# A DIESEL ENGINE PERFORMANCE MEASUREMENT WITH DIESEL FUEL AND BIODIESEL

by

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*Rapid growth in the energy consumption has conditioned the need for discovering the alternative energy resources which would be adapted to the existing engine constructions and which would satisfy the additional criteria related to the renewability, ecology, and reliability of use. The experimental research are conducted according to the (European Stationary Cycle - Directive 1999/96/EC) 13-mode. Using biodiesel fuel average thermal efficiency is kept at the level of the application of conventional diesel fuel, average emission of CO is reduced by 13.6%, average emission of* $NO_x$ *is increased by 27.6%, average emission of hydrocarbon is increased by 59.4%, and average particles emission is reduced by 43.2%.*

Key words: *biodiesel, environmental characteristics, energy characteristics, internal combustion engine.*

## Introduction

Half of all energy and raw material sources on our planet are practically engaged in production and exploitation of vehicles. The vehicles exist due to the same resources that all living beings depend on: soil, raw materials, water, air and space. Obviously, the vehicles have significant influence on human environment; hence, a special attention must be given to them [1, 2].

Transport completely depends on oil supply and it is the source of important part of GHG emission. All predictions for the future have shown that the transport will increase and that it is important to find the solutions for secure fuel supply and the possibilities for pollution reduction. One of the solutions for these problems is the utilization of alternative fuels, which had been examined as possible fuels for spark ignition (SI) engines at the beginning of the XX century. The first attempts to utilize ethanol were made by H. Ford, while R. Diesel predicted the use of vegetable oils [3].

In April 2009, Directive 2009/30/EC was adopted, which revised the Fuel Quality Directive [Directive 98/70/EC]. It amends a number of elements of petrol and diesel specifications, as well as introducing, in Article 7a, a requirement that fuel suppliers reduce the GHG intensity of energy supplied for road transport (Low Carbon Fuel Standard). Fuel suppliers must reduce emissions by 6-10 % by 2020 (relative to 2010 fossil fuels). In addition, the Directive establishes sustainability criteria that must be met by biofuels if they are to count towards the greenhouse gas intensity reduction obligation [4].

The EU Biofuels Directive has created a legislative framework in EU Member States and has therefore triggered rapid market availability of biofuels. In 2010, the share of biofuels in the EU-28 was 5.2% of all petrol and diesel sold for transport purposes. This was still somewhat

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below the original 5.75 % policy objective, under Directive 2003/30/EC, to be achieved by the end of 2010. These targets were subsequently revised following the adoption of Directive 2009/28/EC - which was subsequently amended in 2013 and again in 2015 - on the promotion of the use of energy from renewable sources (repealing two previous Directives). The revision sees the share of renewable energy to be used in transport rising to a minimum of 10% in every Member State by 2020. The new directive on renewable energy also aims to ensure that only sustainable biofuels that generate a clear and net GHG saving and have no negative impact on biodiversity and land use are used in the EU. Only biofuels that comply with the sustainability criteria under the Renewable Energy Directive are to be counted towards this target and, therefore, proper monitoring is only possible from 2010. In addition, to stimulate the growth of certain shares of renewable energy sources in transport, renewable electricity in electric road vehicles is considered to be 2.5 times the energy content of the electricity input from RES. Similarly, the contribution of biofuels produced from wastes, residues, non-food cellulosic material, and lingo-cellulosic material is considered to be twice that of other biofuels. Nevertheless, the 10 % target is expected to be met primarily through biofuels. Also, each Member State shall seek to achieve a minimum level of biofuel consumption, taking effect from April 2017. A reference value for this target is a 0.5 percentage point growth in the share of energy from renewable sources in all forms of transport by 2020, to be met with biofuels produced in feedstocks and other fuels listed in part A of Annex IX [5].

Energy demand is increasing day by day due to modernization and industrialization of any country in world. Most of the developing countries like Serbia import fossil fuels to fulfil their energy demand. In the current situation, fast depletion of fossil fuels, increasing cost of petroleum fuels and stringent emission norms imposed by the government have urged the researchers to search for an alternative fuel for compression ignition (CI) engines like biofuel and biomass. Vegetable oils and biomass fuels have been found to be potential fuel for Diesel engines. These fuels are easily available, biodegradable, environment friendly, and renewable in nature.

Rapid growth in the energy consumption has conditioned the need for discovering the alternative energy resources which would be adapted to the existing engine constructions and which would satisfy the additional criteria related to the renewability, ecology, and reliability of use.

A great number of scientific papers that were dealing with the problem of vegetable oil methyl esters application for diesel driven engines has shown that the vegetable oil esters are renewable source of alternative and environmental bio fuels. Such fuels, usually called biodiesel can be used in Diesel engines with minimum, or even without any engine modifications [6-8]. Strict law regulations on the engine exhaust emission, exhaustion of fossil fuels and the constant political tensions about the oil sources in the world, have forced a lot of countries in the world to look for alternatives to fossil fuels. A lot of research, dealing with the vegetable oil esters (biodiesel) in Diesel engines has also shown the potential of these fuels for $CO_2$ emissions reduction [9, 10].

The performances of the engine with various bio fuel types of biodiesel and mixtures of pure vegetable oils with diesel fuel has also been a lot investigated. Many researches are based on a comparison of engine output performances such as engine power, specific fuel consumption and effective thermal efficiency when working with biodiesel or vegetable oils and their blends with performance of engines powered by diesel fuel. A number of researchers has found that the use of biodiesel as fuel leads to increased fuel consumption but also to something greater thermal efficiency of the engine compared to those obtained during the operation with standard diesel fuel [9-12]. On the other hand, the use of various biodiesel in the engine results in a change of performance and exhaust emissions as a consequence of their different physical and chemical characteristics [13]. The research of influence of biodiesel on the characteristics of the fuel injection system, as well as the characteristics of the fuel spray is also carried out [14, 15].

The main objectives of the paper are to obtain the results of own experimental research on the application of biodiesel compared to diesel fuel.

## Experimental set-up

### *Test engine and experimental procedure*

The research is carried out at the Laboratory for Internal Combustion Engines and Fuels at Faculty of Engineering University of Kragujevac. Standard production single cylinder Diesel engine 3 DA 450, manufactured in Engine Factory *21 maj - Belgrade*, was used for testing, tab. 1.

**Table 1. Engine specifications**

| Type | 3DA450 |
|---|---|
| Description | Four stroke, single cylinder, air - cooled, natural aspirated |
| Swept volume | 454 $cm^3$ |
| Rated speed | 3000 rpm |
| Valve timing | Intake valve opened : 16° CA bTDC<br>Exhaust valve opened : 40° CA bBDC<br>Intake valve closed : 40° CA aBDC<br>Exhaust valve closed : 16° CA aTDC<br>Valve overlap 32° CA* |
| Working process | Diesel direct injection (DI) |
| Rated power | 6.6 kW |
| Compression ratio | 17.5 |
| Fuel system characteristic | Mono-block fuel pump, Fixed timing 18.5° CA bTDC,<br>Mech. closed cup injector,<br>All-regime mech. governor |

*CA - crank angle

Tests are performed at hydraulic dynamometer SCHENK U116/2. The AVL DICOM 4000 analyser has measured raw exhaust emission. The gas sampling line has not been heated, so the measured HC emission is lower than in reality. This instrument also includes the chamber for the measurement of opacity of exhaust gas. In addition, the instrument for the measurement of exhaust smoke using BOSCH method is installed at the exhaust pipe, fig. 1.

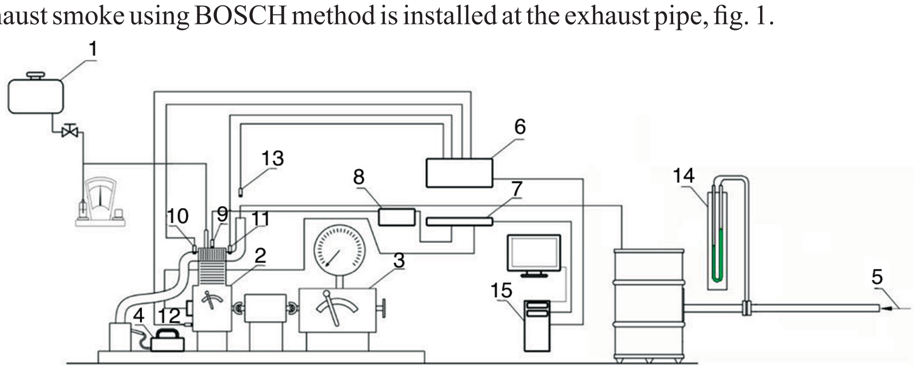


**Figure 1. Experimental instalation;** *1– fuel tank, 2– engine, 3– dynamometer, 4–AVL ditest, 5–air-flow, 6–the HBM UPM 60, 7– the AVL indimer 619, 8–kistler 5007, 9– cylinder pressuresensor, 10– exhaust port, 11– intake port of temperature sensor, 12– oil temperature sensor, 13– enviroment temperature sensor, 14– U manometer, 15– PC*

*Fuel properties*

Tests were conducted with biodiesel fuels produced by "VICTORIA OIL" from Šid (cetane number CN = 53.2) and with standard Euro diesel fuel (cetane number 52.4), tab. 2. The CN of fuels are determined by own engine method, previously published in [16].

**Table 2. Test fuel properties**

| Characteristic | Fuel standard dimensions | Diesel fuel SRPS EN590:2005 | Biodiesel EN14214 | Test method |
|---|---|---|---|---|
| Density at 15 °C | $kgm^{-3}$ | 835 | 884 | IP 190/64 |
| Viscosity at 40 °C | $mm^2s^{-1}$ | 2.20 | 3,86 | Vogel-Ossag |
| Flashpoint | °C | 76.3 | 177 | EN ISO 22719 |
| Higher heating value | $kJkg^{-1}$ | 45770 | 38920 | SRPS B.H8.318 |
| Lower heating value | $kJkg^{-1}$ | 42850 | 36220 | SRPS B.H8.318 |
| Cetane number | CN | 52.0 | 55.5 | MFK method [17] |
| Elemental composition: | | | | |
| Carbon | % m/m | 87.0 | 77.0 | [18, 19] |
| Hydrogen | % m/m | 13.0 | 12.0 | [18, 19] |
| Oxygen | % m/m | 0.0 | 11.0 | [18, 19] |
| Stoichiometric A/F ratio | $kg_{air}/kg_{fuel}$ | 14.7 | 13.8 | [18, 19] |
| Molecular weight | kg/kmol | ≈ 200 | ≈ 292 | [18, 19] |

Comparing with standard diesel fuel, biodiesel fuel has next different essential characteristics: higher density for 6%, higher kinematic viscosity for 34%, higher cetane number for 2%, 13% chemically linked oxygen, and lower heat value for 15%. These differences affect mixture formation and combustion that influences the results of exhaust emissions and thermal efficiency [16].

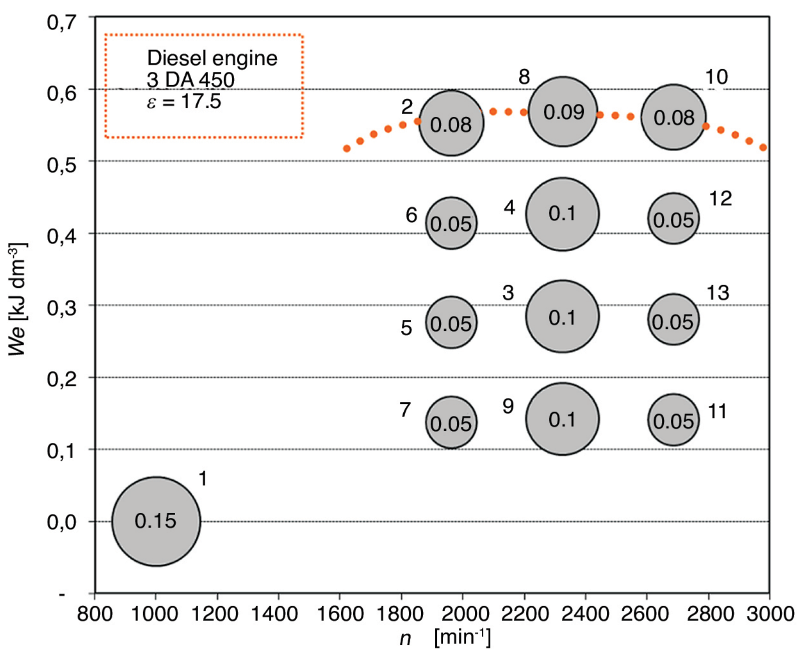


**Figure 2. Testing regimes of the 3 DA 450 Diesel engines according to the ESC 13-mode cycle and weighting factors**

## Estimation of emission and efficiency indicators

Performance measurements, in the research, are conducted according to the ESC (European Stationary Cycle - Directive 1999/96/EC) 13-mode cycle, fig. 2 [20].

In order to compare engine emission characteristics by overall working area, emissions are measured during each mode of the ESC test cycle and averaged over the cycle using a set of weighting factors. The final emission results are expressed in [gkW$^{-1}$h$^{-1}$].

The test emission indicators are determined by using the prescribed procedure, except for the particle emission which was calculated using the Motor Industry Research Association correlation based on the measured Bosch smoke number (BSN), eq. (1). This method is applicable because of the technological level of the Diesel engine [17, 20].

$$PM_{\text{conc}} = 982 \cdot BSN \cdot 10^{(BSN \cdot 0.1272 - 1.66)}$$
$$PM_{\text{mas}} = \frac{1}{1.293 \cdot 10^{-3}} PM_{conc} G_{ig} \tag{1}$$

where $PM_{\text{conc}}$ is volumetric concentration PM, $PM_{\text{mas}}$ is mass concentration PM, $BSN$ is Bosch Smoke Number, and $G_{\text{ig}}$ is wet exhaust gases flow [20].

Indicated, $\eta_i$, and effective, $\eta_e$, efficiency are measured and calculated during each mode the ESC test cycle and averaged over the cycle using the same set of weighting factors and methodology as in calculations of emissions [17, 20].

Indicated parameters were measured by AVL Indimer 619 system on the sample of 50 consecutive cycles. Their average values were used in later calculations and diagrams. Statistical parameters of the sample (standard deviation *etc.*) were used to determine regime's stationarity during the measurements.

## Research results and discussion

### *Environmental characteristics of the diesel engine*

The emission of CO of tested engine according ESC cycle is reduced with biodiesel for 13.6% comparing to the operation with standard diesel fuel. This reduction is mainly the result of *chemical supercharging* (oxygen existence in the fuel). Analysing the results of specific CO emission in tested modes, fig. 3, significant reduction at high-speed modes 10, 11, 12, and 13 can be noticed.

At all other regimes CO emission is greater especially at modes 4 and 1 (idle). The possible cause is that the conditions for mixture formation in engines with conventional injection systems at these regimes are unfavourable (lower injection pressure and smaller intensity of intake swirl), when higher fuel viscosity increases spray length and aggravates its atomization. Combustion of fuel evaporated from chamber wall, in spite of oxygen excess, occurs in the conditions of locally rich mixtures.

Similar results obtained by Jamrozik *et al*. [9] which stated that CO emission increases at low loads while it decreased at high load with the addition of ethanol to fuel blend.

Bibin *et al*., [12] are concluded that the reduction CO with biodiesel fuel is proportionally

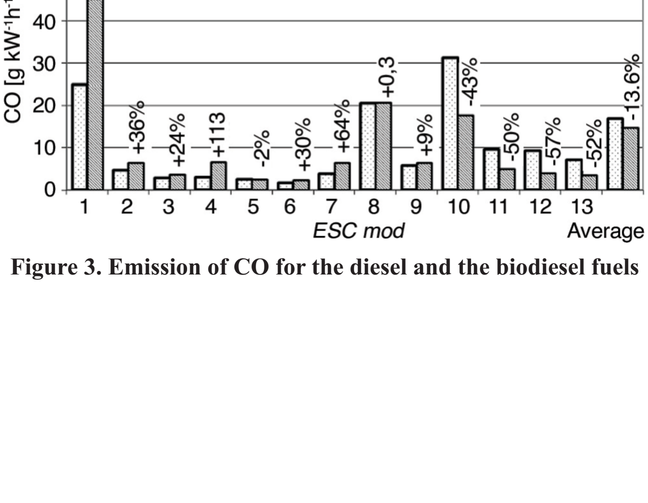


**Figure 3. Emission of CO for the diesel and the biodiesel fuels**

small with the low engine load. The reason for this lies in the fact that the fuel with high biodiesel content has higher kinematic viscosity in comparison to the diesel fuel. Therefore, low load and low temperature in the engine cylinder cause poor atomization and air-fuel mixing.

The emission of unburned hydrocarbons (HC) of tested engine according ESC cycle is increased with biodiesel for 59.4% comparing to the operation with standard diesel fuel. This result seems apparently opposite to the results of CO emissions, having in mind that both components are the product of incomplete combustion. However, it should be noted that biodiesel is not been finally distilled so it contains other organic compounds in addition to methyl ester. It is certain that the products of incomplete combustion of this fuel differ in physical and chemical properties compared to those originating from conventional diesel fuel. All this affects the process of deposition and condensation of unburned HC in the installation of exhaust gas sampling. In addition, it should be noted that the HC concentration is expressed in equivalent hexane.

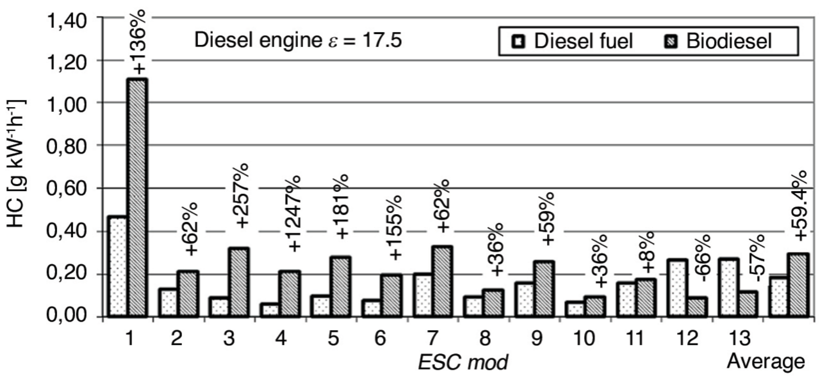


**Figure 4. Emission of HC for the diesel and the biodiesel fuels**

Comparative results of specific HC emissions by test modes are shown in fig. 4. A drastic increase of the emission in central part of the working area (modes 3, 4, 5 and 6) and idling can be seen. Emission reduction was noted only at high speed with low load regimes, where are high intensity of intake swirl, (modes 12 and 13).

Similar results obtained by Jamrozik *et al*. [9] which stated that HC emission generally increases compared to diesel fuel due to high heat of evaporation of ethanol leaving un-burned ethanol in the exhaust. This effect was more significant at low and medium loads. Lower emissions of HC can be a consequence of higher fuel burn efficiency. When biodiesel is added to the fuel, more oxygen is available in the combustion which improving the burning quality.

The emission of $NO_x$ of tested engine according ESC cycle is increased with biodiesel for 27.6% comparing to the operation with standard diesel fuel. Comparative results of the specific $NO_x$ emissions per test modes are shown in fig. 5. With biodiesel fuel, the diesel engine emits more $NO_x$ at all speeds. The differences reduce when the load increases at the same speed mode, while for the same load, with speed increase, the difference increases.

Tomic *et al*., [7] have noticed that higher engine load caused linear increase of $NO_x$ emission in all test fuels at rated speed and also, the increased share of biodiesel in the blend with diesel fuel causes high $NO_x$ emission.

Bibin *et al*., [11] have noticed that the increase in $NO_x$ levels with increase in the amount of methyl esters in the blends biodiesel with diesel fuel was seen.

Increased $NO_x$ emission is a consequence of increased local flame temperature, primarily due to the influence of chemically bound oxygen. Another reason is the early ignition of biodiesel fuel, which results in moving the centre of combustion closer to SMT. Therefore, the higher values of temperature in the cylinder $TZ_{max}$ are achieved, as illustrated in fig. 6.

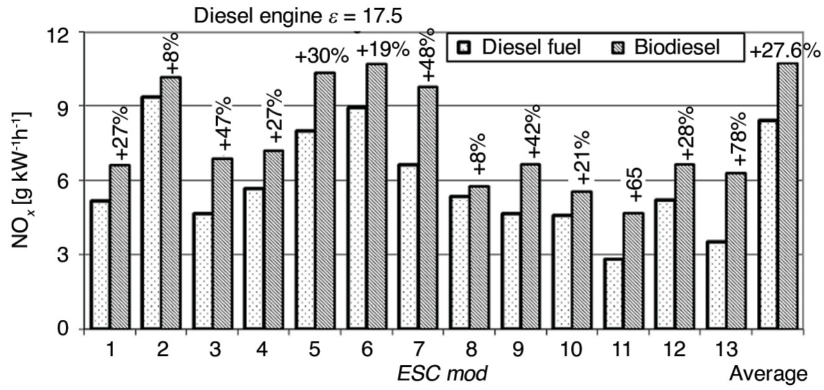


**Figure 5. Emission of $NO_x$ for the diesel and the biodiesel fuels**

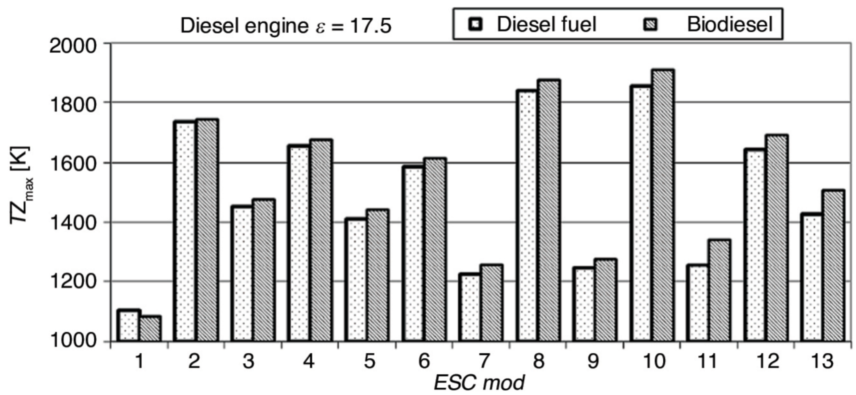


**Figure 6. The higher values of temperature in the cylinder for the diesel and the biodiesel fuels**

Application of bio-diesel fuel has shown a distinct advantage in terms of particulate matter (PM) emission, which is lower by 43.2% in ESC test. fig. 7 shows comparative results of PM specific emission by cycle modes. The greatest differences in emissions of particles have been observed in high-speed modes (modes 11, 13, 12 and 10). Biodiesel fuel has a distinct advantage in high-load regimes when the global mixture is richer (modes 8 and 10) and the particles emission of the diesel engine running on diesel fuel is high.

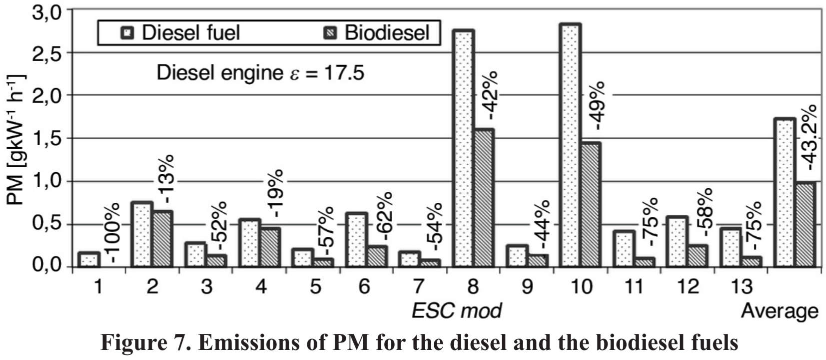


**Figure 7. Emissions of PM for the diesel and the biodiesel fuels**

Bibin *et al.*, [12] have noticed that the smoke emission with an increase in the biodiesel ratio with ethanol-ester-diesel blends. Better diffusive combustion could be the base for the reduction in smoke emission. The results showed decrease in smoke emissions with increased oxygen content.

*Efficiency characteristics of the Diesel engine*

The average indicated thermal efficiency of the Diesel engine is increased by 2.6% by using biodiesel fuel compared to the commercial diesel fuel, fig. 8. This small difference could be easily subsumed under the error of measurement if this result is not obtained by weighing according the methodology of ESC test. If comparative values of indicated thermal efficiency are observed in test modes, can essential differences can be seen. The biggest gains of 13% are achieved at the test mode 9 (2325 rpm; 25% $W_{e,\max}$). The lowest gain of 0.1% is achieved at the test mode 6 (1960 rpm; 75% $W_{e,\max}$). At the idle mode, decreasing of the indicated efficiency of 7.6% is obtained. Decreasing of the efficiency at the test mode 4 (2340 rpm; 75% $W_{e,\max}$) and at the test mode 7 (1960 rpm; 25% $W_{e,\max}$) is obtained.

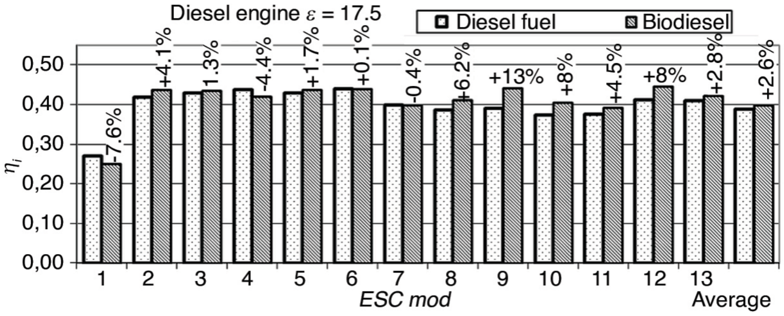


**Figure 8. Indicated thermal efficiencies for the diesel and the biodiesel fuels**

The average effective thermal efficiency of the Diesel engine is increased by 1.3% by using biodiesel fuel compared to the commercial diesel fuel, fig. 9. This small difference could be easily subsumed under the error of measurement if this result is not obtained by weighing according the methodology of ESC test. If comparative values of indicated thermal efficiency are observed in test modes, can essential differences can be seen. The biggest gains of 7.7% is achieved at the test mode 10 (2675 rpm; 100% $W_{e,\max}$. The lowest gain of 0.25% is achieved at the test mode 6 (1960 rpm; 75% $W_{e,\max}$. At the idle mode, decreasing of the indicated efficiency of 5.4% is obtained. Decreasing of the efficiency at the test modes 3 (2340 rpm; 75% $W_{e,\max}$) and at the test mode 7 (1960 rpm; 25% $W_{e,\max}$) is obtained.

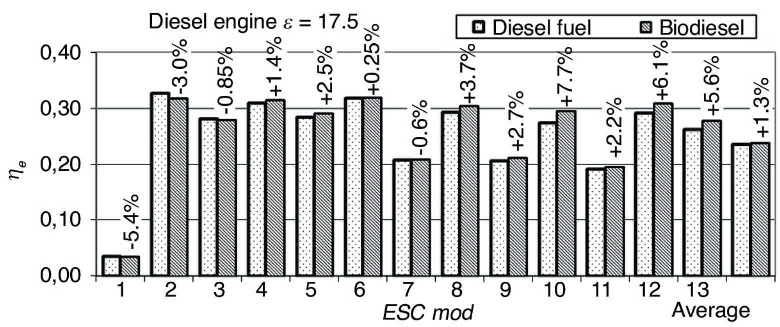


**Figure 9. Effective thermal efficiencies for the diesel and the biodiesel fuels**

Bibin *et al*., [12] have noticed that the thermal efficiency decreased with an increased proportion of biodiesel in the blend with diesel fuel.

Tomic *et al*., [7] have concluded that the thermal efficiency slightly increases with the increase of biodiesel share in the blend, which is the result of faster and more complete fuel combustion.

The U.S. Environmental Protection Agency concluded in their Technical report [21] that biodiesel was also predicted to reduce fuel economy by 1-2%.

## Conclusions

According to the results of the Diesel engine testing in ESC test, next conclusions can be drawn by using biodiesel fuel *vs*. diesel fuel:

- Average effective thermal efficiency is kept at the level of the application of conventional diesel fuel (increasing about 1.3%).
- Average emission of carbon monoxide is reduced by 13.6% (significant reduction about 50% - 57% at high-speed modes 10, 11, 12, and 13 can be noticed).
- Average emission of nitric oxides is increased by 27.6% (the main reason is the early ignition of biodiesel fuel, which results in moving the centre of combustion closer to SMT and increasing the higher values of temperature in the cylinder).
- Average emission of unburned hydrocarbons is increased by 59.4% (HC emission reduction, about 60%, was noted only at high speed with low load regimes, where are high intensity of intake swirl).
- Average particles emission is reduced by 43.2% (biodiesel fuel has a distinct advantage in PM reduction at high-load regimes, reduction is about 60% - 75%; depending on the regime: at modes 11 and 13 reduction is 75%, at the mode 10 reduction is 49%).

## Acknowledgment

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## Nomenclature

CO – emission carbon monoxide, [$gkW^{-1}h^{-1}$]
HC – emission unburned hydrocarbons, [$gkW^{-1}h^{-1}$]
$NO_x$ – emission nitrogen oxides, [$gkW^{-1}h^{-1}$]
PM – emission particulate matter, [$gkW^{-1}h^{-1}$]
$TZ_{max}$ – the higher values of temperature in the cylinder [K]
$W$ – specific work, [$kJdm^{-3}$], or [%]

*Greek symbols*

$\eta$ – efficiency, [–]
$\varepsilon$ – compression ratio, [–]

*Subscript*

$e$ – effective
$i$ – indicated
max – maximum
$Z$ – cylinder

*Acronyms*

CN – cetane number
CA – crank angle [°]
ESC – European stationary cycle
CI – compression ignition
BSN – Bosch smoke number

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