FEASIBILITY ANALYSIS OF THE APPLICATION OF COMPRESSED NATURAL GAS AS A FUEL FOR COMPRESSION-IGNITION ENGINES

This paper discusses Compressed Natural Gas (CNG) as an alternative fuel, whose physicochemical properties allow co-combustion with conventional fuels in diesel engines. For many years, works have been underway to find an affordable and environment friendly fuel that could be used to power vehicles, which has been additionally prompted by the increasingly stringent exhaust emission limits. Simultaneously, a number of potential problems associated with the use of this fuel in diesel engines have been identified. The usefulness and applicability of CNG in diesel engines in the environmental aspect has been determined based on the analysis of such quantities as the octane number, heat of combustion, auto-ignition temperature and auto-ignition limit. The main purpose of this task is to decrease the exhaust emissions into the atmosphere.

Keywords: alternative fuel, compression-ignition engine, compressed natural gas (CNG), environment protection

1. INTRODUCTION

Social and economic development has entailed the advancement of the automotive industry and the need to take measures aimed at eliminating negative effects of increased air pollution. In recent years, there has been a sharp rise in the number of vehicles and traffic congestion. Primary environmental risks associated with a growing number of vehicles include air, soil and water pollution, increased noise levels and automotive waste [1]. Road transport is considered one of the main causes of air pollution and acoustic hazards. The amount of automotive exhaust emissions is determined by two independent factors: heavy traffic and growing congestion [4].

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For many years, research has been carried out to find an affordable and environment friendly fuel that could be used to power vehicles and keep the increasingly stringent exhaust emission limits. The existing vehicle emission limits have been shown in Fig. 1.

One of such alternative fuels attracting growing interest is CNG. The reason for the attention of the combustion engines specialists is its accessibility and even deposits worldwide [2].

2. AUTOMOTIVE FUEL PROPERTIES

Fuels used to power engines in motor vehicles differ widely. The most important fuel parameters are its calorific value and octane number (spark ignition engines). The higher the octane number the greater the resistance to auto-ignition. An important parameter of diesel fuel is the temperature of its auto-ignition. Its lower value compared to gasoline engines facilitates ignition. Detailed parameters of commonly used fuels have been shown in Table 1.

<table>
<thead>
<tr>
<th>Analyzed parameter</th>
<th>Methane NG</th>
<th>LPG</th>
<th>Gasoline</th>
<th>Diesel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Octane number</td>
<td>115 – 130</td>
<td>125</td>
<td>90 – 98</td>
<td>25</td>
</tr>
<tr>
<td>Heat of combustion [MJ/kg]</td>
<td>53.9</td>
<td>49.8</td>
<td>46.7</td>
<td>44.8</td>
</tr>
<tr>
<td>Auto-ignition temperature</td>
<td>537</td>
<td>460 – 510</td>
<td>320 – 360</td>
<td>270</td>
</tr>
<tr>
<td>Auto-ignition limit in air (vol %. fuel in air)</td>
<td>5 – 15</td>
<td>1.8 – 9.0</td>
<td>1.4 – 7.6</td>
<td>0.6 – 5.0</td>
</tr>
</tbody>
</table>
3. THE PROSPECTS FOR COMPRESSED NATURAL GAS

Compressed natural gas can replace gasoline, diesel fuel and propane (LPG). Its combustion produces a lower amount of undesired gases and is safer in the event of a spill, because natural gas is lighter than air and disperses quickly when released. CNG can be found above crude oil deposits or may be collected from landfills or sewage treatment plants where it is known as biogas.

CNG is compressed to high-pressure natural gas. It is stored and distributed in hard containers usually of cylindrical or spherical shapes at the pressure of 20 – 25 MPa, [6 – 4]. Vehicles are increasingly used worldwide (the Asia-Pacific region, Latin America, Europe and North America). In response to environmental concerns, CNG has been widely used in delivery trucks, transit buses, school buses and trains.

The cost of fuel storage tanks is the major barrier in the popularization of CNG as a fuel. It is also the reason for the fact that transport vehicles are the early adopters of CNG, because carriage of goods can quickly return the money invested in the new, cheaper fuel. Not surprisingly, the number of CNG-fueled vehicles worldwide has been growing steadily by 30 percent annually.

The volumetric energy density of CNG is estimated at 42% of liquefied natural gas and 25% of diesel fuel [6].

CNG is essentially methane (CH\textsubscript{4}) of the calorific value of 0.9 MJ/mole. It burns with oxygen to produce 1 mole of CO\textsubscript{2} and 2 moles of H\textsubscript{2}O. By comparison, gasoline can be regarded as essentially benzene (C\textsubscript{6}H\textsubscript{6}) with its calorific value of approx. 3.3 MJ/mole, which burns to produce 6 moles of CO\textsubscript{2} and 3 moles of H\textsubscript{2}O. Consequently, CNG generates more than 1.6 times more energy per mole of CO\textsubscript{2} than gasoline. For the same amount of energy, CNG produces nearly 40 percent less CO\textsubscript{2}. The corresponding figures for nitrogen oxides are 78 and 25.8 grams respectively.

Carbon monoxide emissions are reduced even further. Due to lower carbon dioxide emission, switching to CNG can help to curb the emission of the greenhouse gas [2]. The ability of CNG to reduce the emission of the greenhouse gas over the entire fuel life cycle will probably depend on the source of natural gas and type of fuel it replaces.

For example, the life cycle greenhouse gas emissions for CNG that comes from California's pipeline natural gas is given a value of 67.70 grams of CO\textsubscript{2} equivalent per mega joule (g CO\textsubscript{2} e/MJ) by CARB (the California Air Resources Board), which is approximately 28% less than the average diesel fuel in that market (95.86 g CO\textsubscript{2} e/MJ).

CNG has numerous advantages and the most important are as follows:
- it does not contain lead, thereby eliminates spark plug fouling (unleaded fuel can still cause plugs to foul),
- CNG-powered vehicles have lower maintenance costs compared to vehicles fueled with other hydrocarbon fuels,
- CNG fuel systems are sealed, preventing fuel loss from spills or evaporation,
- CNG ensures increased life of the lubricating oils (CNG does not contaminate and dilute the crankcase oil),
- it mixes easily and evenly with air,
- it is less likely to ignite on hot surfaces, because it has a high auto-ignition temperature (540°C) and a narrow flammability range (5 – 15%),
- it causes less pollution and is more efficient: compared to gasoline, CNG generates lower amounts of carbon dioxide (CO₂), unburned hydrocarbons (UHC), carbon monoxide (CO), nitrogen oxides (NOₓ), sulfur oxides (SOₓ) and particulate matter (PM). For example, an engine running on diesel fuel generates 22 kilograms of CO₂ per 100 km while covering the same distance on CNG it generates only 16.3 kilograms of CO₂.

Detailed data on the reduction of exhaust emissions from diesel engines fueled with CNG in comparison to diesel fuel have been shown in Fig. 2 [3].

![Fig. 2. Reduction of the exhaust emissions from vehicles fitted with CNG-fueled diesel engines compared to conventionally fueled engines [4]](Fig.png)

By 2020, natural gas will remain the only alternative fuel with potentially high market share and, in terms of the economics of supply, it will be able to compete with conventional fuels, which is evidenced by lower fuel and operating costs. Additionally, CNG ensures a reduction of CO₂ and soot emissions. The emission of NOₓ grows but the emission of HC is reduced. Finally, a lower C/H ratio results in a lower CO₂ emission and fewer grams of CO₂ per energy MJ [10].
4. THE INFLUENCE OF FUEL COMPOSITION ON THE EMISSION OF CO₂

In order to determine the fuel composition, the author applied a C/H indicator. This is an indicator that describes an estimated fuel composition by showing the proportion of carbon to hydrogen. The performed source analysis [10] indicates a reduction in the emission of carbon dioxide for fuels of the composition containing less carbon. From Fig. 3 it results that applying CNG (methane) to fuel diesel engines is justified because of a single atom of carbon bonded to four atoms of hydrogen, which, consequently leads to a lower emission of CO₂ than in the case of fuels of multiple hydrocarbon bonds.

![Fig. 3. The C/H ratio as a function of CO₂ to indicate methane (CNG) and diesel oil [5]](image)

5. APPLICATION OF CNG IN DIESEL ENGINES

Due to the reduced emission of CO₂ following the application of fuels of higher C/H coefficient the investigations related to the influence of fuel composition on the exhaust emissions were carried out at Hamburg University of Applied Sciences [7]. For the purpose of the investigations a mixture of diesel fuel and CNG was used to power a medium-speed diesel engine fitted with a Common Rail IV fuel system. Detailed technical specifications have been presented in Table 2.

The investigations were performed maintaining a constant value of the excess air coefficient of $\lambda = 1.45$, constant engine speed of $n = 1500$ rpm and mean
effective pressure of $p_e \approx 0.7$ MPa. The presented investigations indicate a change in the exhaust emission of the exhaust components by adding CNG as a diesel engine fuel. An increase in the share of CNG in the fuel results in a significant reduction of the emission of carbon dioxide and particulate matter at a simultaneous increase in the emission of hydrocarbons and nitrogen oxides. The results have been shown in Fig. (4).

Table 2

<table>
<thead>
<tr>
<th>Engine specifications [7]</th>
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<tbody>
<tr>
<td>Engine type</td>
<td>4-cylinder, straight, CI engine fitted with EGR</td>
</tr>
<tr>
<td>Capacity</td>
<td>7.01 dm$^3$</td>
</tr>
<tr>
<td>Compression ratio</td>
<td>17</td>
</tr>
<tr>
<td>Power [kW]</td>
<td>129</td>
</tr>
<tr>
<td>Engine speed at maximum power [rpm]</td>
<td>2000</td>
</tr>
<tr>
<td>Torque [Nm]</td>
<td>802</td>
</tr>
<tr>
<td>Engine speed at maximum torque [rpm]</td>
<td>1500</td>
</tr>
<tr>
<td>Fuel system</td>
<td>Common Rail IV</td>
</tr>
<tr>
<td>Injection pressure [MPa]</td>
<td>200</td>
</tr>
</tbody>
</table>
A supplement to the research of the influence of fuel composition on the exhaust emissions are the investigations into the EGR rate during the combustion of a mixture of diesel fuel and CNG. A constant, defined proportion of fuels, 90% of which is CNG, and a constant fuel dose per single injection were applied at the engine speed of $n = 1500$ rpm. The variable was the amount of fuel fed to the engine. The adjustment was performed by replacing the air with recirculated exhaust gas (EGR). The results of the investigations presented in Fig. 5 determine the possibility of reduction of the emission of hydrocarbons (HC) and nitrogen oxides (NO$_x$) by reducing the excess air coefficient ($\lambda$) through a replacement of air with recirculated exhaust gas. A negative consequence of such an adjustment is a significant increase in the emission of particulate matter (PM) and carbon dioxide (CO$_2$).

![Fig. 5. The concentration of CO$_2$, HC, NO$_x$ and PM as a function of excess air coefficient for CNG][10]

### 6. CONCLUSIONS

Due to its ecological, economic and safety-related properties, natural gas is dynamically breaking into world fuel markets. Studies show that the most involved countries utilizing CNG to power vehicles are USA, Canada, Australia, New Zealand, Argentina, and in Europe, Italy, Russia, France, Germany and Sweden.

Natural gas can be used to power passenger cars, buses, taxicabs, minibuses, delivery vans and utility vehicles. Most car manufacturers are widening the range of vehicles fueled with natural gas in their commercial offer [7] or are ready to adapt vehicles for natural gas fueling.

The research for alternative fuels is also carried out due to the declining global stocks of liquid fuels and the need to reduce exhaust emissions from vehicles by utilizing environment friendly fuels. Natural gas meets these requirements. In
addition, it is documented that the world reserves of natural gas are significantly larger than the deposits of crude oil [9].

The usage of CNG in Internal Combustion Engines has defined impact on exhaust gases emission.

Until the application of liquid hydrogen is possible on a large scale, natural gas, due to its physicochemical properties will be the main alternative to gasoline and diesel fuel.

REFERENCES

Streszczenie

W artykule przedstawiono CNG jako alternatywne paliwo, którego właściwości fizyczno-chemiczne pozwalają na współspalanie z paliwem konwencjonalnym w silniku o ZS. Od wielu lat prowadzone są prace mające na celu znalezienie taniego, ekologicznego paliwa, które może posłużyć do napędu pojazdów, stymulowane coraz bardziej rygorystycznymi normami dotyczącymi emisji substancji szkodliwych. Zwrócono uwagę na problemy związane z potencjalnym wykorzystaniem tego paliwa w silniach o ZS. Przydatność i możliwość stosowania gazu CNG w silnikach o zapłonie samoczynnym określono na podstawie analizy takich wielkości jak: liczba oktana, ciepło spalania, temperatura samozapłonu, granica samozapłonu, zmniejszenie emisji związków szkodliwych spalin przez silniki spalinowe o ZS zasilane gazem CNG.