Acta Polytechnica **54**(1):10–14, 2014
doi:10.14311/AP.2014.54.0010

THE EFFECT OF ADDING HYDROGEN ON THE PERFORMANCE AND THE CYCLIC VARIABILITY OF A SPARK IGNITION ENGINE POWERED BY NATURAL GAS

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Abstract. This paper deals with the influence of blending hydrogen (from 0 to 50 % vol.) on the parameters and the cyclic variability of a Lombardini LGW702 combustion engine powered by natural gas. The experimental measurements were carried out at various air excess ratios and at various angles of spark advance, at an operating speed of 1500 min^{-1}. An analysis of the combustion pressure showed that as the proportion of hydrogen in the mixture increases, the maximum pressure value also increases. However, at the same time the cyclic variability decreases. Both the ignition-delay period and the period of combustion of the mixture become shorter, which requires optimization of the spark advance angle for various proportions of hydrogen in the fuel. The increasing proportion of hydrogen extends the flammability limit to the area of lean-burn mixtures and, at the same time, the coefficient of cyclic variability of the mean indicated pressure decreases.

Keywords: adding hydrogen, natural gas, cyclic variability, spark ignition engine.

1. Introduction

Nowadays, there is increased emphasis on environmental protection in transport. As a consequence reduced consumption of traditional fuels is required, and alternative fuels are sought, in order to reduce dependence on fossil fuels. A possible solution is the use of hydrogen as a substitute fuel for petrol in spark-ignition engines. There is an absence of carbon during complete combustion of hydrogen, and as a result only water vapour and nitrogen are yielded, i.e. no carbon dioxide (CO_2) is released. However, pure hydrogen has some drawbacks as a fuel. There are problems with acquisition and storage of hydrogen, low energy density, higher formation of nitrogen oxides (NO_x), possible abnormal combustion, etc. [1–3]. For these reasons, it seems advantageous at the present time to utilize mixtures of hydrogen with natural gas (or with methane). Synergy of these two fuels can generate general benefits from the resulting mixture, as follows:

flammability limits — as the content of hydrogen mixed with natural gas increases, the range of flammability limits of the mixtures becomes wider. For 50 % content of hydrogen in a mixture, the theoretical limits of flammability under atmospheric conditions range within the air excess ratio $\lambda = 0.48$–3.53 compared with natural gas $\lambda = 0.57$–1.92);

delay of ignition — as the content of hydrogen in mixtures with natural gas (H2NG) increases, the period of physical and chemical preparation of the mixture becomes shorter before the actual visible combustion than when just natural gas is combusted;

energy of spark — the actual ignition of the stoichiometric mixture of gas and air requires the addition of a higher quantity of energy (higher ignition temperature) than when igniting a stoichiometric mixture of hydrogen and air;

nature of burning — as the proportion of hydrogen in a mixture with natural gas steadily grows, the speed of flame spreading increases and thus reduces the actual burning time during which thermal energy is released more rapidly;

emissions — as the content of hydrogen in the mixture with natural gas increases, the atomic ratio of hydrogen to carbon (H/C) also increases, leading to a decrease in emissions that contain carbon (CO_2, CO, CH_x). The production of water vapour becomes greater, as does the production of NOx, which is related to the higher temperature of combustion.

Table 1 presents the basic properties of a mixture of natural gas (NG) and hydrogen (H_2). As can be seen, with an increasing content of hydrogen the mass lower heating value increases, while the fuel density decreases, so that the final fuel energy density decreases as the proportion of hydrogen increases.

The next section of the paper presents experimental results obtained from a Lombardini LGW702 spark-ignition engine, which was used as a power-generator in a micro-cogeneration unit operating on natural gas [4].

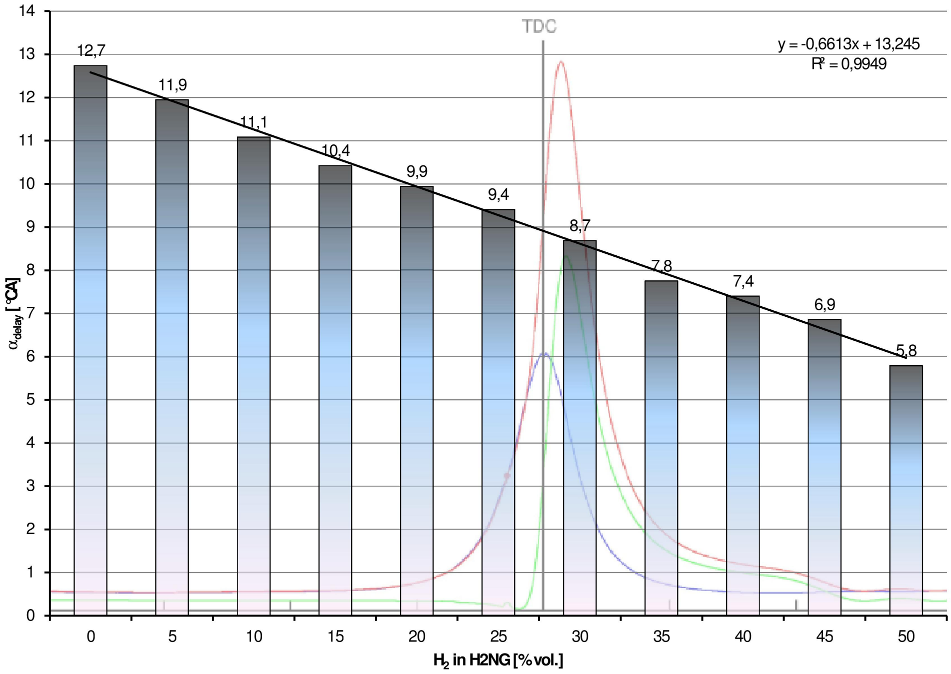

Figure 1. Delay of ignition values (α_{delay}) for various mixture compositions (H2NG0–H2NG50), with indicated line equation and coefficient of reliability (full load, revolutions 1500 min−1, advance of ignition 33.5° CA BTDC, stoichiometric air-fuel mixture).

Parameter	Unit	H2NG0	H2NG10	H2NG20	H2NG30	H2NG40	H2NG50
NG/H2	[% vol.]	100/0	90/10	80/20	70/30	60/40	50/50
Lower heating value	[$\mathrm{kJ\,kg^{-1}}$]	48729	49670	50812	52227	54025	56388
Density	[$\mathrm{kg\,m^{-3}}$]	0.705	0.643	0.582	0.520	0.459	0.397
Molar mass	[$\mathrm{kg\,kmol^{-1}}$]	16.73	15.26	13.79	12.32	10.85	9.37
Air to fuel ratio	[$\mathrm{kg\,kg^{-1}}$]	16.96	17.19	17.47	17.82	18.26	18.84

Table 1. Basic physical-chemical properties of fuel mixtures.

2. Experimental measurements and results

To reduce operating costs (fuel consumption), the experimental measurements necessary for basic fuel analyses were performed on a Lombardini LGW 702 internal combustion engine. The engine is a double-cylinder water-cooled petrol engine with a swept volume of 686 $\mathrm{cm^3}$. The mixture is prepared by a mixer with a diffuser to control the richness of the mixture, with the help of the VOILA electronic control unit. The engine is equipped with an ignition system with manually adjustable advance of ignition. The spark plug is equipped with a KISTLER piezoelectric pressure sensor, which is able to record the dynamic process pressure in the combustion chamber. The pressure was corrected to its absolute value via the reference pressure in the intake manifold in the area of the bottom dead centre (BDC) at the time of the intake stroke. The pressure was measured with a piezoresistive sensor. The resulting pressure signals, together with the signal giving the position of the top dead centre (TDC) and the signal of the spark plug, were processed in a special program generated in Matlab. A total of 190 recording cycles were later analysed. The measurements on the internal combustion engine were performed within the whole range of revolutions, i.e. for various advances of ignition and various compositions of mixtures of natural gas with hydrogen (from 0 to 50 % vol. H_2).

Figure 1 shows the delay of ignition at revolutions 1500 min−1 for various compositions of H2NG mixture. The ignition delay was determined as the period between the moment of initial sparking and the moment when the combustion curve deviated from the compression curve. The greatest delay of ignition was the delay from burning pure natural gas (H2NG0), namely 12.7° CA, which represents 1.4 ms on the time axis. When the proportion of hydrogen increases, this period is reduced, and combustion of the H2NG50 mixture (50 % NG, 50 % H_2) leads to a reduction of this period up to approximately half of the original value (5.8° CA), which is approx-

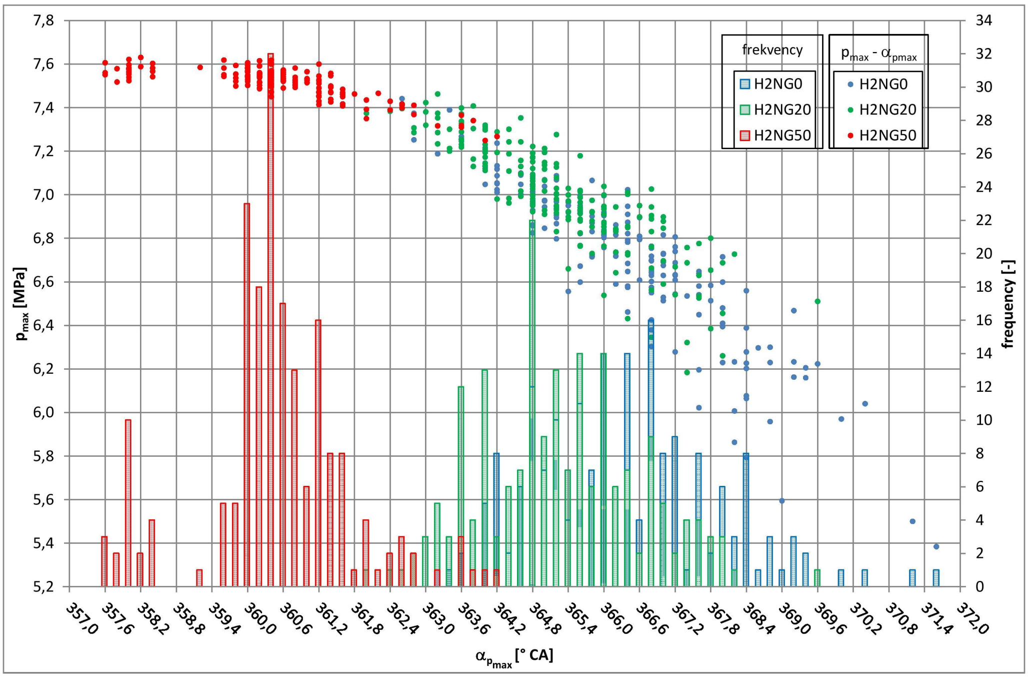

Figure 2. Values of maximum pressure (p_{max}) in the combustion chamber and their position (α_{pmax}), indicating the frequency of repetitions (full load, revolutions 1500 min^{-1}, advance of ignition 33.5° CA BTDC, stoichiometric air-fuel mixture).

imately 0.64 ms. The correlation between the delay of ignition and the proportion of hydrogen in the mixture is strongly negative and almost linear (correlation coefficient $r = -0.99743$). Subsequent connection of the points by a straight line creates an equation of the line that has the confidence coefficient $R^2 = 0.9949$.

The pressure development data that were obtained can indicate the characteristics of the operation of the internal combustion engine (variability of cycles), which is most often expressed by the so-called coefficient of variation (COV). The coefficient of variation is calculated as follows:

The actual reduction in cycle variability contributes to improved performance for the same fuel consumption. As the proportion of H2 increases, the presence of hydrogen in the fuel helps to reduce this coefficient (COV). This will be discussed below. Figure 2 shows the dependence of the position of maximum achieved pressure in the cylinder and the angle at which this maximum is achieved, for various compositions of mixtures of hydrogen with natural gas when the engine operates at revolutions 1500 min^{-1}. It also shows the frequency of occurrence (histogram) of particular pressure values at a given crankshaft angle for 190 cycles. As the proportion of hydrogen increases, the maximum pressure value also increases, and the position of this pressure is lifted closer to TDC, or, more precisely, before TDC, at an unchanged angle of ignition advance. In combusting natural gas, the average value of the maximum pressure is 6.73 MPa at an average angle of 366.3° CA (16 repetitions, measuring value 366.8° CA).

For combusting mixtures containing 50 % hydrogen (H2NG50) the mean maximum pressure was 7.52 MPa at an average angle of 360.5° CA (32 repetitions at 360.4° CA). The coefficient of variation for the H2NG0 mixture was 5.23 %, and for the H2NG50 mixture the COV was 0.894 %. The graph shows that there is a need for regulation of ignition advance in dependence on the content of hydrogen, to achieve the best possible efficiency. Admixing hydrogen to the mixture increases the rate of fire-through of the mixture, which leads to a more rapid increase in the pressure in the combustion chamber.

Figure 3 is a three-axis graph of the optimum ignition angle of spark advance to achieve maximum torque, depending on the ratio of hydrogen mixed with natural gas within the entire speed range. While searching for the optimum, at low speeds we were limited by the minimum adjustable advance (15° CA BTDC). It can be concluded that increasing the hydrogen content shifts the advance value closer to TDC for the entire revolution range.

Another important parameter is the data on the rate of pressure rise, which has a significant impact on the overall service life of the engine. As the number of revolutions increases, the rate of pressure rise decreases for all mixture compositions, see Figure 4. As the content of hydrogen increases, the rate of the pressure increase rises within the entire range of revolutions. The difference between the values for the increase in the rate of pressure rise valid for the H2NG50 mixture and for the H2NG0 mixture is about 0.1 MPa/1° CA for all engine revolutions, which represents an increase by approximately 35 %.

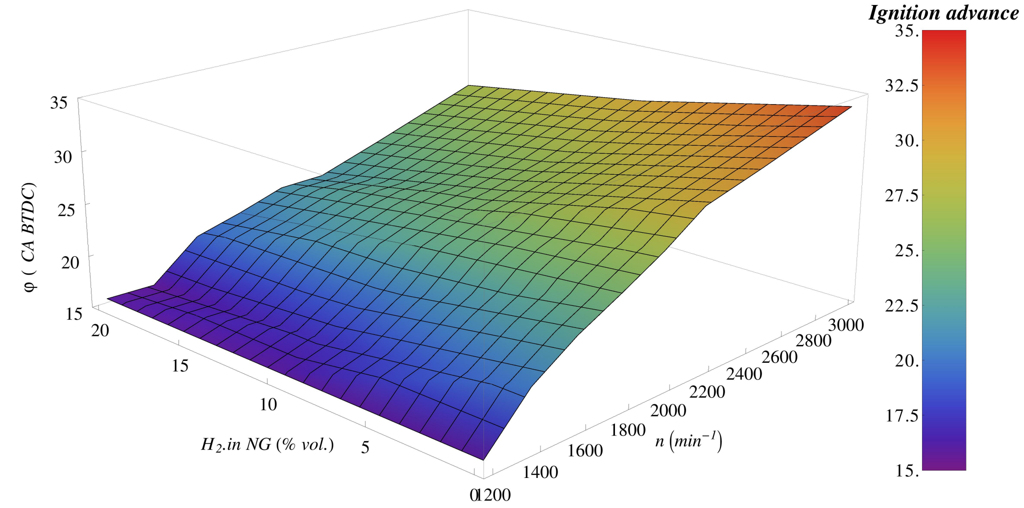

Figure 3. Courses representing the optimum angle of spark advance (φ) for mixtures of various compositions (H_2 in NG), depending on the revolutions (n) of the combustion engine (full load, stoichiometric air-fuel mixture).

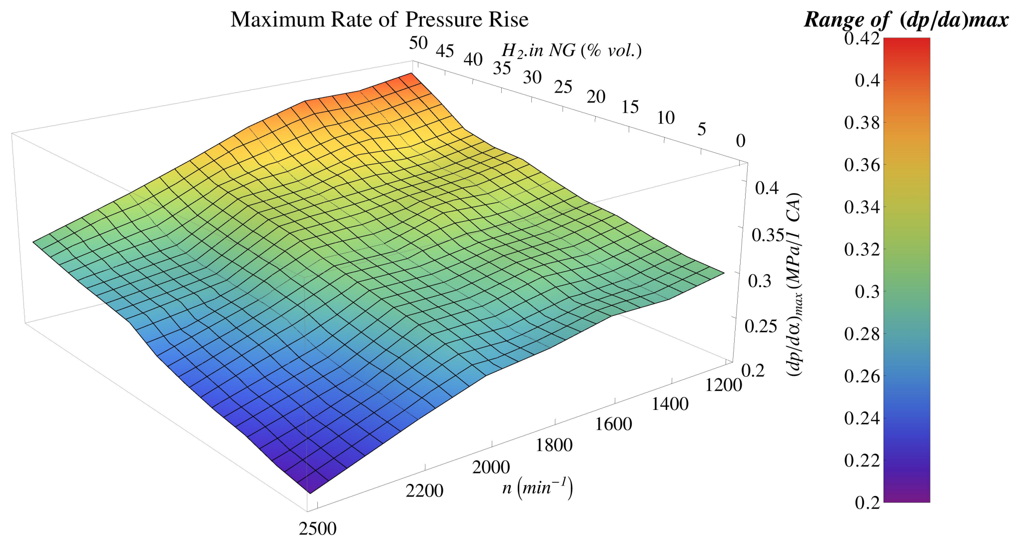

Figure 4. Course of values representing the rate of pressure rise $\left(\frac{\mathrm{d}p}{\mathrm{d}\alpha}\right)_{\max}$ depending on the revolutions (n) for various compositions of mixtures (H_2 in NG) of natural gas and hydrogen (full load, stoichiometric air-fuel mixture, ignition advance 33.5° CA BTDC).

3. Conclusions

Applications that utilize mixtures of natural gas and hydrogen in various proportion compositions have a positive influence on the actual operation of an internal combustion engine. The most important effects of hydrogen are as follows:

- a higher content of hydrogen in the mixture shortens the ignition delay, as the period of physical and chemical preparation of the mixture before visible burning shortens,
- as the content of hydrogen grows, the maximum achieved pressure value increases, and the angle at which this value is obtained is shifted closer to TDC,
- as the content of hydrogen increases, the coefficient of variation of the maximum pressure at all engine revolutions decreases,
- the rate of pressure rise increases as the proportion of hydrogen rises, throughout the entire revolution range,
- to obtain maximum torque, a higher content of hydrogen reduces the value of the optimum angle of ignition advance,
- as the proportion of hydrogen increases, the volumetric efficiency decreases,
- as the proportion of hydrogen increases, the brake specific fuel consumption decreases,
- mixing hydrogen with natural gas in a fuel mixture decreases the concentration of carbon dioxide and the unburned hydrocarbons in the exhaust gases. As a follow-up, the proportion of water vapour and also the amount of nitrogen oxides both increase.

Acknowledgements

This work was supported by the Slovak Research and Development Agency under contract APVV-0015-12 and contract APVV-0090-10.

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