The dynamic development of the automotive industry makes the consumption of diesel oil grow rapidly. Due to the increasing ecological requirements, research is conducted that aims at the reduction of the negative influence of this branch of industry on the environment. One line of research is the search for ecological fuels, such as dimethyl ether. The application of this fuel with a simultaneous use of modern injection systems allowing for injecting fuel under very high pressure enables emission reduction, as compared to diesel oil. It turns out that the combustion of DME in modern self-ignition engines results in almost negligible emission of particulate matter, which used to be one of the main drawbacks of the engines fuelled conventionally.

Keywords: DME, emission, alternative fuels, ecology, combustion engine, self-ignition

1. INTRODUCTION

An increasing number of newly produced passenger automobiles are equipped with self-ignition engines. Their use in goods vehicles, buses or construction machines is almost one hundred per cent. The popularity of SI engines is mainly due to such features as: high efficiency, which means reduced fuel consumption, high torque, or longer anticipated service life than it is in the case of spark-ignition engines.

The main fuel which is used for powering self-ignition engines is diesel oil (ON). However, because of the activities leading to a reduction in the dependence on crude
oil of the European Union countries, more and more investment is targeted on finding alternative fuels which could replace that one. Among those winning more and more popularity is dimethyl ether, whose properties are very much like the ones of diesel oil. A comparison of selected properties is presented in table 1.

One of the fundamental parameters influencing the course of the process of fuel combustion in the self-ignition engine is the self-ignition temperature, which amounts to 234 °C in the case of an alternative fuel and is lower than the self-ignition temperature of diesel oil. Another feature of fuel largely affecting the operation of SI engine is the cetane index determining the fuel’s ability of self-ignition. The value of cetane index for DME stands at 57, whereas the value for diesel oil is between 40-50 on average. One of the drawbacks of DME is its low density and low calorific value. The values of these parameters, which are worse than it is in the case of diesel oil, result in the necessity of supplying double the amount of alternative fuel in order to reach the same power [1].

Table 1

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Dimethyl ether</th>
<th>Diesel oil</th>
</tr>
</thead>
<tbody>
<tr>
<td>Critical pressure</td>
<td>[MPa]</td>
<td>5.37</td>
<td>3.00</td>
</tr>
<tr>
<td>Lower calorific value</td>
<td>[MJ/kg]</td>
<td>27.6</td>
<td>42.5</td>
</tr>
<tr>
<td>Lower explosion limit</td>
<td>[% vol.]</td>
<td>3.2</td>
<td>0.6</td>
</tr>
<tr>
<td>Liquid density</td>
<td>[kg/m³]</td>
<td>667</td>
<td>831</td>
</tr>
<tr>
<td>Upper explosion limit</td>
<td>[% vol.]</td>
<td>18</td>
<td>7</td>
</tr>
<tr>
<td>Kinematic viscosity of liquid</td>
<td>[cSt]</td>
<td>&lt;0.1</td>
<td>3</td>
</tr>
<tr>
<td>Cetane index</td>
<td></td>
<td>57</td>
<td>40–50</td>
</tr>
<tr>
<td>Molar mass</td>
<td>[g/mol]</td>
<td>46</td>
<td>170</td>
</tr>
<tr>
<td>Surface tension</td>
<td>[N/m]</td>
<td>0.012</td>
<td>0.027</td>
</tr>
<tr>
<td>Vapor pressure</td>
<td>[kPa]</td>
<td>530</td>
<td>&lt;10</td>
</tr>
<tr>
<td>C/H ratio</td>
<td></td>
<td>0.337</td>
<td>0.516</td>
</tr>
<tr>
<td>Stoichiometric ratio of air and fuel</td>
<td></td>
<td>9</td>
<td>14.6</td>
</tr>
<tr>
<td>Chemical structure</td>
<td></td>
<td>CH₃O–CH₃</td>
<td>–</td>
</tr>
<tr>
<td>Critical temperature</td>
<td>°C</td>
<td>126</td>
<td>434</td>
</tr>
<tr>
<td>Self-ignition temperature</td>
<td>°C</td>
<td>234</td>
<td>249</td>
</tr>
<tr>
<td>Boiling point at 1atm</td>
<td>°C</td>
<td>–25</td>
<td>176–370</td>
</tr>
<tr>
<td>Oxygen content</td>
<td>[% mass]</td>
<td>34.8</td>
<td>0</td>
</tr>
<tr>
<td>Carbon content</td>
<td>[% mass]</td>
<td>52.2</td>
<td>86</td>
</tr>
<tr>
<td>Hydrogen content</td>
<td>[% mass]</td>
<td>13</td>
<td>14</td>
</tr>
</tbody>
</table>

The degree of the impact on the environment in the “well to wheel” process also affects the attractiveness of alternative fuel. In recent years, more and more emphasis has been placed precisely on the ecological characteristics of fuels. This results in
targeting the development of combustion engines on the reduction of the emissions of harmful and toxic compounds contained in exhaust gases.

In the self-ignition engines, the ignition of the injected fuel occurs due to the temperature in the combustion chamber which results from the increasing value of pressure. When the temperature in the cylinder reaches the fuel self-ignition temperature, the fuel ignites. The engine parameters are to a large extent dependent on the time and amount of the injected fuel.

Numerous factors affect the emission of harmful compounds such as carbon monoxide (CO), carbon dioxide (CO₂), nitrogen oxides (NOx), hydrocarbons (HC), or particulate matter (PM). In the case of SI engines, the biggest problem is the emission of nitrogen oxides and particulate matter. The research conducted by Kato et al [3] proves that by appropriate control of the moment and fuel dose, and especially by applying split dosing, it is possible to reduce the emission of particulate matter. In order to limit the emission of nitrogen oxides, one most commonly uses exhaust gases recirculation. It is confirmed by research presented by Hountlas et al [4] and Mai-boorn et al [5]. Positive results of their research have created the need to systematize the knowledge on the impact of the change in these parameters on the emission of engines powered by alternative fuels.

2. THE STRUCTURE OF THE FUEL SUPPLY SYSTEM FOR THE SI DIMETHYL ETHER ENGINE

Because of different physical properties of alternative fuel, and in order to enable its application in self-ignition engines, it is required to prepare a special fuel system. For this purpose, it is first of all necessary to prepare a container wherein dimethyl ether shall be stored under a slight pressure. In the temperature of 25 °C, it is necessary to compress the alternative to at least 0.5 MPa, so that it occurred in the liquid phase [6].
Due to strong possibilities of controlling the time and moment of fuel injection, the fuel supply systems of the common rail type have turned out to be suitable for fuelling SI engines. However, because of lower density and worse lubricating properties, it is essential to implement certain changes involving, inter alia, the replacement of seals and providing adequate lubrication of the moving parts. Also, due to the heating of fuel going through the high pressure pump, the unused part of the fuel (returning to the container) must be cooled [7].

3. THE PARAMETERS OF INJECTION AND ATOMIZATION OF DIMETHYL ETHER

The use of modern fuel supply systems of the common rail type for fuelling an SI engine by using DME allows for a very wide range of fuel injection control. Starting from the setting of an elective moment of injection, till the determination of the number of parts that the dose is to be divided up into, as well as identifying the moment of injection of each part.

The research conducted by Suh et al [8] shows that for fixed parameters of injection such as the duration of the opening signal of the injector or fuel pressure, the quantities of the supplied fuel differ depending on the fuel used. It can be observed in Fig. 2 that the maximum quantity of the injected alternative fuel is 2.5 mg/ms larger due to the increased velocity of the spray in the initial phase of injection. The fuel peak flow rate increases in both cases along with the increase in pressure, and occurs earlier in the case of lower pressure.
The impact of Various Strategies of Injection on the emission of the DME …

The difference in the flow rate also affect the changing structure of the spray. The research conducted by Kim et al [9] show that dimethyl ether is characterized by better atomization (Fig. 3).

A smaller diameter of the droplets allows the fuel to evaporate more quickly and to easily mix with the air, thus the whole volume of the combustion chamber is filled with the mixture of a more uniform composition.

One can even achieve better evaporation by the means of dose distribution of the injection. Fig. 4 shows a comparison of sprays of the injected alternative fuel and diesel oil. Both in the case of a pilot dose injection, as well as in the case of the dose division into parts, much better evaporation of dimethyl ether can be noticed.
The impact of various strategies of injection on the parameters of engine work has been tested, inter alia, by Youn [11]. During the conducted tests the measurement of combustion pressure was recorded, which allowed for determining the achieved maximum pressure in the chamber. Fig. 5 shows the influence of various strategies of injection on this parameter. An analysis of the results made it possible to notice that in the case of fuelling the engine with dimethyl ether, the maximum combustion pressure is higher than in the case of diesel oil. The difference is further increased, the later fuel injection occurs.

The mechanism of nitrogen oxides formation has not been fully explained, however, the research conducted, inter alia, by Sayin [12] points to the dependence
of their formation on the occurrence of high temperature and duration time of the combustion reaction. This is confirmed during the combustion of dimethyl ether.

One can notice in Fig. 6 that the emission of NOx decreases with the delay in time of fuel injection. The higher emission of nitrogen oxides during the combustion of DME than during the combustion of diesel oil results from the higher temperature caused by the higher combustion pressure. The reduction in the emission of nitrogen oxides together with the increase in the angular velocity results from shortening the duration of the combustion reaction.

The high temperature also contributes to soot formation. In Fig. 6 one can notice that in the case of diesel oil the amount of soot emitted decreases with the delay of the moment of injection. For DME, the emission of this type of pollution is negligible. This is caused by very good evaporating and mixing fuel with the air, and by the existence of an oxygen atom separating carbon atoms in the particle. As a result, there do not occur local oxygen deficiencies which are one of the main factors of incomplete combustion of fuel [13]. Together with the rise in the angular velocity of the engine, there is an increase in the quantity of particulate matter emitted by the engine fuelled by diesel oil. This is due to the fact that the carbon oxidation reaction proceeds slower and more time is needed in order to combust fuel completely. At higher velocities, this time is insufficient.

![Fig. 6](image)

**Fig. 6.** The emission of a) nitrogen oxides and b) particulate matter for DME and ON and different injection moments [11]

The quantity spread of the emitted hydrocarbons shown in Fig. 7 point to the relationship between the emission of this compound and the moment of injection. With the increase in the delay of the injection moment, there is a rise in the quantity of unburned hydrocarbons. This dependence is particularly evident in the case of higher angular velocities. The emission of HC in the case of the engine fuelled by dimethyl ether is lower than in the case of ULSD (Ultra Low Sulfur Diesel). The increased emission is observed only for a very late injection at high angular
velocities. The decreased emission of hydrocarbons in the case of DME results from better evaporation of fuel, even of the fuel remaining at the ending of the spray nozzle, which is the main factor causing the emission of HC.

Fig. 7b presents the measurement results of the emission of carbon monoxide. The emission of CO for dimethyl ether is, as is it in the case of the emission of HC, lower than for ULSD. What is only noticeable, is a slight increase in the emissions for high angular velocities and the late fuel injection. For ULSD the increase in the emission of CO is significantly higher under these conditions. The formation of carbon monoxide is primarily due to the ratio of fuel and air and the occurrence of incomplete combustion. The presence of an oxygen atom in the molecule speaks in favor of DME, thus the stoichiometric ratio is less than in the case of ON. However, in the case of the injection performed late, there is no time for complete combustion of fuel.

4. CONCLUSIONS

The application of modern injection systems in self-injection engines allows for the possibility of controlling the moment, duration of the injection, and dose division into parts at very wide ranges. This enables better control of the combustion process, which results both in the reduction of the emission of harmful compounds and in the increased performance of the engines fuelled by either conventional fuels or alternative ones.

The research conducted in the world’s leading scientific centers show that different moments of injection lead to a change in the emission of individual toxic compounds. Both for fueling engines with diesel oil and dimethyl ether, an increase in the
delay of injection leads to a decrease in the emission of nitrogen oxides. Because of the higher combustion pressure, the emission of NO\textsubscript{x} is slightly higher while using DME, compared to ON. In the case of diesel oil, the delay in injection also leads to a reduction in the soot emission. It is very difficult to confirm this relation for dimethyl ether because the emission of PM within the whole range is at a very low level, close to the lower range of the measuring device.

The emission of compounds such as hydrocarbons and carbon monoxide for different injection strategies shows an inverse relation than it was in the case of NO\textsubscript{x}. An increase in the injection delay results in a dramatic rise in the emission of hydrocarbons. This relation concerns mainly the engine fuelled with diesel oil, since in the case of DME, this relation is only noticeable at higher angular velocities. As the emission of CO is concerned, this relation is very similar. For dimethyl ether, a slight increase in the emissions is only observable at higher angular velocities.

REFERENCE


ACKNOWLEDGEMENTS

The publication was prepared as part of the Project “Engineer of the Future. Improving the Didactic Potential of Poznan University of Technology”, nr POKL.04.03.00-00-259/12, co-financed by the European Union under the European Social Fund.

Wpływ różnych strategii wtrysku na emisję silnika zasilanego DME – artykuł przeglądowy

Streszczenie

Dynamiczny rozwój przemysłu motoryzacyjnego sprawia, że zużycie oleju napędowego bardzo szybko rośnie. W związku z rosnącymi wymaganiami ekologicznymi prowadzone są badania mające na celu zmniejszenie uciążliwości na środowisko tej gałęzi przemysłu. Jednym z kierunków prowadzonych badań jest poszukiwanie nowoczesnych paliw ekologicznych, do których możemy zaliczyć eter dimetylowy. Zastosowanie tego paliwa przy wykorzystaniu nowoczesnych układów wtryskowych, pozwalających na wtryskiwanie paliwa pod bardzo wysokim ciśnieniem, pozwala na obniżenie emisji w stosunku do oleju napędowego. Okazuje się, że spalanie DME w nowoczesnych silnikach ZS powoduje niemal pomijalną emisję cząstek stałych, co było do tej pory jedną z głównych wad silników tego typu zasilanych paliwem konwencjonalnym.

Słowa kluczowe: DME, ekologia, emisja, paliwa alternatywne, silnik spalinowy, zapłon samoczynny