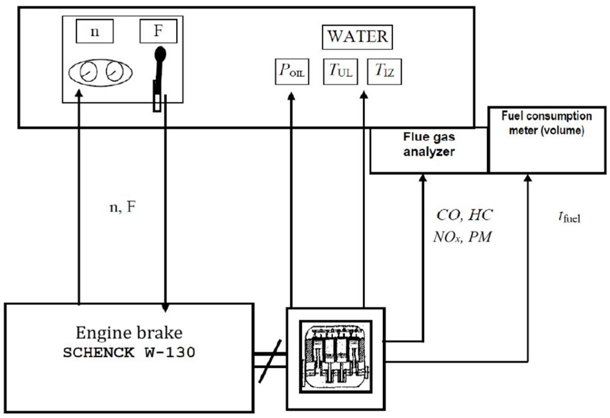

Figure 1. Schematic view of measuring and test installation

The following values were measured during the tests: engine speed, force on the brakes, time of fuel efflux from the tank, coolant inlet and outlet temperature and oil pressure in the engine.

Investigations of the engine characteristics on the test stand were carried out with pure fuels (ED and BD), as well as blends of ED with 5, 10, 15 and 20% (*V/V*) BD.

2.4 Road tests

Tests were conducted on the vehicle FIAT PUNTO with built in standard 1,3 diesel engine. The measuring system DATRON that utilises non-contact measurement of distance, time, speed and acceleration was used to record vehicle performances (Figure 2). Performances of the vehicle were recorded on a flat with slope of ±0.7% and the wind speed V_{max} = 3 m/s. To eliminate the influence of slope and wind, recordings were made in both directions.

Tests were conducted with pure fuels and blends of ED with 5, 10, 15 and 20% (*V/V*) of BD and comprised:

- vehicle acceleration,
- vehicle elasticity,
- maximum speed,
- fuel consumption and
- drivability check-out and behaviour of the vehicle on the road.

Figure 2. Measuring system Datron for recording vehicle performances

Accelerations of the vehicle were recorded in regimes from 0 to 100 km/h, and the elasticity from 40 to 120 km/h. Fuel consumption was recorded in the same conditions as performances with the mass balance in all gears and at constant regimes 90 and 120 km/h.

3. TEST RESULTS

3.1 Fuel

Test results for the most important characteristics of pure fuels (ED and BD) from the aspect of utilization in engines, as well as allowed values according to the appropriate standards and methods used during testing are presented in Tables 1 and 2, and for the blends of ED and BD in Table 3.

Based on performed test, the following can be concluded:

- ED fulfils all requirements defined by standard SRPS EN 590.
- BD does not fulfil requirement of the standard for flash point. Extremely low flash point is a consequence of the presence of residual methanol from the production process. The reasons for the lack of methanol from the FAME separation can be due to insufficiently high temperature in that phase of production, or insufficiently long flushing of raw BD. In subsequent research stages of biodiesel production special attention will be devoted to solving this problem. Anyway, since the flash point of BD is prescribed in order to ensure safe handling, transport and storage, this lack (non-fulfillment of standard requirements) does not affect performance of the engine using this fuel.
- The tested sample of BD meets the requirements for CFPP during summer period, but does not meet the requirements for CFPP during winter period. In winter it is necessary to add the appropriate additives for pure bio diesel to improve low-temperature characteristics.
- The tested blends of ED and BD meet all requirements of standards for diesel fuel EN 590 for the following characteristics: density, corrosion, viscosity and heating value. Blends with 5 and 10% (*V/V*) of BD meet the requirement for CFPP and in the winter (the value is at the allowed limit), while blends with 15 and 20% (*V/V*) have somewhat higher value of CFPP than allowed by the standard for winter period.
- The tested blends of ED and BD do not fulfil requirement of the standard for flash point (except for the mixture with 5% (*V/V*) BD) as a result of low flash point of the sample of pure BD and the presence of methanol in the sample of pure BD.

In accordance with the standard EN 590:2010 it is allowed to add 7% (*V/V*) of BD in diesel fuel without special labeling, and this blend fully meets all the requirements of mentioned standard. The blend of diesel fuel with 20% *V/V* BD is a mixture which should be interesting to the consumers and which would be used for application in specific machinery (agricultural machines, fleet of the public companies, etc.).

3.2 In-cylinder measurements and analysis

Experimentally obtained indicator diagrams and self developed software were used for determination of combustion rates shown in Figures 3 and 4. In these diagrams heat release was calculated with the real isentropic coefficients which are defined by the used software. In the case of engine operating with BD, due to higher cetane number, a shorter period of ignition delay was observed and a smaller amount of fuel burned during the period of uncontrolled combustion which, resulted in lower values of the pressure rise gradient [14,15].

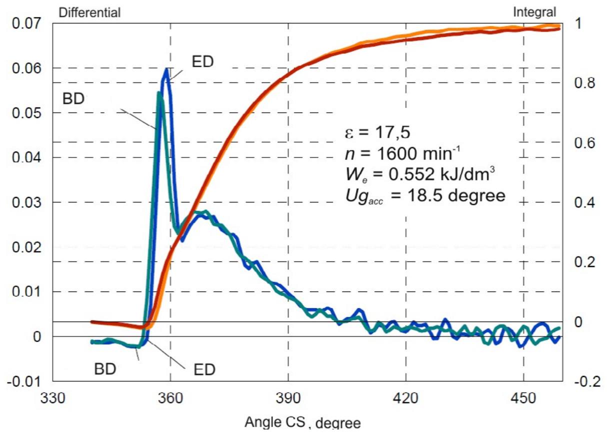

Figure 3. Integral and differential combustion rate for biodiesel and commercial diesel fuel at full load, for engine speed 1600 min^{-1} [14, 15].

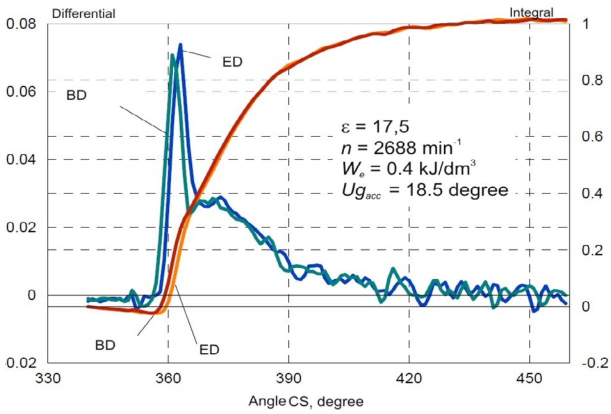

Figure 4. Integral and differential combustion rate for biodiesel and commercial diesel fuel at full load, for engine speed 2688 min^{-1} [14, 15].

Results of pollutant emissions are shown in Figure 5. Based on the obtained results, it can be observed that in the case of operation with BD there are significant changes of pollutant emissions:

- carbon monoxide (CO) is decreased by about 52%,
- unburned hydrocarbon is decreased by about 55%,
- particulate matter (PM) is decreased by about 44%,
- nitrogen oxides is increased by about 5.7%.

Emission reduction of CO, unburned hydrocarbon and PM are caused by the presence of oxygen in used fuel blends, which contributes to more efficient combustion process, higher combustion temperatures and increasing NO_x emissions.

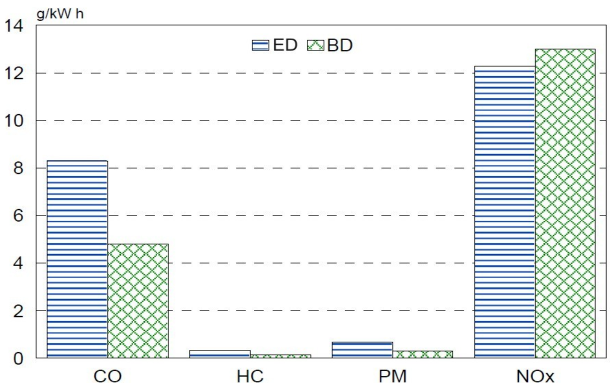

Figure 5. The values of emission of toxic components obtained by the European Steady-state Cycle (ESC), for engine operating with compression ratio of 17.5, with ED and BD [14, 15].

3.3 Testing of the engine characteristics at the test stand

Figure 6 shows engine full load characteristics of the engine 188 A4.000, and in Table 4, the maximum value of power, torque and minimum fuel consumption with pure fuel (ED) and blends of ED and BD are given. Figure 7 shows the engine flat road load characteristics recorded in the fourth gear.

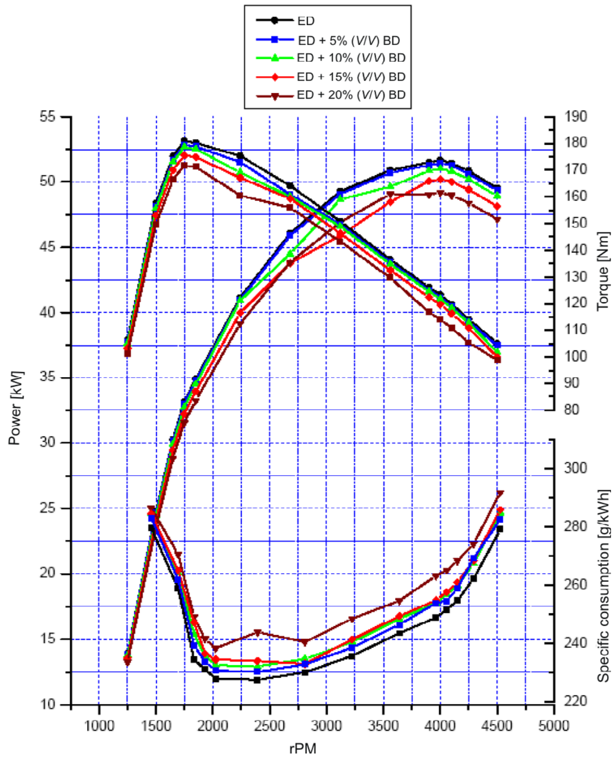

Figure 6: Diagram of engine full load characteristics recorded with ED and blends of ED and BD

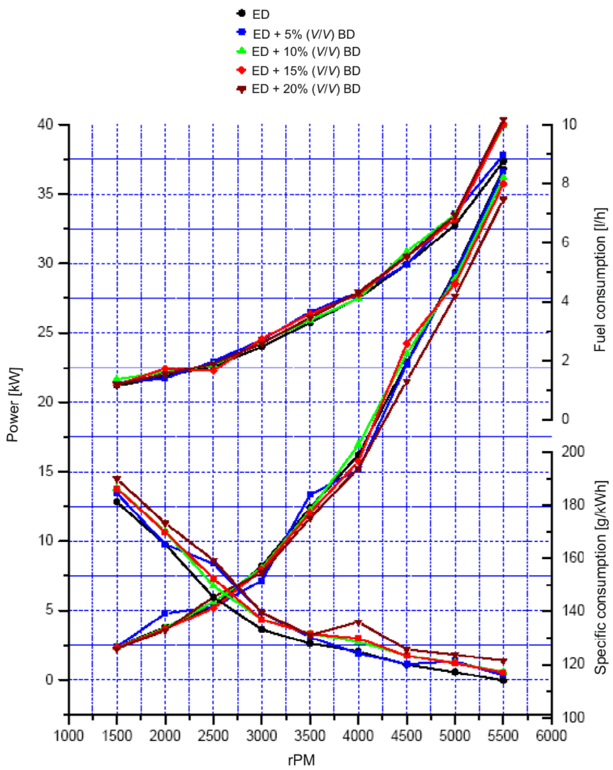

Figure 7: Comparative engine flat road load characteristics recorded for operation with ED and blends of ED and BD

Analyzing the results of the pure ED fuel and blends of ED and BD it is visible that engine full load characteristics (power curve, torque and specific fuel consumption) for operation with blends has a similar character as the curves recorded for operation with pure fuel. Increasing the amount of BD in the ED is accompanied by decreased power and torque with simultaneous rise of the specific fuel consumption. The maximum decrease in power (4.8%) and torque (5.0%) is recored for mixture with 20% BD compared to base fuel (ED). At the same time, minimum specific fuel consumption is increased by about 10 g/kWh, but this is not comparable due to the different heating values. The increase of fuel consumption is lower than the decrease of heating value as a consequence of the oxygen content in BD and lower excess air for combustion. From the diagram of engine flat road load characteristics it can be seen that the power curves, specific and liter consumption recorded with a pure fuel are of similar character as the curves recorded with blends of ED and BD. Rise of the amount of BD in a mixture with ED is fraught with a slight increase in specific fuel consumption.

3.4 Road tests

Test results for vehicle acceleration are shown in Figures 8 and 9 and the results of consumption in Figure 10 and in Table 5.

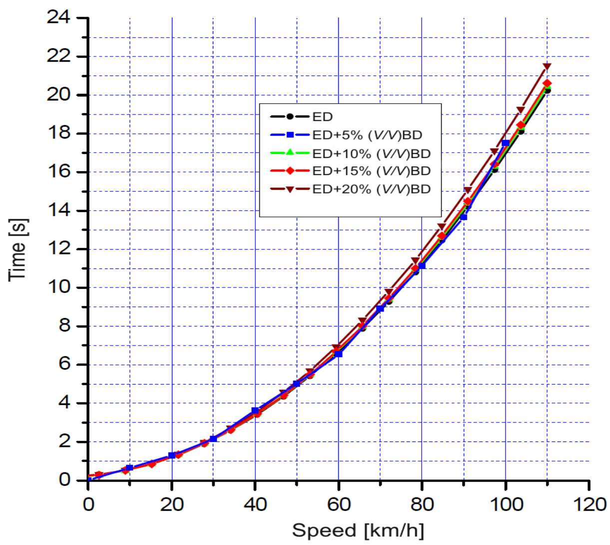

Figure 8. Vehicle acceleration from 0 to 100 km/h

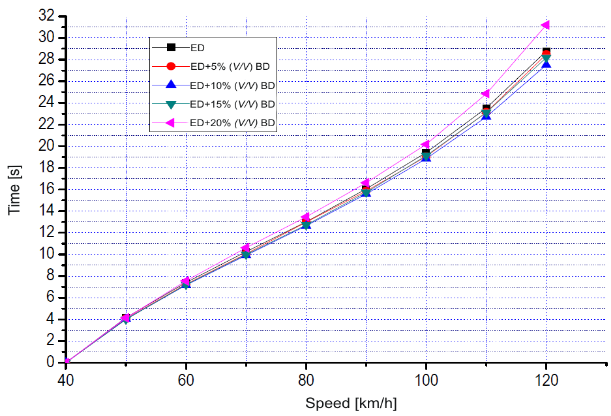

Figure 9. Vehicle acceleration from 40 to 120 km/h

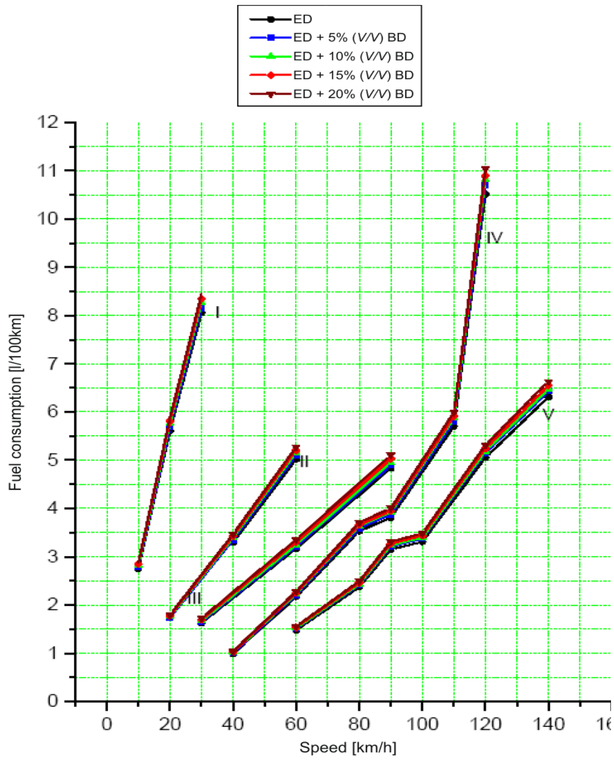

Figure 10. Fuel consumption of vehicle with ED and blends of ED and BD in all gears

Analyzing the results of the road tests with pure fuel ED and blends of ED and BD, it can be observed that adding only 5% *V/V* BD slightly affects the acceleration and engine elasticity, while concentration of 20% *V/V* BD significantly worsens vehicle performance and engine elasticity, with slightly higher fuel, consumption. The character of the fuel consumption curves in all gears with blends of ED and BD is similar to the character of the curves recorded with a pure fuel ED.

4. CONCLUSION

Based on investigations performed, and results obtained for the blends of biodiesel (originated from damaged sunflower seed and used cooking oils) and diesel fuel it can be concluded as follows:

- mixture of diesel with 5% *V/V* of biodiesel complies with all requirements for diesel fuel and it could be used in all weather conditions as a fuel for CI engines without any additives. In accordance with the current standard for diesel fuel (SRPS EN 590) this mixture could be used on the market and such a fuel would be sold as EURO DIESEL FUEL (marking that it contains 5% *V/V* of biodiesel is not necessary because this standard permits utilization of up to 7% *V/V* of biodiesel in diesel fuel without special marking);
- the process of biodiesel production has to be improved with the final goal to comply with the requirement for flash point (necessary for blends with the content of biodiesel 10% *V/V* and more). The problem of low flash point is the consequence of higher content of methanol in biodiesel. There are two solutions for this problem, to increase the temperature during methanol separation phase, or to extend the period of separation;

- blends of diesel with 15 and 20% *V/V* of biodiesel can not be used without addition of additives for the improvement of CFPP during the winter period.

The obtained diagrams of the combustion rates (Figure 4) with pure fuels (diesel and biodiesel) have shown better characteristics of combustion process with pure biodiesel (shorter period of ignition delay, smaller amount of fuel burned during the period of uncontrolled combustion and lower gradient of pressure rise), which could be explained with higher values of cethane number for BD. During these tests, the lower emissions of CO, HC and particulates are recorded for BD due to the higher oxygen content and more complete combustion (Figure 5), but at the same time, due to the higher combustion temperatures, emission of NO_x is increased.

Analyzing the test results, it can be observed that the curves of engine power, torque and fuel consumption are approximately identical for mixture with 5% of BD and with pure ED (Figures 6, 7 and 10). For other investigated blends there is deviation in all analysed characteristics compared to the pure ED. The minimum values for power and torque are obtained for mixture with 20% BD, and at the same time the highest fuel consumption is recorded.

Related to the vehicle acceleration it can be concluded (Figures 8 and 9) that addition of BD into pure ED up to 15% make no changes in acceleration from 0 to 100 km/h and from 40 to 120 km/h, while addition of 20% BD lead to the decline of both accelerations.

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ТЕСТИРАЊА МОТОРА И ДРУМСКИ ТЕСТОВИ МЕШАВИНА БИОДИЗЕЛ И ДИЗЕЛ ГОРИВА

Душан Несторовић, Владимир В. Јовановић, Небојша Г. Манић, Драгослава Д. Стојиљковић

Коришћење алтернативних горива у саобраћају је веома важно због зависности од нафте, великог пораста броја возила и као последица тога, високе емисије CO2. Истраживања биодизела као алтернативног горива обухватају сировине, производњу, квалитет (чисто или у мешавини са дизелом), моторска и возилска испитивања и одређивање усклађености са критеријумима одрживости. У овом раду су приказани резултати истраживања обављених са биодизелом

припремљеним од оштећениh семенки сунцокрета и отпадног уља за кување коришћењем најновије технологије за пречишћавање биодизела од метанола засноване на принципу јонске размене. Главни циљ је био да се испита могућност коришћења различитих мешавина биодизела и дизела у дизел моторима и њихов утицај на снагу мотора, обртни момент, потрошњу горива и издувну емисију. Приказани су резултати стандардних и нестандардних моторских и возилских испитивања мешавина биодизела и дизела.

Table 1. Test results for pure diesel fuel

Characteristic	Unit	ED	Standard SRPS EN 590	Method
Density at 15 °C	kg/m^3	825	820-845	SRPS ISO 12185
Flash point	°C	65	above 55	SRPS ISO 2719
Copper corrosion	-	1a	Class 1	SRPS ISO 2160
CFPP	°C	-11	max -10*	SRPS B.H2.412
Viscosity at 40 °C	mm^2/s	2.76	2-4.50	SRPS ISO 3104
High heating value	MJ/kg	45.12	not defined	SRPS B.H8.318

*required in winter period (November 16, to March 15)

Table 2. Test results for pure biodiesel

Characteristic	Unit	BD	Standard SRPS EN 14214	Method
Density at 15 °C	kg/m^3	884	860-900	SRPS ISO 12185
Flash point	°C	27	min 120	SRPS ISO 2719
Copper corrosion	-	1a	Class 1	SRPS ISO 2160
CFPP	°C	-3	max -10*	SRPS B.H2.412
Viscosity at 40 °C	mm^2/s	4.26	3.5-5.0	SRPS ISO 3104
High heating value	MJ/kg	38.62	min 35.00**	SRPS B.H8.318

* required in winter period (November 16, to March 15)
**according to the standard SRPS EN 14213

Table 3. Test results for characteristics of ED and BD blends

Characteristic	Unit	Blend			
		ED + 5% (*V/V*) BD	ED + 10% (*V/V*) BD	ED + 15% (*V/V*) BD	ED + 20% (*V/V*) BD
Density at 15 °C	kg/m^3	834	836	838	841
Flash point	°C	60	49	35	34
Copper corrosion	-	1a	1a	1a	1a
CFPP	°C	-10	-10	-9	-9
Viscosity at 40 °C	mm^2/s	2.80	2.89	2.95	2.98
High heating value	MJ/kg	44.15	44.12	43.88	43.52

Table 4: Max. values of power, torque and minimum specific fuel consumption

Fuel	Power [kW]/rpm	Torque [Nm]/ rpm	Specific consumption [g/kWh]/rpm	Power difference [%]	Torque difference [%]
ED	51.66/4000	180.85/1750	231.12/1750	/	/
ED +5 % *V/V* BD	51.45/4000	179.49/1850	230.32/2240	0.40	0.8
ED +10 % *V/V* BD	51.01/4100	178.57/1750	232.176/2680	1.26	1.3
ED+15 % *V/V* BD	50.21/4000	172.52/1750	233.05/2680	2.80	4.6
ED +20 % *V/V* BD	49.19/3900	171.82/1850	240.59/2680	4.80	5.0

Table 5: Fuel consumption of vehicle with ED and blends of ED and BD at 90 and 120 km/h in 5th gear

Velocity [km/h]	Fuel				
	ED	ED +5 % (*V/V*) BD	ED +10 % (*V/V*) BD	ED +15 % (*V/V*) BD	ED +20 % (*V/V*) BD
	Fuel consumption [dm^3/100 km]				
90	3.2	3.2	3.3	3.4	3.4
120	5.1	5.2	5.3	5.4	5.4