Comparative analysis of selected combustion parameters in the diesel engine powered with biodiesel - ethanol blends

INTRODUCTION

Nowadays different methods are used for the reduction of pollution from internal combustion engines, and one of them is the use of oxygenated components in blend with the conventional fuels. Most popular of them are biodiesel (known as FAME – fatty acid methyl esters), bioethanol and selected ethers (for example, ethyl tert-butyl ether, dimethyl ether, diethyl ether) [1-10]. One of the main advantage of the use of those fuels is possibility to provide higher concentration of oxygen in the mix and therefore higher potential for reduction of tailpipe emissions. Besides that almost all of the mentioned fuels can be produced from renewable materials, which is important in the case of fulfillment of Renewable Energy Directive (2009/28/EC), which amending and subsequently repealing Directive 2003/30/EC, and which define a framework for the use of energy from renewable sources promoting also cleaner transport.

There have been numerous studies showing generally positive influence of oxygenated biofuels on lowering carbon dioxide emission as well as on other harmful components of exhaust gases, using two of the popular oxygenates (ethyl tert-butyl ether (ETBE) and ethanol) in mix with gasoline. There have to be noted that the use of those fuels, as also oxygenates, in pure form in diesel engine is limited based on the physico-chemical properties of fuels. If the properties of biodiesel is quite similar to diesel fuel and only some differences (higher density, viscosity and cetane number; lower heating value) can be observed which do not seriously impact the work of engine, then the use of bioethanol in pure form is not possible at all. Ethanol can be used as only as an alcohol-diesel fuel emulsion or blend, alcohol fumigation, and also in dual-fuel injection system [16]. The use of different blends of diesel fuel and ethanol is restricted by the fact, that diesel fuel and alcohols are immiscible. As can be seen in Fig. 1, separation of the components (diesel oil and neat ethanol) was visible in wide range of temperatures. Only for temperature of +30 ºC the blend was stable (homogeneous) without of phase separation. It is known, that stability of such mixtures are strongly affected not only by temperature variations but also by water content. It is also known, that miscibility of diesel oil-ethanol blends may be improved by adding of emulsifier such as biodiesel [10-12]. Ethanol-diesel blends have also other limitations which impact the use of them in the engines: lower viscosity, reduced ignitability, higher volatility [13]. Mixing of biodiesel and ethanol is more valuable, as it could be mixed not only with alcohols, but also with diesel fuel, and even can be used as an emulsifier in blends diesel-biodiesel-alcohol.

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Combustion characteristics of diesel engine are influenced by different physico-chemical parameters of fuels, such as: density, viscosity, cetane number, etc. For example, output power of the engine depends on differences of the fuel injected in the cylinder, which is affected by the changes in density. As the ethanol has a lower density, but biodiesel has a higher viscosity compared to conventional diesel fuel, then the changes of it in fuel mix can be regulated using exact concentration of fuels. The same situation is also according viscosity and cetane number, which is higher for biodiesel, but lower for ethanol. Low cetane number can promote long ignition delay period and as a result – rapid pressure rise causing undesirable audible knock with higher stresses of the engine. In that case more attention have to be turned on the physico-chemical properties of the obtained mix from three rather different fuels. By the way, different researches and studies were realized to find out the best concentrations of the mentioned fuels and a number of studies on investigating the effect of ethanol addition to diesel oil, but there are limited researches focused on the application of ethanol–biodiesel blends to diesel engine. Some of them have shown promising results. For example, Aydin et al. used ethanol as an additive for biodiesel in form of BE20 fuel (80% biodiesel and 20% ethanol) in single cylinder diesel engine and found that power and specific fuel consumption was almost the same as that of standard diesel [12]. According emissions there was observed lower CO emission for all engine speeds, but NOx and CO2 – only in some of them. Nevertheless this work suggests that blends of biodiesel and ethanol fuel can be used as alternative fuels in conventional diesel engines without any major changes and can potentially remove serious problem revealed with the use of high percentages of biodiesel in operation of unmodified diesel engines. Also Zhu et al. have tested 4-cylinder direct injection diesel engine with 5%, 10% and 15% by volume of ethanol blend with biodiesel (produced from waste cooking oil) [2]. Researchers found increase in ignition delay and retard of the start of combustion for the biodiesel-ethanol blends compared to pure biodiesel. Tests also confirmed faster combustion of those blends than biodiesel or even diesel fuel, which lead to the increase in break thermal efficiency. Other research (Parke et al.) compared the injection and atomization characteristics of diesel, biodiesel (produced from soybean oil) and biodiesel-ethanol blend (80% biodiesel and 20% ethanol) and observed that the addition of ethanol improves biodiesel atomization due a to lower size of droplet in comparison to biodiesel [15].

1. THE GOALS OF THE RESEARCH

The main aim of this research was to find out how the performance of diesel engine could be affected by adding of ethanol to biodiesel (FAME). A stationary engine test bench equipped with sensors allowed to evaluate the effect of these fuels on the engine work including analysis of selected parameters of fuel injection and combustion. In particular during the research it was investigated the effect of ethanol addition to biodiesel on variation of such parameters as:

- crank angle degree (°CA) at start of fuel injection,
- °CA at start of fuel combustion,
- ignition delay angle,
- maximum pressure rise rate,
- maximum pressure in combustion chamber.
2. MATERIALS AND METHODS

The impact of ethanol added to biodiesel on variations of selected injection and combustion parameters was tested on an AD3.152 engine (Tab. 1) produced by URSUS Co. in Warsaw.

Tab. 1. Technical specification of AD3.152 diesel engine

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cylinder number and arrangement</td>
<td>3, in line</td>
</tr>
<tr>
<td>Engine capacity</td>
<td>2502 cm³</td>
</tr>
<tr>
<td>Compression ratio</td>
<td>16.5</td>
</tr>
<tr>
<td>Maximum power</td>
<td>34.6 kW at 2150 rpm</td>
</tr>
<tr>
<td>Maximum torque</td>
<td>165 Nm at 1200 rpm</td>
</tr>
<tr>
<td>Fuel injection system</td>
<td>Lucas - CAV type DPA</td>
</tr>
<tr>
<td>Injection pump timing</td>
<td>17 °CA before TDC (set at idle run)</td>
</tr>
<tr>
<td>Fuel injector opening pressure</td>
<td>17.5 MPa</td>
</tr>
<tr>
<td>Type of fuel injector</td>
<td>Multi-hole (made by WZM Warsaw Co.)</td>
</tr>
<tr>
<td>Injector nozzle holes number</td>
<td>4</td>
</tr>
</tbody>
</table>

AD3.152 is a 4-stroke, 3-cylinder, naturally aspirated, direct-injection engine equipped with a mechanically controlled fuel injection system. The engine /#7 in Fig.1/ was loaded by a hydraulic dynamometer /#8 in Fig.1/ controlled by steering module /#5 in Fig.1/. The in-cylinder pressure was measured with AVL QC34D water-cooled piezoelectric pressure transducer /#6 in Fig.1/ with a sensitivity of 190 pC/bar and a measuring range of 0-25 MPa.

The engine was operated on the grade B European diesel oil (DO), meeting EN 590:2006 standard, biodiesel (BD) - rapeseed methyl ester (FAME) and on two blends containing:
- 10% (v/v) of ethanol with 90% (v/v) of biodiesel (mixture code: ET10),
- 20% (v/v) of ethanol with 80% (v/v) of biodiesel (mixture code: ET20).

Diesel oil used in tests was produced by PKN ORLEN Co. Biodiesel was supplied by Latvian company BIOVENTA. Synthetic ethanol with purity of 99.9% was supplied by WIRASET Co. Tested blends were prepared just before the experiments by splash mixing technique in the proportions mentioned before. The main properties of the fuels, either measured or calculated, are shown in Table 2.
Tab. 2. The main characteristics of analyzed fuels and blends

<table>
<thead>
<tr>
<th>Properties</th>
<th>Unit</th>
<th>Method</th>
<th>Diesel</th>
<th>Biodiesel</th>
<th>Ethanol</th>
<th>B90E10</th>
<th>B80E20</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diesel content</td>
<td>% vol.</td>
<td>Prepared</td>
<td>100</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Biodiesel content</td>
<td>% vol.</td>
<td>Prepared</td>
<td>0</td>
<td>100</td>
<td>0</td>
<td>90</td>
<td>80</td>
</tr>
<tr>
<td>Ethanol content</td>
<td>% vol.</td>
<td>Prepared</td>
<td>0</td>
<td>0</td>
<td>100</td>
<td>10</td>
<td>20</td>
</tr>
<tr>
<td>Oxygen content</td>
<td>% wt.</td>
<td>Calculated</td>
<td>0</td>
<td>0</td>
<td>10.9</td>
<td>34.7</td>
<td>13.1</td>
</tr>
<tr>
<td>Carbon content</td>
<td>% wt.</td>
<td>Calculated</td>
<td>86.6</td>
<td>76.9</td>
<td>52.2</td>
<td>74.7</td>
<td>72.4</td>
</tr>
<tr>
<td>Hydrogen content</td>
<td>% wt.</td>
<td>Calculated</td>
<td>13.4</td>
<td>12.2</td>
<td>13.1</td>
<td>12.3</td>
<td>12.4</td>
</tr>
<tr>
<td>Density at 15 °C</td>
<td>kg/m³</td>
<td>Measured</td>
<td>841</td>
<td>885</td>
<td>796</td>
<td>876</td>
<td>867</td>
</tr>
<tr>
<td>Kinematic viscosity at 40 °C</td>
<td>mm²/s</td>
<td>Measured</td>
<td>2.8</td>
<td>5.3</td>
<td>1.1</td>
<td>4.9</td>
<td>4.5</td>
</tr>
<tr>
<td>Cetane No.</td>
<td>-</td>
<td>-</td>
<td>51</td>
<td>55</td>
<td>8</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Lower heating value</td>
<td>MJ/kg</td>
<td>Estimated</td>
<td>43.2</td>
<td>37.5</td>
<td>27.4</td>
<td>36.6</td>
<td>35.7</td>
</tr>
</tbody>
</table>

Engine tests were performed at constant speed of 1200, 1600 and 2000 rpm under load of 80 and 120 Nm. Such conditions are typical for the AD3.152 engine operated in middle loads. In each measurement point 50 cycles of engine work were recorded. As there was very little difference between measurements then in order to minimize any experimental inaccuracy, averaged values were used for calculations and comparisons.

3. RESULTS

As it was mentioned, the paper is focused on analysis of selected combustion parameters of AD3.152 engine operated in conditions of middle loads. However, additionally the authors would like to present variations of the angle at the beginning of fuel injection ($\alpha_{\text{inj}}$) due it is necessary to estimate the angle of ignition delay. As it can be seen in Figure 1, the values of $\alpha_{\text{inj}}$ depend on rotational speed of the crankshaft and engine load. These parameters are dependent on characteristic of the fuel pump regulator and amount of fuel leakages. Increase of the rotational speed of the crankshaft causes the growth of the angle at beginning of fuel injection. On the other hand, the values of $\alpha_{\text{inj}}$ are lower approximately by 2 °CA for the engine operated with load of 120 Nm in comparison with 80 Nm. Moreover, research showed that the beginning of fuel injection is a bit delayed with higher concentration of ethanol in blend with diesel oil. The difference is not large (less than 1 °CA), but it could impact on the beginning of fuel ignition (Fig. 2).

![Fig. 2. Impact of tested fuels on the crankshaft angle position at the beginning of fuel injection in AD3.152 engine operated at partial load of: a) 80 Nm, b) 120 Nm](image-url)

In Fig. 2 the variations of CA position at $\alpha_{\text{ign}}$ – the beginning of fuel ignition are showed. As it can be seen the values of $\alpha_{\text{ign}}$ are approximately 2 °CA higher for blends containing ethanol (ET10 and ET20) when compare with diesel oil or biodiesel.
It is known that CN of ethanol (Tab. 2) is very low. Thus, increasing the fraction of ethanol added to biodiesel leads to a decrease in the CN-value. Also, the latent heat of vaporization of ethanol is higher compared to the case of diesel oil as well as biodiesel alone (see Tab. 2). It should decrease the temperature in combustion chamber due to the cooling effect of ethanol vaporization process and increase the physical delay period in the first step of combustion. For this reason the angle of ignition delay estimated for biodiesel-ethanol blends (ET10 and ET20) is about 1-2 °CA higher.

It was observed that the start of combustion for all biodiesel-ethanol blends is very similar or a bit delayed to that of diesel fuel not only for small, but also for larger loads. As it was mentioned, it could be explained by the impact of ethanol on reduction of cetane number of blends till value similar to diesel fuel. Besides to the lower cetane number, ethanol reduces also viscosity and improves atomization, which increases part of fuel premixed and its complete burning during expansion cycle. It should be noted that such ignition delay is compensated by a faster combustion process (higher rates of in-cylinder pressure rise) especially for oxygenated fuels and blends (Fig. 5), for the engine operated under higher load such as 120 Nm, which could be connected with the increase of brake thermal efficiency.
Fig. 5. Maximum rates of pressure rise calculated for AD3.152 engine fuelled with tested fuels at partial load conditions of: a) 80 Nm, b) 120 Nm.

As it can be seen in Fig. 5, a combustion process of oxygenated fuels occurs with higher rates of in-cylinder pressure rise. It impacts on a bit higher values of peak pressure in combustion chamber for all tested conditions of AD3.152 engine. Results confirmed that maximum pressures are reached at largest loads and exactly for biodiesel-ethanol blends. As can be seen in the Fig. 6, 20% (v/v) of ethanol blended with biodiesel increases a peak pressure values by about 2 - 4 %, for an engine operated under load of 120 Nm. In case of 80 Nm, the values of in-cylinder peak pressure recorded from tested engine fuelled with ethanol-biodiesel blends are comparable but slightly lower compared to 120 Nm.

Fig. 6. Values of peak pressure recorded in combustion chamber of AD3.152 engine powered with tested fuels at partial load of: a) 80 Nm, b) 120 Nm.

Analysis of above presented parameters confirms, that the engine can be fuelled with ethanol-biodiesel blends. However, it has impact on combustion process (especially on the angle of fuel ignition delay and values of maximum rates of in-cylinder pressure rise).

CONCLUSIONS

In this paper the authors focused attention on ethanol, which may be used effectively as an oxygenated additive to diesel oil in a CI engine. Particularly, the effect of adding ethanol to biodiesel on variations of selected combustion parameters – the angle of beginning of fuel ignition, the angle of ignition delay, maximum rates of in-cylinder pressure rise and finally peak pressure in combustion chamber – were examined.
It is known, that ethanol is a chemical commonly reported with extremely low CN of 8. For this reason, it was expected that addition of ethanol to biodiesel should increase the self-ignition delay angle in tested engine and in fact it was confirmed by the results of the tests. Therefore, if ethanol is to be blended with biodiesel, it should be supplemented with a cetane number improver. It allows reduce ignition delay period as well as to avoid the occurrence of diesel knock phenomenon. The research showed that ethanol added to biodiesel impacts on higher values of maximum rates of pressure rise, especially for higher engine loads. It may increases emission of the noise from the engine and promotes increase wear of the combustion chamber and its components. In extreme conditions it may results in engine failure. It should be pointed that a lot of problems focused on vehicles/engines durability were presented by Lotko et al. in the papers [17-18].

**Abstract**

The present work is focused on a comparative experimental study for determining the effect of fuel properties of oxygenated fuels on selected work parameters of direct injection (DI) diesel engine. The engine was operated on fossil diesel oil (DO), biodiesel (BD also known as FAME) and biodiesel with 10% and 20% ethanol addition, accordingly (ET10) and (ET20). Each of the fuels were tested at steady state running conditions. In such conditions the high-speed parameters of the engine work were recorded. In particular the variation of in-cylinder pressure as well as the fuel injector needle lift signals were analyzed. It allowed to calculate and compare the values of selected combustion parameters of the AD3.152 engine fuelled with biodiesel-ethanol blends. The experimental work was done with an AD3.152 diesel engine installed in the laboratory of the Vehicle Technical Exploitation Department at Technical University of Radom (Poland).

**BIBLIOGRAPHY**


7. Lotko W., Górska K.: Zasilanie silników wysokoprężnych mieszaninami ON i EETB, WNT 2011.


