NEW ENGINE METHOD FOR BIODIESEL CETANE NUMBER TESTING

by

Radivoje B. PEŠIĆ, Aleksandar Lj. DAVINIĆ, and Stevan P. VEINOVIĆ

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Substitution of fossil fuels with fuels that come from part renewable sources has been a subject of many studies and researches in the past decade. Considering the higher cost and limits of production resources, a special attention is focused on raising the energy efficiency of biofuel usage, mainly through optimization of the combustion process. Consequently, in biofuel applications, there is a need for determination of auto-ignition quality expressed by cetane number as a dominant characteristic that influences combustion parameters. The fact that the method for cetane number determination is comparative in nature has led us to try to develop substitute engine method for cetane number determination, by the use of the available laboratory equipment and serial, mono-cylinder engine with direct injection, DMB LDA 450. Description of the method, results of optimization of engine's working parameters for conduction of the test and method's Accuracy estimation are given in the paper. The paper also presents the results of domestic biodiesel fuels cetane number testing with the application of described engine method, developed at the Laboratory for internal combustion engines and fuels and lubricants of the Faculty of Mechanical Engineering from Kragujevac, Serbia.

Key words: *auto-ignition, biodiesel, cetane number, engine test method*

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, sunflower oil, rapeseed oil, *etc*., offer a potentially very interesting alternative regarding harmful emissions, engine wear, cost, and availability [1, 2]. Compared to mineral diesel, biodiesel fuels have comparable energy density and cetane number; they have little sulphur and much oxygen. biodiesel has excellent lubricating properties. 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.

Recent engine durability testing with soybean-based biodiesel has shown that biodiesel may be subject to fuel filter plugging problems caused by sediment and gum formation. The currently accepted explanation for the presence of sediment and gum is that the fuel changes chemically to produce these compounds and this are identified as a fuel stability problem. biodiesel's oxidation is accelerated by heat and light. Generally, when air is present, oxidation will proceed.

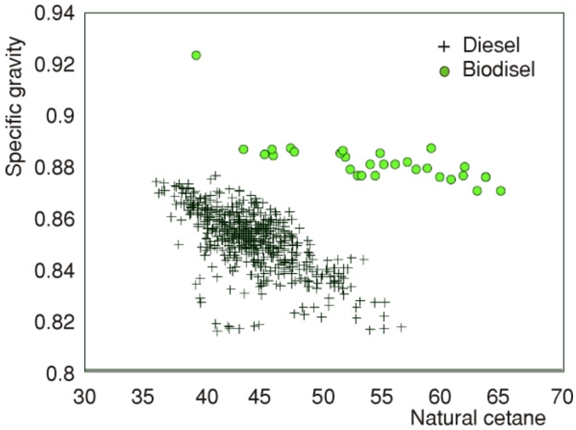

Figure 1. Natural cetane and specific gravity of biodiesel and conventional diesel (color image see on our web site)

To illustrate how biodiesel and conventional diesel differ, the authors [3] examined the distribution of specific gravity and natural cetane (fuel without cetane improver additives), since these two fuel properties were measured for nearly every one of the neat biodiesels in the database [3]. Figure 1 shows the results. In this figure, the biodiesel with the lowest natural cetane (and correspondingly highest specific gravity) is virgin oil. The remaining neat biodiesels have relatively constant specific gravity, but widely varying natural cetane. Although not shown here, there was little variation in the other fuel properties for neat biodiesel.

Table 1. Average biodiesel emissions compared to conventional diesel, according to EPA

Emission type	B100	B20
Regulated		
Total unburned hydrocarbons	–67%	–20%
Carbon monoxide	–48%	–12%
Particulate matter	–47%	–12%
NO_x	+10%	+2% to –2%
Non-regulated		
Sulfates	–100%	–20% (1)
PAH (polycyclic aromatic hydrocarbons) (2)	–80%	–13%
nPAH (nitrated PAH's) (2)	–90%	–50% (3)
Ozone potential of speciated hydrocarbons	–50%	–10%

(1) Estimated from B100 result
(2) Average reduction across all compounds measured
(3) 2-nitrofluorine results were within test method variability

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 [3]. By using waste olive oil methyl ester as biodiesel, the NO_2 emissions may increase up to 81%. The emissions of CO, NO, and SO_2 may decrease while the combustion efficiency remains constant using either biodiesel or mineral diesel. According to a U. S. Department of Energy study completed at the University of California at Davis, the use of pure biodiesel instead of petroleum-based diesel fuel could offer a 93.6% reduction in cancer risks from exhaust emissions exposure [3].

Research and optimization of diesel engine's operating process assume knowledge of the engine characteristics of used fuel, especially its auto-ignition expressed by cetane number (CN). In the case of application of the fuels originating from biomass and also of classical fuels with additives for auto-ignition improvement (so called cetane improvers) [4], engine method is the only option for determination of CN. Standard tests like ISO 5165 (ASTM D613), DIN 51773, and similar tests demand the application of specific, very expensive laboratory installations, so a relatively small number of institution is accredited for these tests. The Laboratory for IC engines and fuels and lubricants at the Faculty of Mechanical Engineering from Kragujevac, Serbia, has been engaged in research of application of ecologically acceptable fuels from part renewable sources [5], so a real need for finding the possibilities for determination of the CN of diesel fuel emerged. Analysis of standard [6] and capabilities of our laboratory equipment have given encouraging results, which led to development of specific engine method for determination of auto-ignition characteristics. The paper will present the methodology, the results of optimization of operating parameters of a test engine and assessment of method's precision. The engine with variable compression ratio can utilise all advantages of high CN in wide operating regimes, not only at the start regime.

Methodology

General remarks

The CN is one of the most commonly cited property of diesel fuel quality (it's an engine characteristic of fuel). It measures the readiness of the fuel to auto ignite when injected into the engine. It is generally dependent on the composition of the fuel and can impact the engine's start ability, noise level, and exhaust emissions. CN of diesel fuel is determined by comparison between its auto-ignition characteristic and ignition characteristics of reference fuels with known CN, using the engine test under standard operating conditions. The auto-ignition characteristic then means a period of ignition delay. Practically, according to standard [6], CN of examined sample is determined by interpolation between values of two reference fuels having known CN and a little lower (LRF) and a little higher (HRF) value than the sample itself.

During the test, the following values are kept constant: engine speed, injection flow rate, ignition delay, and thermal parameters of the test engine. Compression ratio is varying according to achieve the same ignition delay for both: the sample and reference fuels. Values read on the scale of the device for compression ratio variation are used for linear interpolation of sample's CN.

We use a modified serial engine DMB 3LD 450. It is a mono-cylinder, air-cooled diesel engine with direct injection, equipped with fuel pump governor and throttle-body in the inlet manifold. Engine is loaded by hydraulic brake (fig. 2). At each change of fuel, the engine is being unclogged and brought to the same, *basic operating regime*. Condition of constant ignition delay for fuels having different ignition characteristics is achieved by inlet manifold throttling. Thereby, the start of combustion must begin at top dead centre and engine speed remains constant, by which, so called *reference operating regime* is achieved. CN of the examined sample is determined by interpolation between CN of different fuels in function of intake manifold depression or comparative throttle position. These are the main differences in relation to ISO 5165 methodology. Other procedures, test sequences and mode of calculation of results are mainly the same.

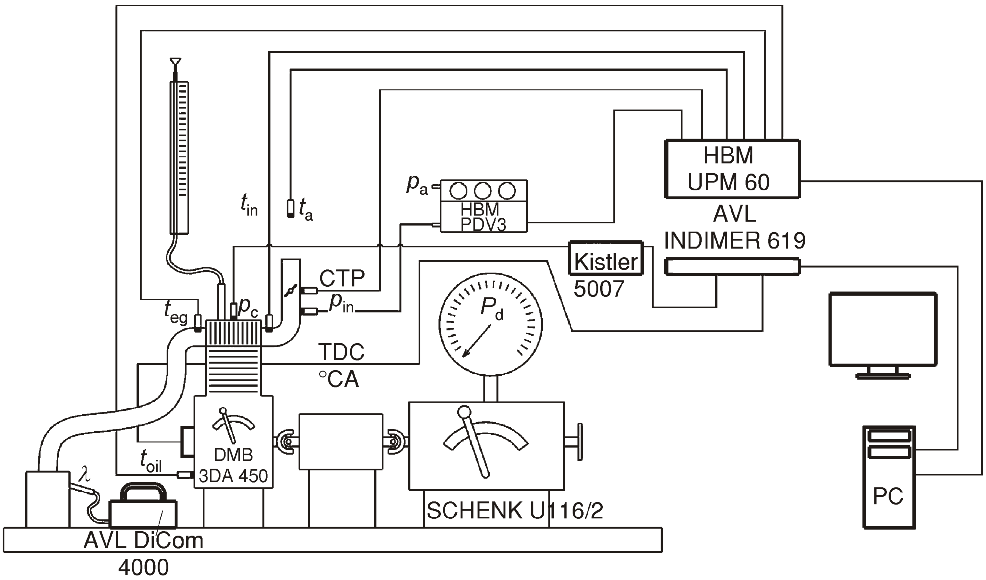

Figure 2. Test bench and instrumentation disposition

AVL DiCom 400 – Exhaust gas measurement system; AVL INDIMER 619 – Cylinder pressure measurement system; CA – Crank angle degree; CTP – Comparative throttle position; DMB 3LD 450 – Test engine; Kistler 5007 – Amplifier; HBM PDV3 – Pressure measurement system; HBM UPM 60 – Measurement system; Fd – Force on dynamometric brake; PC – Personal computer; p_a – Pressure of ambient; p_c – Pressure in cylinder; p_{in} – Pressure in inlet system; t_a – Temperature of ambient; t_{eg} – Temperature of exhaust gas; t_{in} – Temperature of inlet air; t_{oil} – Temperature of oil; TDC – Top dead centre; SCHENK U116/2 – Engine test bench; λ – Air- fuel mixture

Ignition delay determination

Ignition delay is determined by the initial moment of fuel injection and by fuel-air mixture ignition point. Start of injection is previously set and remains constant during tests.

For determination of the ignition point, we have used indication of cylinder pressure in the domain of crank shaft angular position, by the use of AVL INDIMER 619 measurement system. Based on processing of the indication results from 50 consecutive cycles, the following values were calculated: indicated mean pressure of the cycle ($p_{\rm i}$), indicated mean pressure of the high-pressure part of the cycle ($p_{\rm ih}$), and indicated mean pressure of the low-pressure partof the cycle ($p_{\rm il}$), and heat release pattern. Discrete values of combustion positions of burned fuel quantities (AQ0%, AQ5%, AQ10%, AQ50%, and AQ90%) are gained. All quantities are presented by their mean values and standard deviations [7].

First of all, start of combustion criteria is selected. Figure 3 shows the influence of the CN of fuel on heat release pattern and it can be seen that the range of variation of combustion point of a 5% burned fuel, ΔAQ5%, is twice as high as the range of variation of combustion point ΔAQ0%. The same conclusion may be reached from the diagrams shown in figs. 4 and 5, where dependence of parameters AQ0% and AQ5% from engine speed for different injection advance settings are shown. Besides, it is noticeable that standard deviation of parameter AQ5% is considerably smaller than of AQ0%, especially in the case of smaller injection advance angle. This proves that parameter AQ5% is more sensitive and more precise and it has been selected as a start of combustion criteria.

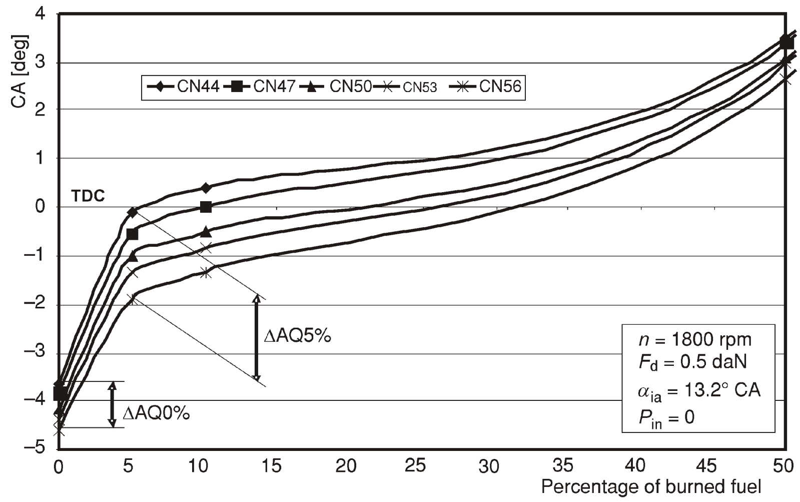

Figure 3. Cetane number influence on heat release pattern (color image see on our web site)

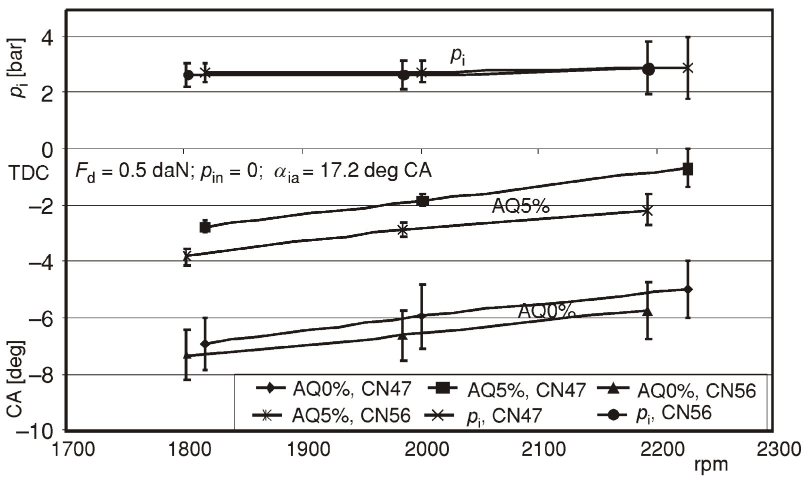

Figure 4. Influence of rpm on fuel combustion parameters for factory injection advance setting (color image see on our web site)

Selection of the basic and achievement of the reference operating regime

Basic operating regime means a combination of engine speed and load of none throttled (p_{in} = 0) engine, registered by the force on dynamometric brake, F_d.

The following criteria were taken into account during selection of the engine basic operating regime:
- aimed testing range of cetane numbers, CN = 47– 56,
- stable engine operation with fuels from the given range, and
- fuel ignition point for CN = 47, nearly before TDC.

Selection of engine speed for basic operating regime is closely connected to injection timing angle. Engine 3DA 450 has a fixed injection timing (factory setting of α_{ia} = 17.2 deg CA). In fig. 4, it may be seen that then an optimal engine speed is above 2000 rpm, when engine enters in less stabile operating range. Parameter AQ5% deviations abruptly grow, like deviations of mean indicator work. Much more stabile engine operation is achieved by injection timing retard to α_{ia} = 13.2 deg CA, until optimal engine speed is n = 1800 rpm (fig. 5).

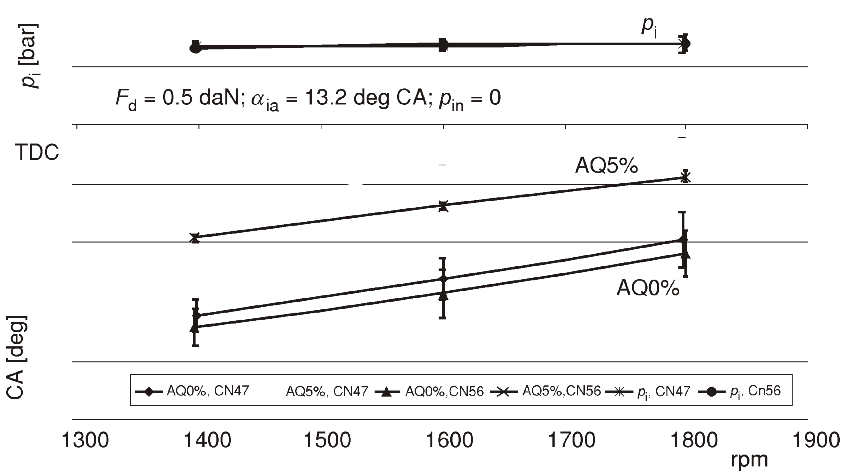

Figure 5. Influence of rpm on fuel combustion parameters for retarded injection advance setting (color image see on our web site)

It should be noticed that mean value and stability of engine speed have radical influence on test results, so the engine speed must be kept in as narrow limits as possible. We have achieved n = 1800 ± 8 rpm during all measurements.

Engine load at basic operation regime is given by braking force F_d = 0.5 daN. Reasons are explained below.

Reference operating regime is achieved by the throttle of the intake manifold of the engine operating at basic regime, as long as the ignition point is brought to outer dead centre by constant engine speed. Since the throttling disturbs the engine operating process, reduction of engine speed is inevitable. Fuel pump governor compensates at certain level for developed change at the cost of increase of cycle fuel quantity. There are two ways to get back the engine speed to initial value:

– by correction of regulator's command position (F_d = const), and
– by unloading the engine, that is by reduction of braking force, F_d.

Figure 6 show that the first way of obtaining the reference regime demands higher throttling. Due to increased quantity of injected fuel, drop of indicated mean pressure in relation to basic regime is very small, which means that enrichment of air fuel mixture is achieved by both counts.

Accomplishment of the reference regime by unloading of the engine has advantages which may be seen in fig. 7. By throttling, pump loses grow (p_{il}), while indicated mean pressure of high-pressure portion of the cycle, p_{ih}, remains almost the same, so it may be considered that cycle fuel quality is approximately the same.

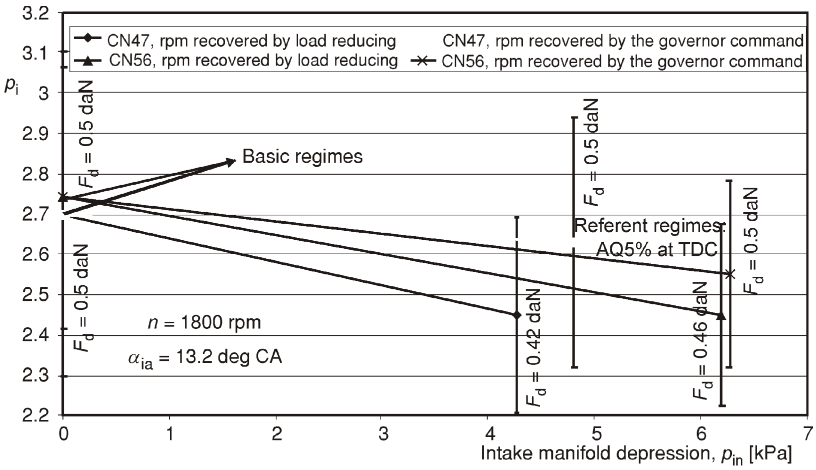

Figure 6. Different wazs for referent regime accomplishment (color image see on our web site)

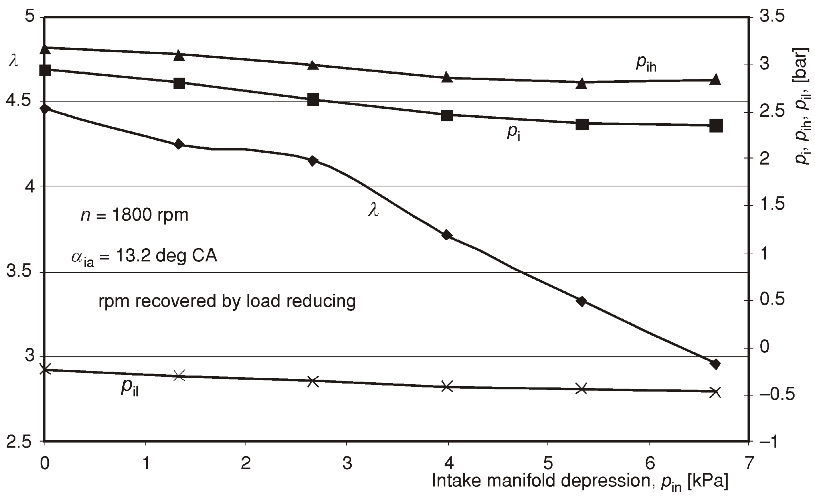

Figure 7. Intake manifold depression influence on air-fuel ratio and p_i, p_{ih}, and p_{il} (color image see on our web site)

Considerable change of air-fuel mixture structure (fig. 7) is inevitable consequence of the achievement of reference regime by throttling, followed by the increase of residual. How and to what extent it influences the test results, so far is unknown to us. In any case, low load in basic operating regime, smaller throttle in the reference operating regime and keeping the constant engine speed by unloading reduce the influences mentioned before.

Reference fuels

Reference fuels used in the test are obtained by mixing of certain volumes of the two basic components (so called secondary reference fuels), *T-fuel* (CN = 67.3) and *U-fuel* (CN = = 29), according to ISO 5165.

Test calibration

Test calibration is conducted with five different fuel mixtures (CN = 44, 47, 50, 53, and 56). Basic operating regime was given by $n = 1800$ rpm and $F_d = 0.5$ daN and bringing to reference operating regime was conducted by engine unloading. Then, variations of the two parameters were observed: pressure drop in intake manifold, p_{in} and comparative throttle position (CTP), fig. 8. It may be noticed that both parameters change almost linearly with change of CN. Also, it can be concluded that the test is sufficiently sensitive $\Delta p_{in}/\Delta CN = 0.27$ kPa/CN$_{unit}$ and $\Delta CTP/\Delta CN = 28$ mV/CN$_{unit}$.

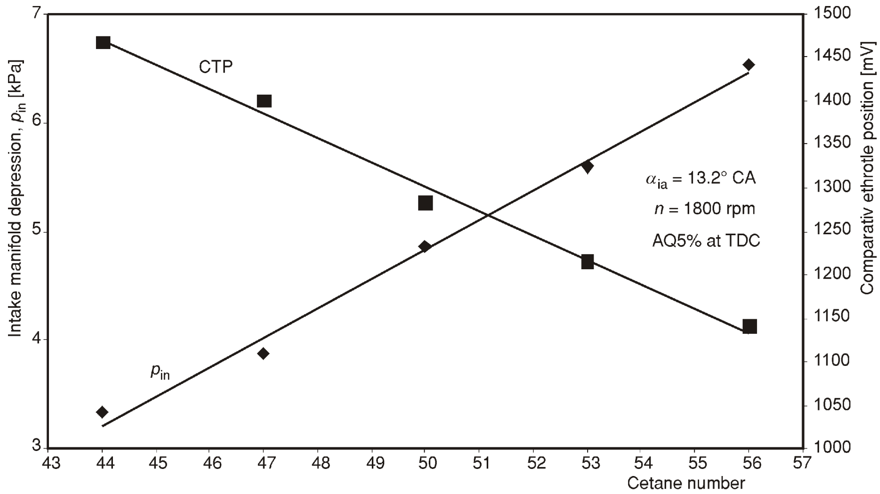

Figure 8. Test parameters calibration results (color image see on our web site)

Figure 9 presents mean values and standard deviations of parameter AQ5% in all reference regimes. The ignition point has always occurred in immediate vicinity of TDC within tolerances given by ISO 5165.

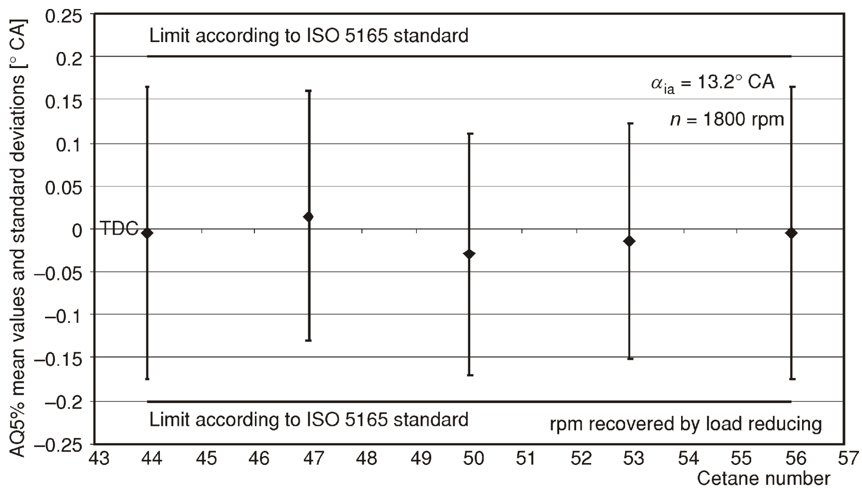

Figure 9. Start of combustion criteria precision at referent regimes (color image see on our web site)

The estimation of method accuracy

In order to estimate the method's precision, repeatability test was conducted. The basic operating regime is set to n = 1800 rpm and F_d = 0.5 daN and setting to reference regime was conducted by engine unloading.

The three fuels with known CN were selected: LRF with CN_{LRF} = 47, sample fuel S with CN_S = 50, and HRF with CN_{HRF} = 53. Complete test procedure was conducted four times in a row, according to table in fig. 10.

	Intake manifold depression p_{in} and comparative throttle position (CTP) readings																				
HRF		2		4				8		10		12		14				18		20	
Samle fluel	1				5		7				11				15		17				21
LRF			3			6			9				13			16			19		
	Sequence A										Sequence A										
						Sequence B										Sequence B					

Figure 10. Repeatability test schedule

Calculation of CN_S was conducted each time according to the following formulas:
(a) by the use of parameter of intake manifold depression:

$$CN_S = CN_{LRF} + \frac{p_{inS} - p_{inLRF}}{p_{inHRF} - p_{inLRF}}(CN_{HRF} - CN_{LRF}) \quad (1)$$

(b) by the use of parameter of comparative throttle position:

$$CN_S = CN_{LRF} + \frac{CTP_S - CTP_{LRF}}{CTP_{HRF} - CTP_{LRF}}(CN_{HRF} - CN_{LRF}) \quad (2)$$

Results obtained are presented in tables in figs. 11 and 12.

Regardless of what parameter was used for linear interpolation, the test repeatability complies with ISO 5165 condition which is 0.9 CN units for this value of CNS

Reproducibility of our test can not be checked because there is no laboratory with similar equipment. Nevertheless, in order to estimate the method itself, it should be noticed that ISO 5165 guarantees inter-laboratory reproducibility of its test of 4 CN units, for average cetane number value of 50.

Cetane number of domestic biodiesel

CN should not be confused with the cetane index. The cetane index predicts the CN from equations derived for petroleum distillates and is not applicable to diesel containing cetane additives, biodiesel or other alternative diesel fuels. In that case the only option for determination of CN is the engine method [4].

Fuel	LRF	Sample	HRF	
CN	47	50	53	
Test 1	Intake manifold depression [kPa]			Sequence A
	4.09252	4.57876	5.28756	Calculated CN_S: 49.8
	4.43694	4.92318	5.32838	
Mean	**4.26473**	**4.75097**	**5.30812**	
Test 2	Intake manifold depression [kPa]			Sequence B
	4.43694	4.82188	5.53098	Calculated CN_S: 50.0
	4.5585	5.1663	5.4702	
Mean	**4.49772**	**4.99409**	**5.50059**	
Test 3	Intake manifold depression, [kPa]			Sequence A
	4.53824	5.1663	5.69306	Calculated CN_S: 50.3
	4.8624	5.28786	5.63228	
Mean	**4.70032**	**5.22708**	**5.66267**	
Test 4	Intake manifold depression [kPa]			Sequence B
	4.8624	5.42968	5.69306	Calculated CN_S: 50.7
	4.80162	5.51072	6.05774	
Mean	**4.83201**	**5.4702**	**5.8754**	
				CN_S average: 50.2

Figure 11. Test repeatability results using intake manifold depression parameter

Most of the B100 made today that meets U.S. ASTM D6751 has a CN higher than 47. This is compared to the minimum of 40 for highway diesel fuel, whose national average is between 42 and 44. Therefore, biodiesel has a higher cetane number than most U. S. diesel fuel, which is believed to provide easier starting and quieter operation. Highly saturated B100, such as animal fats and used cooking oils, can have a cetane number of 70 or higher. Common polyunsaturated fuels that contain high levels of C18:2 and C18:3 fatty acids include soy, sunflower, corn, and canola (rapeseed) oils. These will be at the lower end of the scale, at 47 or slightly higher. Figure 13 shows the CN of various pure fatty acid methyl esters [8].

Our investigation was conducted on the sample methyl esters from soybean oil. The sample produced by Prva Iskra – Namenska proizvodnja AD from Barič, Serbia, with next characteristics:

Density at 15 °C	0.892 g/cm^3
Water	0.16%
Iodine value	112.69 J_2/100 g
Acid number	1.80 mg KOH/100 g
Date of production	September 7, 2006

According to determine a basic operating regime we conducted some suitable preliminary measurements. After that, the basic operating regime is set to n = 2000 rpm and F_d = 0.5 daN. Measurement was conducted according to the method described above, and result is CN_{SME} =

Fuel	LRF	Sample	HRF	
CN	47	50	53	
Test 1	Comparative throttle position (CTP) [mV]			Sequence A
	1379	1309	1212	Calculated CN_S: 49.9
	1319	1249	1201	
Mean	**1349**	**1279**	**1206.5**	
Test 2	Comparative throttle position (CTP) [mV]			Sequence B
	1319	1262	1172	Calculated CN_S: 50.2
	1299	1214	1180	
Mean	**1309**	**1238**	**1176**	
Test 3	Comparative throttle position (CTP) [mV]			Sequence A
	1302	1214	1155	Calculated CN_S: 50.5
	1251	1200	1161	
Mean	**1276**	**1207**	**1158**	
Test 4	Comparative throttle position (CTP) [mV]			Sequence B
	1252	1176	1150	Calculated CN_S: 50.9
	1258	1171	1111	
Mean	**1255**	**1173.5**	**1130.5**	
				CN_S average: 50.4

Figure 12. Test repeatability results using comparative position parameter

= 66.5. The value of CN of sample methyl esters from soybean oil, attained by the suggested method, occurs within literature data. The value is nearby high limit value, which can be explained by oxidation and the old age of the sample.

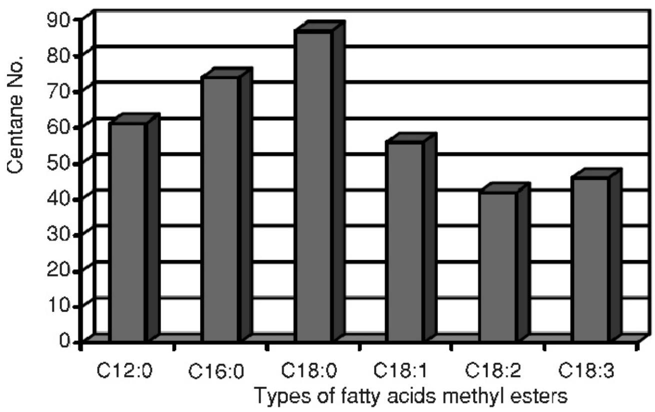

Figure 13. Cetane number of fuels made from pure fatty acids [8]

Second investigation was conducted with the sample of soybean methyl made by VICTORIAOIL from Šid, Serbia. The sample was produced at July 5, 2007. Measurement was conducted according to the method described above, and result is $CN_{SME} = 51.5$.

Fuel which has been distilled oxidizes much more quickly than un-distilled fuel. While the distillation process does not affect the CN, the oxidation results in a CN increase. When the fuel was oxidized to a peroxide value of 82, the CN increased between 7 and 8 points. Further increases in the peroxide value did not increase the cetane number [9].

Conclusions

In the case of application of the fuels originating from biomass and also of classical fuels with additives for improvement of auto-ignition characteristics (so called cetane improvers), the only option for determination of CN is the engine method.

Determination of ignition characteristics of fuel may be conducted in non-standard conditions at the serial engine, by application of corresponding method.

Basic operating regime is selected in such a way that ignition of LRF fuel occurs immediately before TDC.

Reference operating regime, defined by air-fuel mixture ignition at TDC, is obtained by simultaneous throttling and unloading.

For calculation of sample's CN, linear interpolation of CN values of different fuels may be used, either in relation to intake manifold depression or in relation to comparative throttle position.

Average measurement error and repeatability of the results of the suggested method are comparable to ISO 5156 standard method.

Important feature of the suggested method is that ignition characteristic is determined at approximately the same effective engine power. In standard ISO5156 method, testing is conducted at the same fuel consumption. Theses facts gain more importance in the case of determination of CN of the fuel having drastically different characteristics in relation to reference fuels (*e. g.* alcohol based fuels). In such case, the results of the proposed test will not be most likely comparable with results of the standard test.

Reported values of the CN for biodiesel vary widely. For soybean oil-derived biodiesel, the values range from 48 to as high as 67. Some of this variation may be due to differences in the fatty acid composition of the soybean oil but other factors are also important. The longer the fatty acid carbon chains and the more saturated the molecules, the higher the CN.

Fuel which has been distilled oxidizes much more quickly than un-distilled fuel. While the distillation process does not affect the CN, the oxidation results in a CN increase. When the fuel was oxidized to a peroxide value of 82, the CN increased between 7 and 8 points. Further increases in the peroxide value did not increase the CN.

The values of CN of samples domestic methyl esters from soybean oil, attained by the suggested method are comparative with literature data.

Acknowledgment

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Nomenclature

AQ*xx%* – discrete values of combustion positions (crank angle) of burned fuel quantities of xx%
F_d – force on dynamometric brake, [daN]
n – engine speed, [rpm]
p – pressure, [Pa]
p_a – pressure of ambient [Pa]
p_c – pressure in cylinder, [Pa]
p_i – indicated mean pressure of the cycle, [Pa]
p_{ih} – indicated mean pressure of the high-pressure part of the cycle, [Pa]
p_{il} – indicated mean pressure of the low-pressure part of the cycle, [Pa]
p_{in} – pressure in inlet system, [Pa]
t_{oil} – temperature of oil, [°C]
t_a – temperature of ambient, [°C]
t_{eg} – temperature of exhaust gas, [°C]
t_{in} – temperature of inlet air, [°C]

Greek letters

α – crank angle
α_{ia} – injection timing
λ – air-fuel mixture

Abbreviations

ASTM – American Society for Testing and Materials
AVL DiCom 400 – exhaust gas measurement system
AVL INDIMER 619 – cylinder pressure measurement system
B20 – 20% biodiesel, 80% petroleum diesel
B100 – 100% biodiesel
CA – crank angle degree
CI – compression ignition
CN – cetane number
CN_{HRF} – cetane number of high reference fuel
CN_{LRF} – cetane number of low reference fuel
CN_S – cetane number of sample fuel
CN_{SME} – cetane number of soybean methyl ester
CTP – comparative throttle position
CTP_{HRF} – comparative throttle position of high reference fuel
CTP_{LRF} – comparative throttle position of low reference fuel
CTP_S – comparative throttle position of sample fuel
DMB 3LD 450 – test engine
EPA – U. S. Environmental Protection Agency
HBM PDV3 – pressure measurement system
HBM UPM 60 – measurement system
HRF – high reference fuel
IC – internal combustion
LRF – low reference fuel
PC – personal computer
S – sample
SCHENK U116/2 – engine test bench
SME – soybean methyl ester
TDC – top dead centre

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Authors´ address:

R. Pešić, A. Davinić, S. Veinović
Faculty of Mechanical Engineering, University of Kragujevac
6, Sestre Janjić, 34000 Kragujevac, Serbia

Corresponding author: R. Pešić
E-mail: pesicr@kg.ac.yu

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