Effect of Gas Mixture Composition on the Parameters of an Internal Combustion Engine

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Abstract

This paper deals with the use of the internal combustion piston engine, which is a drive unit for micro-cogeneration units. The introduction is a brief statement of the nature of gas mixture compositions that are useful for the purposes of combustion engines, together with the basic physical and chemical properties relevant to the burning of this gas mixture. Specifically, we will discuss low-energy gases (syngases) and mixtures of natural gas with hydrogen. The second section describes the conversion of the Lombardini LGW 702 combustion engine that is necessary for these types of combustion gases. Before the experimental measurements, a simulation in the Lotus Engine simulation program was carried out to make a preliminary assessment of the impact on the performance of an internal combustion engine. The last section of the paper presents the experimental results of partial measurements of the performance and emission parameters of an internal combustion engine powered by alternative fuels.

Keywords: natural gas, hydrogen, synthesis gas, engine parameters.

1 Introduction

In the current development of combustion engines, there is a trend to put emphasis not only on performance and cost parameters, but also on environmental parameters, the aim being to achieve the most acceptable values. The spotlight is also therefore on non-traditional power sources. One of these energy carriers is hydrogen.

A mixture of natural gas and hydrogen will above all be used to drive vehicles in urban areas, where there are higher requirements on complying with emission regulations. This mixture combines the advantages of the individual components of the mixture. The current natural gas (H2NG0) is made up mainly of methane (97 % vol.), and has a calorific value of 50 $\mathrm{MJ} \cdot \mathrm{kg}^{-1}$ and an octane number of 130. A combination of this natural gas with oxygen to power internal combustion engines can achieve multiple benefits in terms of combustion and emissions:

- *Limited flammability* – as the proportion of hydrogen in the mixture with natural gas increases, the flammability range also increases. A mixture that contains 30 % of hydrogen has the theoretical flammability range limit $\lambda = (2.67$ to $0.52)$, while when natural gas is burned $\lambda = (1.92$ to $0.57)$.
- *Ignition delay time* – adding hydrogen to natural gas reduces the delay time of ignition, and in the case of a 5 % proportion of hydrogen the delay time is reduced to about one half of the delay when an internal combustion engine operates on natural gas.
- *Burning rate* – increasing the proportion of hydrogen in the gas mixture increases the flame speed, and hence the time of burning the mixture itself, resulting in faster heat release.
- *Emissions* – there is some reduction in the content of carbon (CO_2, CO, CH_x), since the addition of hydrogen increases the H/C ratio. However, the addition of hydrogen increases the amount of NO_x, because there is an increase in the combustion temperature.

The second fuel types that will be used for powering internal combustion engines in cogeneration units are called synthesis gases. These gases are derived mainly by gasification of wastes. The fuel composition depends on the gasifier that is used, and on the type of waste. Synthesis gases can be divided into two basic groups. The first group is synthesis gas with a 30 % proportion of inert gases, and the second group is synthesis gas with a 60% proportion of inert gases. The first group is characterized as fuel SYNGAS 1, with the following composition — (CH_4 – 15 % H_2 – 25 % CO – 30 % CO_2 – 25 % N_2 – 5%). A typical fuel in the second group is referred to as SYNGAS 2, and has the following composition — (CH_4 – 10 % H_2 – 15 % CO – 15 % CO_2 – 10 % N_2 – 50 %). In the rest of this paper these fuels (H2NG0, H2NG15, SYNGAS 1 and SYNGAS 2) will be used to drive a Lombardini LWG 702 internal combustion engine, and the parameters will be evaluated.

2 Lombardini LGW 702 combustion engine

Our workplace has been applying H2NG gas mixtures (0 to 30 % vol. H_2) to drive an LGW 702 internal combustion engine. This is a two-cylinder gas engine with electronically controlled richness of the mixture. The basic characteristics of the LGW 702 engine are summarized in Table 1.

Before the actual application of the gas mixture in a combustion engine, it was necessary to make a simulation analysis to obtain an indicative idea of the behaviour of the internal combustion engine with a given fuel mixture. Simulations were performed on a one-zone model of combustion for the LGW 702 engine, in the Lotus Engine Simulation calculation program (LES). This program is used for simulating the operation of the internal combustion engine, and it is also used as a valuable source of information on the operational parameters of the LGW 702 internal combustion engine in reaction to various gas mixtures that will be experimentally verified step-by-step.

The basic parameters required as input data characterizing a fuel in the LES program are shown in Table 2.

Figure 1 shows a model of the LGW 702 engine in the LES program. This model will serve us later to optimize the combustion engine in terms of performance parameters for various types of fuel blends.

Table 1: Main parameters of the LGW 702 internal combustion engine

Principle of operation	Spark ignition
Number of cylinders and their positions	2, in-line
Angle of crank throw [°]	360
Displacement [cm^3]	686
Bore [mm]/Stroke[mm]	75/77.6
Compression ratio [–]	12.5 : 1
Double overhead camshafts, drive	OHC, gearing belt
Valve timing	IVO – 18° BTDC, IVC – 34° ABDC EVO – 32° BBDC, EVC – 32° ATDC
Preparation of mixture	External, in a mixer, with electronic regulation of the air excess ratio, VOILA Plus system
Cooling	By liquid, with forced circulation, double circular, controlled with a thermostat, cooler ventilated
Lubrication	Pressure, forced-feed lubrication, with filtration, oil 1.6 l
Mass without fillings [kg]	66

Table 2: Basic physical-chemical properties of fuel mixtures

Fuel	M	H/C	ρ	r	H_u	L_t
	[$\mathrm{kg \cdot kmol^{-1}}$]	[–]	[$\mathrm{kg \cdot m^{-3}}$]	[$\mathrm{J \cdot kg^{-1} \cdot K^{-1}}$]	[$\mathrm{kJ \cdot kg^{-1}}$]	[$\mathrm{kg \cdot kg^{-1}}$]
H2NG0	16.64	3.93	0.705	499.7	48 825	17.00
H2NG15	14.45	4.28	0.613	575.4	50 314	17.36
SYNGAS 1	23.72	2.44	0.969	350.5	11 147	3.67
SYNGAS 2	24.52	2.80	1.002	339.1	6 418	2.11

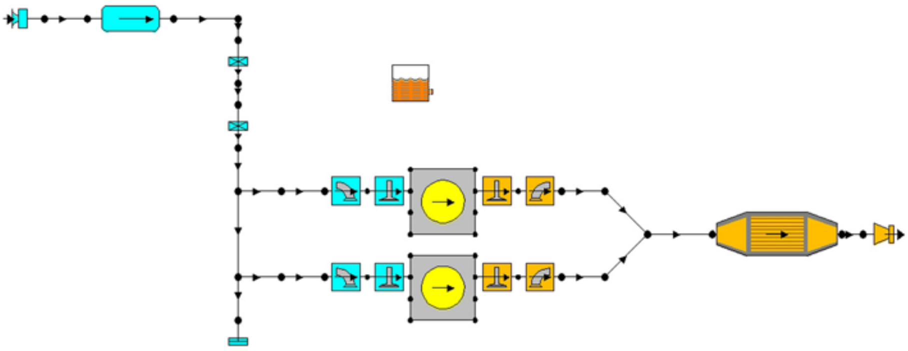

Figure 1: Virtual model of the LGW 702 engine in the Lotus Engine Simulation program

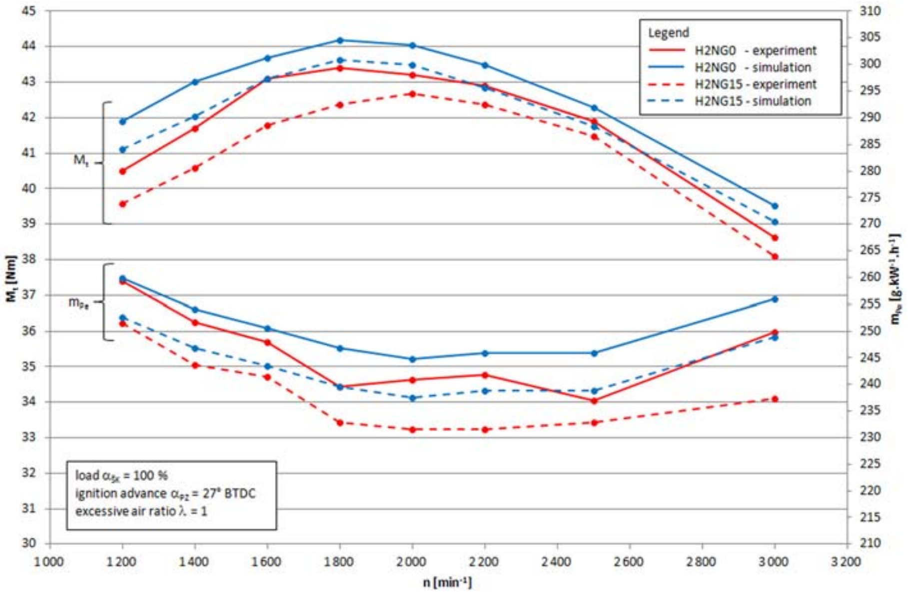

Figure 2: Course of the measured and calculated torque M_t, and specific fuel consumption m_{pe}, depending on the speed n of the LGW 702 engine for H2NG0 and H2NG15 mixtures

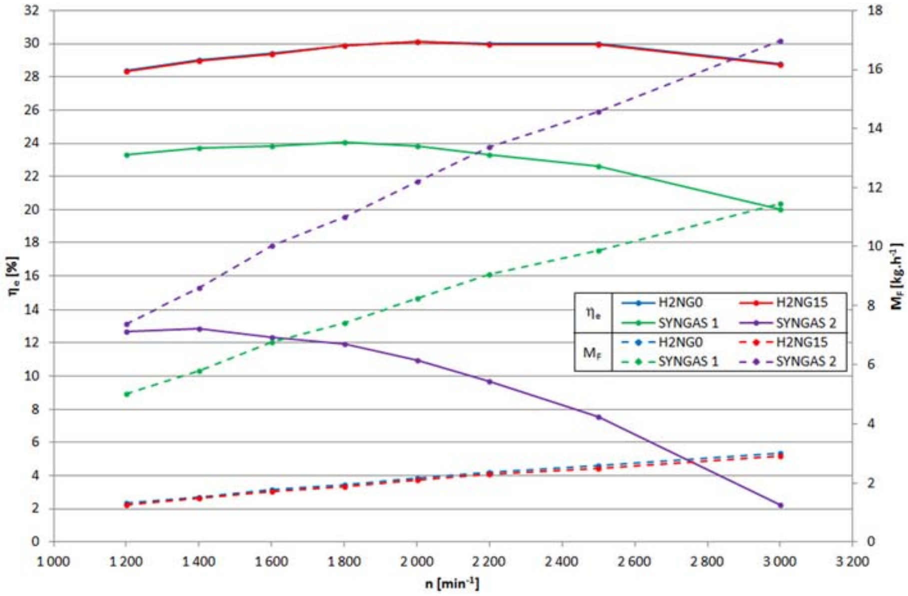

Figure 3: Course of the calculated effective efficiency η_e and the fuel consumption M_F of the LGW 702 internal combustion engine for various fuels for a stoichiometric mixture and a full load

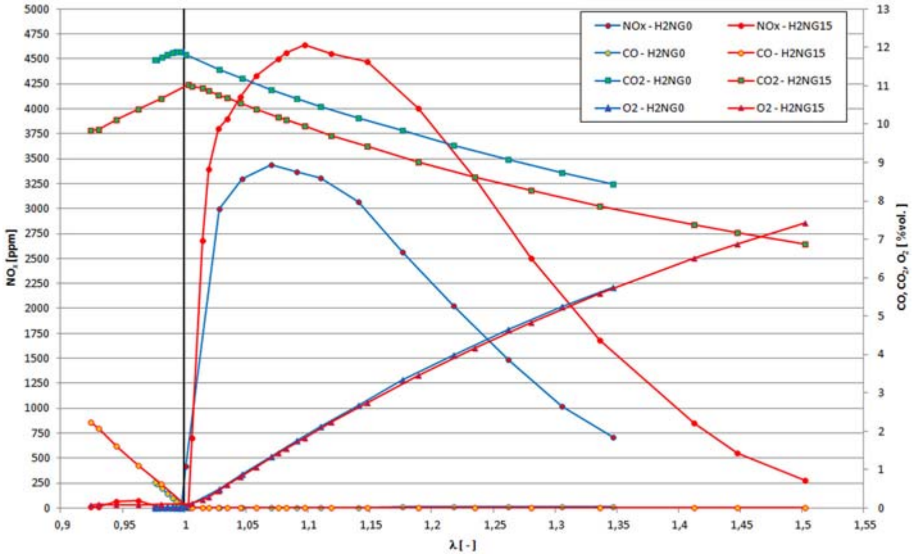

Figure 4: Course of the composition of the exhaust gases, measured behind the catalytic converter, in dependence on the richness of the mixture, for blends H2NG0 (0 % vol. H2) and H2NG15 (15 % vol. H2) at full load and at an internal combustion engine speed of 1 800 min^{-1}

3 Results of the simulations and experiments

Figure 2 shows two basic indicators of the internal combustion engine (torque and specific fuel consumption), which serve for comparing the simulation and the experiment. A comparison of the simulations and the experimental measurements showed that the difference between the real engine and the virtual model of the engine was approximately 2 %. The experimental results also showed that the torque of the engine in operation with H2NG15, compared to natural gas (H2NG0), was on an average 2 % lower, which on an average meant a decrease of 0.8 N·m. The specific fuel consumption was on an average 3.3 % lower when the engine was running on the H2NG15 mixture than when running on natural gas (H2NG0).

Figure 3 shows a simulation of the effective efficiency and the fuel consumption for the four basic fuels listed above. The graph shows that the most effective efficiency was achieved when the engine operated on natural gas, and it was 30 % in the speed range from 1 800 to 2 000 min^{-1}.

By contrast, the lowest effective efficiency was achieved when the engine operated on SYNGAS 2 (60 % inert gases), and the efficiency being around 11 % in the speed range from 1 200 to 2 000 min^{-1}. The mass consumption of the fuel as a stoichiometric mixture was highest when the engine operated on the SYNGAS 2 mixture. In comparison with the use of SYNGAS 1, there was a rise in consumption of about 48 %. The decrease in the H2NG15 mass fuel mixture was about 3 % lower than when the engine operated on natural gas (H2NG0).

Several previously published results have shown a significant effect of blending hydrogen into natural gas with the aim to improve the emission parameters of internal combustion engines. The reason is that hydrogen blending increases the molar proportion of H/C, thus reducing the emissions of CH_x, CO and CO_2. Figure 4 shows the course of the composition of the exhaust gases, depending on the air excess ratio for various fuel types (H2NG0 and H2NG15). As can be seen, there is significant production of carbon monoxide CO in the operation of natural gas (H2NG0) in rich mixtures, where the influence of oxygen deficiency prevents perfect oxidation of CO to CO_2. Conversely, the production of CO in lean mixtures is practically zero. The nature and course of the CO yield is the same when the engine is running on the H2NG15 mixture (15 % vol. H_2).

Complete combustion of hydrocarbon fuels produces carbon dioxide CO_2. It can be seen that the largest proportion of CO_2 is for a slightly lean mixture, with the highest combustion efficiency. From this value, the proportion of CO_2 decreases similarly as in the rich mixture, which is caused by lack of oxygen to complete the conversion to CO_2. The same situation also arises in the lean mixture, because of the limited amount of carbon in the fuel. When the engine runs on the H2NG15 mixture, there is a 9 % reduction in CO_2, on an average, throughout the course, compared to H2NG0. This is because the proportion of carbon in the fuel decreases.

Nitrogen oxides NO_x, in the case of engine operation on natural gas are formed by oxidation of nitrogen and oxygen present in the air. Nitrogen and oxygen oxidize each other at high temperature. As can be seen, the highest growth occurs for a slightly lean mixture that has the highest combustion temperature with a relative abundance of oxygen. With the gradual transition into leaner areas, the amount of NO_x decreases with lower combustion temperature. In the area of rich mixtures with a lack of oxygen, there is a decrease in NO_x. The course of NO_x formation is similar to the combustion of H2NG15 mixture, but due to the higher combustion temperatures, the concentration of NO_x increases to about 35 % of the maximum NO_x values.

The formation of NO_x is closely related to the proportion of residual oxygen in the exhaust gas. In operation with H2NG15 mixture, the formation is lower by about 5 %, than in operation with H2NG0 natural gas. As shown in Figure 4, an increase in the admixture of hydrogen to natural gas increases the operating range of an internal combustion engine, mainly in lean mixtures. The addition of 15 % vol. hydrogen shifts the operating range of an internal combustion engine from around $\lambda = 1.35$ to a value of $\lambda = 1.5$.

4 Conclusion

Mixtures of natural gas and hydrogen have a major advantage over other types of fuels for powering internal combustion engines: they produce lower exhaust emissions, particularly unburned hydrocarbons, namely carbon monoxide and carbon dioxide. However, adding hydrogen to natural gas increases the amounts of NO_x, which can be partly removed in operation modes with lean mixtures. With an increasing proportion of hydrogen, there is a decrease in the performance parameters of the internal combustion engine. However, the benefits include operating the engine on a lean mixture at partial load, because with added hydrogen the operation range of a combustion engine working with a lean mixture increases.

Another benefit of our investigation is its contribution to the application of synthesis gas in internal combustion engines. Synthesis gases have significant potential for effective utilization of low-energy gases in co-generation units.

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