The use of gaseous fuels mixtures for SI engines propulsion

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Abstract. Paper presents results of SI engine tests, carried on for different gaseous fuels. Carried out analysis made it possible to define correlation between fuel composition and engine operating parameters. Tests covered various gaseous mixtures: of methane and hydrogen and LPG with DME featuring different shares. The first group, considered as low carbon content fuels can be characterized by low CO₂ emissions. Flammability of hydrogen added in those mixtures realizes the function of combustion process activator. That is why hydrogen addition improves the energy conversion by about 3%.

The second group of fuels is constituted by LPG and DME mixtures. DME mixes perfectly with LPG, and differently than in case of other hydrocarbon fuels consists also of oxygen makes the stoichiometric mixture less oxygen demanding. In case of this fuel an improvement in engine volumetric and overall engine efficiency has been noticed, when compared to LPG. For the 11% DME share in the mixture an improvement of 2% in the efficiency has been noticed.

During the tests standard CNG/LPG feeding systems have been used, what underlines utility value of the research. The stand tests results have been followed by combustion process simulation including exhaust forming and charge exchange.

1. Introduction

The use of alternative fuels is one of the main solutions allowing the reduction of pollutants emissions nowadays. Those fuels allow also the increase of energy conversion efficiency in the entire life cycle as well as during the chemical energy conversion to mechanical or electrical. Among gaseous alternative fuels the most significant substitutes to conventional fuels are natural gas, LPG and DME in their quite popular applications in both vehicles and stationary applications. Carried on research on those fuels proved that it is possible to replace with them conventional fuels allowing it also to differentiate energy sources. Gaseous fuels have been normalized by means of their chemical composition and physicochemical properties, while modern propulsion and engine control systems became precise enough allowing it to achieve satisfactory ecological and economical results [1,2,3,5,6,7]. The number of dual- fuel and monofuel gas powered vehicles is therefore increasing. Considering the use of already highly accurate and dedicated sequential injection systems, the effective use of gaseous fuels energy still becomes a challenge. The problems with effective combustion process control are mainly related to high ignition temperature, low flame front speed especially in the case of natural gas [8,9,10].

One of the ways of solving this problem is increasing the flame front propagation speed, mainly by adding more reactive fuels like hydrogen or DME. The influence of the addition of those fuels to natural gas and LPG on the combustion process have been presented in many publications.

Fuel mixtures of NG and hydrogen have been widely studied in IC engines [6-11] and their results show that the engine performance can improve and the exhaust emissions can be reduced by adding a small amount of hydrogen.
2. Fuels properties and measurement set-up

Selected chemical and physical properties of gaseous fuels have been presented on figure 1. Fourteen of different fuels were used: gasoline, methane, LPG and fuel blends consisting of:

- methane with Hydrogen addition from 5%, to 50%, by volume,
- LPG with DME addition from 0% to 28% DME by mass, respectively.

![Figure 1](image)

**Figure 1.** Main properties of selected gaseous fuels as a function of c/h ratio (at $p = 100$ kPa, $T = 283$ K, $\lambda = 1$).

The popular passenger car powered by 1.6 liter engine, naturally aspirated with a compression ratio of 9.6, port fuel injection, two valves per cylinder, flat pistons and without external EGR was used in the experiments. The experiments were performed on a BOSCH FLA 203 chassis dynamometer. Main features characterizing the engine installed on the tested vehicle have been listed in the Table 2. Engine performance has been estimated on the basis of acquired dynamic characteristics, defining the power on wheels in function of vehicle speed. Test stand has been equipped with various transducers and sensors allowing the identification of engine operating conditions. Basic measurements and control systems allowed continuous acquisition of engine operating conditions, through registrations of:

- in-cylinder pressures, crank angle, with the TDC identification,
- power on wheels, manifold pressure, inlet air temperature,
- exhaust gases temperature,
- fuel mass flow to the engine.

The in-cylinder pressure was measured by Kistler 6121 piezoelectric pressure transducers and a charge amplifier, Kistler 5011A. The signals were processed in type NI PCI-6143 board in a computer for online pressure measurements. The pressure recording system was also connected to the Kistler 2613B crank angle encoder giving the temporal resolution of the pressure recordings of 0.5 CA. The pressure measurements were recorded and stored on a computer, with recordings performed for 300 subsequent cycles in each test, and were further processed with the help of a script debugged in LabView 7.1 environment.
Table 1. The composition of mixtures prepared for tests.

| Fuel                  | Symbol used on figures | Molecular mass of fuel [kg/kmol] | Stoichiometric air fuel ratio A/F [kg/kg] |
|-----------------------|------------------------|----------------------------------|------------------------------------------|
| LPG 50/50 Methane     | LPG                    | 51                               | 15.76                                    |
| 95%CH₄ and 5%H₂ by vol.| 95NG5H                 | 15.3                             | 17.596                                   |
| 90%CH₄ and 10%H₂ by vol.| 90NG10H               | 14.6                             | 17.72                                    |
| 80%CH₄ and 20%H₂ by vol.| 80NG20H               | 13.2                             | 18.01                                    |
| 70%CH₄ and 30%H₂ by vol.| 70NG30H               | 11.8                             | 18.37                                    |
| 60%CH₄ and 40%H₂ by vol.| 60NG40H               | 10.4                             | 18.826                                   |
| 50%CH₄ and 50%H₂ by vol.| 50NG50H               | 9                                | 19.424                                   |
| 95%LPG and 5%DME by mass| DME                   | 50.75                            | 15.466                                   |
| 89%LPG and 11%DME by mass| DME                   | 50.45                            | 15.101                                   |
| 83%LPG and 17%DME by mass| DME                   | 50.15                            | 14.73                                    |
| 79%LPG and 21%DME by mass| DME                   | 49.95                            | 14.482                                   |
| 74%LPG and 26%DME by mass| DME                   | 49.7                             | 14.168                                   |

Table 2. Engine characteristic.

| Cylinder number and layout | 4R                   |
|---------------------------|----------------------|
| Maximum power             | 55 kW @ 5200 rpm     |
| Maximum torque            | 128 N·m @ 2800 rpm   |
| Displacement              | 1598 ccm             |
| Bore stroke               | 79.0 x 81.5 mm       |
| Compression ratio         | 9.6                  |

3. Research Methodology

The research has been developed according to the predefined program which covered:
- Estimation of power on wheels of the tested vehicle in the function of vehicle speed for the all of the tested blends,
- Estimation of in cylinder pressure in function of crank angle,
- Identification of specific fuel consumption.

The research covering engine indication and specific fuel consumption measurements were carried on the idle, and for WOT at speeds of 1500, 2000, 2500 and 3500 rpm, for each of the prepared blends. During the tests no modifications in the engine control were done. Ignition timing was set up for the petrol operation, while stoichiometric air fuel ratio was continuously controlled in a closed loop mode by the means of the ECU responsible for gas fuel dosing. EGR valve remained closed.

Results recorded during stand tests were used as an input to the mathematical model in the GT-Power. The so-called “reverse run combustion simulation” uses the recorded in cylinder pressure traces as well as other required data including: fuel mass and composition, engine volumetric efficiency to calculate main combustion parameters. The model calculations are based on the equations of energy balance in a closed combustion chamber. The model calculations are supplementary to conducted measurements.

Figures 5 and 6 present the influence of the hydrogen and DME content on the investigated vehicle basic parameters, describing its performance.

4. Results and Discussion

4.1. Effects of Fuel Composition on Power
One of the important performance factors is definitely power measured on wheels $P_w$. The measurements were done on chassis dynamometer at the WOT, for different engine speeds. For the purpose of engine output power estimation, it is necessary to take into consideration transmission efficiency. For the investigated vehicle a correction ratio of $k=0.946$ (according to EEC standard) has been assumed. Tests on a chassis dynamometer determined the influence of different fuels on engine overall performance. Power and torque results have been presented on the chart. Generally torque and power curves have a similar shape, the only difference regards varied position of peak values for different fuels.

Figure 2 presents power on wheels for all tested blends. The power increases with rising hydrogen share. The exceptions are 5% and 10% hydrogen mixtures. Lower power output registered in these cases results from the fact that at 7% of hydrogen share in the mixture, the flame front speed is the lowest. In the case of DME enriched LPG, with a share not exceeding 17%, a small power increase has been noticed. Increasing the DME share above 17%, results in the drop of both power and when compared to propane-butane mixture.

Figure 2. The variation of power at the wheels, for the hydrogen enriched methane and LPG DME blends, for $rpm=2500$, 100% load, $\lambda=1.0$.

4.2. In-Cylinder Pressure Traces and Heat Release

The combustion analysis has been undertaken using in-cylinder pressure traces. Figure 3 shows the $p$-$V$ diagrams, while the IMEP for the methane hydrogen mixture at 2500 rpm and $\lambda = 1$ has been presented on Figure 4. In order to identify the cycle that most significantly represents the average burn characteristics of the evaluated point, the representative cycles have their IMEP, PMEP, peak pressure and location of peak pressure closest to that of the mean value of each parameter, which in turn have been calculated on the bases of 300 subsequently recorded cycles.

Increasing the hydrogen share results in the IMEP drop for mixtures featuring 15 % of hydrogen, higher IMEP values compared to methane can be noticed for shares of hydrogen over 15 %.
Figure 3. p-V diagram and IMEP for engine fuelled by methane enriched by hydrogen, at 2500 rpm; WOT and $\lambda = 1.0$.

Figure 4. IMEP for engine fuelled by methane enriched by hydrogen, at 2500 rpm; WOT and $\lambda = 1.0$

Increasing the hydrogen share in the mixture accelerates the combustion process, however in the cases of hydrogen shares under 15% the amount of heat released in the combustion process is lower or equal to the one obtained for pure amount of heat released in the combustion process is lower or equal to the one obtained for pure methane.

The DME-LPG blends insignificantly increased the peak and the mean pressure values despite the fact that the engine speed and ignition timing remained unchanged. The stability of the combustion process, described by COV_IMEP does not exceed 2.5 % for the mixtures with the DME shares up to 17 % while for higher amounts of DME it reaches 4 %.
In the case of the LPG-DME blend stoichiometric mixture combustion, an early growing in-cylinder pressure and a higher value of the peak pressure have been observed but only in the case of mixtures that did not exceed 17 % of the DME share, Fig. 5. With the increase of the DME fraction above 17 % the cylinder pressure curve rise retarded and the peak pressure crank-shaft angle was delayed leading to a decrease of the peak cylinder pressure along with the increasing DME fraction in the blends. Although the flame propagation speed rises with the increase of the DME fraction in the blends, the retardation in the optimum ignition timing with the increase of the DME fraction still delays the rise of the cylinder pressure. In addition, the constant heating value of the blend with an increase of the DME fraction without the correction of the ignition angle lowers the peak value of the cylinder pressure. Lower ignition energy and temperature of DME is also the main reason for reaching of the maximum pressure values that are close to TDC. The DME mass share in the mixture, however, has a significant influence on the crankshaft angle at which the pressure reaches its maximum value. For the mixtures featuring 5 and 11 % DME content the maximum pressure was obtained faster than in the case of the LPG fuel feed. IMEP for all LPG DME mixtures has been presented on Figure 6.
4.3. Burn Rates
Figure 7 shows typical mass fraction burned (MFB) curves obtained from the GT-Power reverse run simulations.
For a given fuel, at constant $\lambda$ and spark advance, as well as in reduction of the final MFB inside the cylinder. The burn rate also falls as the air fuel mixture is progressively diluted. When comparing results between the different fuels, it is evident that natural gas has the lowest burn rate and is considerably more susceptible to dilution than the hydrogen bearing fuels. This is consistent with its lower laminar flame speed and narrower flammability limits.
On the basis of MFB, presented on Figure 7 it can be noticed that mixtures featuring the DME shares of 5% and 11% not only initiate the combustion faster, but also the dynamics of their combustion is higher than for LPG. For those mixtures the combustion duration is also shorter, while the DME share rising over the 11% retards the combustion initiation, and prolongs the process of combustion. This tendency is characteristic for the entire range of engine speeds.

![Figure 7](image_url)

Figure 7. Variations of CA corresponding to 10, 50 and 90% MFB for various cases of Hydrogen share and DME mass fraction 2500 rpm; load 100%; spark advance 30°, $\lambda = 1.0$.

5. Efficiency of Energy conversion
One of the most factor describing efficiency of Energy conversion in the IC engine is definitively brake specific fuel consumption [g/kWh]. The value if this indicator in the case of described research has been calculated on the basis of the fuel consumption and engine power measurements acquired during completed stand tests. The individual fuel consumption of engine powered by methane with hydrogen addition decreases with increasing volume of hydrogen in mixture, Fig. 8.
Decreasing of the brake specific consumption affects the efficiency of the engine, a changes of efficiency are shown on Figure 9. Increasing efficiency of the engine with rising hydrogen amount in the blend does however limited, because it is connected with the risk of knocking combustion occurrence. The presence of this phenomenon can be noticed in the acquired in-cylinder pressure signal, and was audible in the engine during test.
In the case of LPG and DME mixture the bsfc and overall efficiency evolution have been presented on Figures 10 and 11. Overall efficiency values have been averaged for all recorded points, obtained for defined DME shares in the mixture, and for different engine speeds at WOT. The highest values of overall efficiency have been obtained for the mixtures featuring the DME shares from 5 to 11%. In this range, the DME share allowed it to obtain higher efficiency than in the case of LPG propulsion. The increase of DME content in the blends, over the 11% caused a slight overall efficiency drop.
6. Conclusions
Research covered stand tests of the vehicle equipped with the SI engine, fueled with methane - hydrogen and DME- LPG blends. It was possible to identify the influence of hydrogen volume rate and DME mass share in the mixtures on the overall engine performance, its efficiency and on the combustion process. Moreover, carried out tests give a possibility to understand fundamental combustion properties of HNG and LPG+DME blends, what is important for developing advanced NG and LPG based combustion engines with necessary operating strategies.

Chemical energy of the charge closed in a combustion chamber is released during combustion process the speed and energy profiles depend on the gaseous fuel composition.

General aim of adding hydrogen to methane and DME to LPG is to minimize negative parts in their combustion. Because of the differences in selected properties of methane, hydrogen, DME and LPG an improvement of the conditions for the flame initiation and shortening of the charge heating period are expected.
It has been shown that:
- Stoichiometric combustion of HNG and LPG-DME mixtures reduced ignition delay and create conductive for faster burn,
- HNG reacts faster than pure methane, allowing it to shorten combustion duration, especially in the first phase of flame development.
- LPG and DME blend reacts faster the pure LPG but only for mixtures which consist of no more than 11 % of DME, by mass ratio.
- Heat release during combustion of HNG compares to pure methane increasing for mixtures containing more than 15 % of Hydrogen. The increase of HR does not does not exceed 4.5 %. Increasing of HR does not exceed 4.5 % for tested engine.
- The share of DME in the mixture of LPG DME significantly influence on changes of HR for tested engine.

Future experimental development would foresee the optimization of the emissions of the both pollutant and CO₂ along the reduction of fuel consumption for vehicle driving cycle. It is necessary to investigate widely following set of engine variables:
- Spark advance,
- Compression ratio,
- A wide spectrum of λ values,
- EGR.

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