Experimental investigation of combustion characteristics and emissions in a spark ignition engine fuelled with gas in lean operation

M. S. Boulahlib[1], F. Medaerts[2] & A. M. Boukhalfa[2]
[1]*Department of Mechanical Engineering, Mentouri University of Constantine, Algeria*
[2]*INSA/CORIA Rouen, France*

Abstract

This paper proposes an experimental study on the performance and emissions in the lean operation (Φ=0.6–0.7) of a six-cylinder spark ignition engine fuelled with natural gas, pure methane and a mixture of hydrogen in methane (85 CH_4, 15%H_2 by volume). Each fuel has been investigated at 1500 rpm and for various load conditions. Emissions, exhaust gas temperature and pressure cylinder were measured. The objective of the study is to determine how the load and equivalence ratio affect engine characteristics operating with natural gas and the hydrogen-methane mixture. The results show that the hydrogen addition increased HC and NO emissions, as well as the performance and cylinder pressure, but reduced the NOx, exhaust gas temperature and the CO and CO_2 emissions.

Keywords: spark ignition engines, natural gas, methane, hydrogen, emissions.

1 Introduction

In recent years there has been a growing interest in increasing the use of gaseous fuel in spark ignition engines commissioned for light and heavy vehicles [1, 5]. Industrial engines and those of transportation are an important source of greenhouse gas emissions (CO_2) and pollutants (HC, NOx and CO) [7]. In many countries, one of the short-term responses to anti-pollution laws would be the use of CNG (Compressed Natural Gas Fuel) or LPG (Liquid Petroleum Gas) as fuel

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[2–4]. The limits of LPG are well known (from oil, heavier than air, etc.). The choice to switch to CNG has become strategic [5]. In recent years there has been increasing interest in the use of gaseous fuels in spark ignition engines for light and heavy vehicles [1–5] because the regulations on gas emissions are becoming increasingly stringent on pollutants (CO_2, NOx, HC and CO) [6–9].

In addition to being in gas-phase at ambient temperatures and pressures, some physical and chemical characteristics of natural gas allow it to be an attractive fuel for spark ignition engines compared to gasoline. The critical compression ratio of internal combustion engines fuelled with methane is approximately equal to 12.8 [10]. Natural gas is widely available in the world; the most promising method is the lean combustion [11–14]. The major difficulty in the operation of engines with lean combustion with a methane-air mixture is its low flame speed [15]. Karim et al. [17], in an experimental study, have shown that the performance of a spark ignition single cylinder engine powered by methane can be significantly improved through the addition of hydrogen with methane. Bade Shrestha and Karim [18] showed that hydrogen production in situ through the electrolysis of water is not efficient, in connection with the operation of the engine (even if the presence of more oxygen produced with hydrogen in principle tends to improve engine performance). To analyze the effect of hydrogen addition to natural gas, the thermal efficiency of engine and emission, Fanhua Ma et al. [16] have conducted an experimental study on a spark ignition engine with natural gas having variable composition. They note that hydrogen enrichment could extend flammability limits, improve engine operation with a lean mixture, and reduce the duration of ignition. However, nitrogen oxides (NOx) increase with the addition of hydrogen when the ignition is not optimized. Akansu et al. [19] have experimentally studied the effects of a mixture of hydrogen and methane of 0%, 10%, 20% and 30% by volume on a spark ignition engine for different equivalence ratios. The rotation speed (2000 rpm) and engine load were kept constant. The results show that the increase of emissions of NO, HC, CO and CO_2 and the lowering of values of efficiency (BTE) increased by increasing the ratio of hydrogen. Dimopoulos et al. [20] presented a state of the art on cars fueled with natural gas for engines optimized for natural gas, mixtures of hydrogen-gas and exhaust gas recirculation (EGR). Mapping and optimal combinations of ignition and the rate of recycling of exhaust gas have led to important advances: a marked increase in efficiency associated with low levels of NOx has been reported, while the unburned or CO are only minimally affected. The efficiency increases by 3% in the low load, and over 5% in the average loads. The increase of hydrogen in the mixture accelerates the combustion efficiency. On the other hand, the analysis of combustion identified improvements in reaction rates that affect mainly the initial stages of combustion. Thurnheer et al. [21] have conducted experiments to study the performance of different fuels used in internal combustion engines: gasoline, methane and mixtures of fuels containing methane, with 5%, 10% and 15% hydrogen by volume, respectively. A two-liter engine with natural aspiration dual-fuel injection was used. The engine operated in a stoichiometric regime. An optimization combining advance spark timing and a better efficiency has been determined. Experiments were conducted at 2000 rpm and 2 bar mean effective brake pressure. Kahraman et al. [22] conducted an experimental study on emissions of a spark-ignition engine, fuelled by a mixture of methane/hydrogen, functioning at different speeds and with varying equivalence ratio. The results show that excessive speed and increase of air dilution reduce the emission of CO. Hydrogen addition to natural gas reduces emissions of CO and HC in the lean operation conditions. The increase of excess air also reduces the maximum peak pressure in the cylinder.

This paper proposes an experimental study on the performance and exhaust emissions in the lean operation of a six-cylinder spark ignition engine fuelled with natural gas, pure methane and hydrogen mixture in methane (85 CH_4, 15%H_2 by volume). Each fuel has been investigated at 1500 rpm and for various load conditions. Emissions values of CO, CO_2 and NO_x, exhaust gas temperature and pressure cylinder were measured. The objective of the study is to determine how the hydrogen addition affects engine characteristics, emissions, exhaust gas temperature, cylinder pressure and therefore the combustion process.

2 Engine instrumentation

This work was carried out using a laboratory engine MAN E2866E shown in figure 1. A six-cylinder diesel engine was modified to operate on natural gas or biogas. Its main technical features are a bore x stroke of 80x88 and a compression ratio of 12.5:1. Details are presented in Table 1. All experiments were performed in INSA laboratories of Rouen (France).

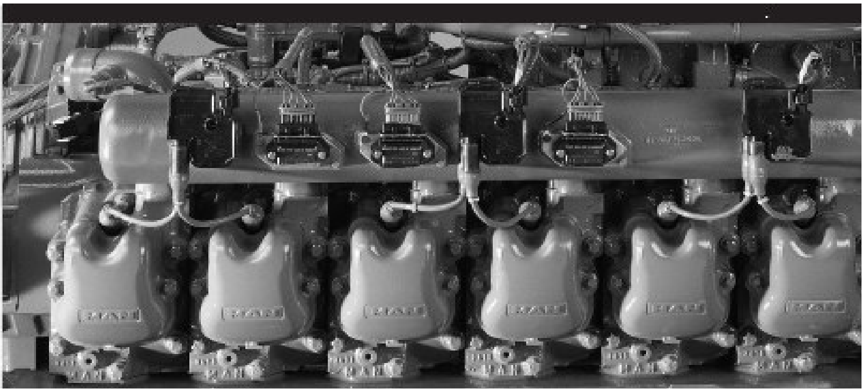


Figure 1: Engine.

2.1 Calibration

A pressure sensor piezoelectric AVL GU13 Z-2 is integrated with a spark plug using an adapter. It has a sensitivity of 15.55 pC/bar, linearity <+/-2% at 400°C, the range of pressure and temperature are respectively 200 bar and 400 ° C and a frequency: 130 kHz. It measures the pressure in the cylinder.

Table 1: Engine specifications.

Engine	MAN E2866E
Thermal power	160 kW
Speed	1500 rpm
Number of cylinders	6 in line
Cooling	Water
Bore	128 mm
Stroke	155 mm
Displacement volume	11 970 cm^3
Torque at 1550 rpm	880 N.m
Equivalence ratio	0.7
Firing order	1-5-3-6-2-4

The measurement of pollutants has been carried out by ECOM JF analyzer, of combustion emissions (O2, CO_2, CO, NO, NO_2, NOx, HC, H2). This multi-gas analyzer has a sampling line heated unburned. For all engine parameters such as rotation speed, power, load, engine temperatures at various points in and out of the water, of the oil lubrication, of the exhaust of the exchanger, are recorded on a control panel connected to a computer system for acquisition and storage.

A measurement campaign was carried out for various load conditions supplied at a constant speed of 1500 rpm. The first focus of our study resides in an investigation on spark ignition engine fuelled with natural gas in lean operation.

The second part is a comparison of pure methane, methane-hydrogen mixture, natural gas, and determine the influence of minor compounds found in natural gas such as ethane (4.8%), nitrogen (1.3%) propane (1.2%) and carbon dioxide (0.79%) on emissions in a spark ignition engine in lean combustion regime (Φ=0.7).

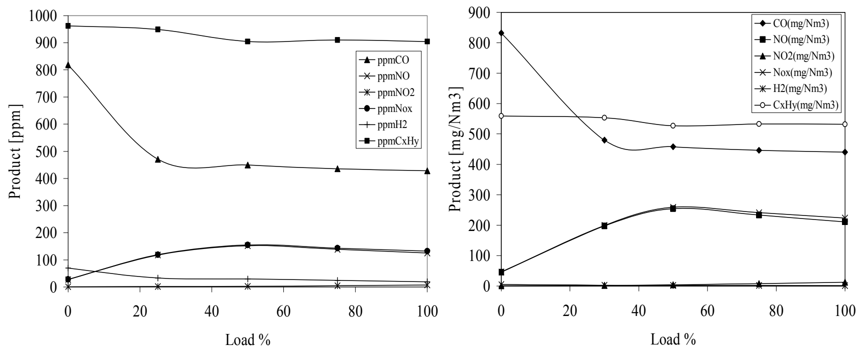
3 Results and discussion

3.1 Natural gas operation

The field of product (CO, NO, NO_2, HC) are showed on the figure 2a and 2b (profiles are normalized by methane volume) versus load on the engine.

The maximum value of product is located in the zone of low load for HC and CO, and it is practically attenuated in the middle and high load for CO. The production of NOx is clearly illustrated. Indeed, the initial mass fraction of NOx increases in the low load and is completely stabilized before 50% load.

In areas with high equivalence ratio, only a small part of NO originates in the flame, most formed in the gases leaving the flame. The process of combustion and NO formation are decoupled. The most important factors governing emissions of NO are equivalence ratio, load, and consequently the gas temperature. Figures 3 and 4 represent the changes in gas temperature as a function of load where we notice an increase in temperature from low load to



(a) (b)

Figure 2: Product values versus load.

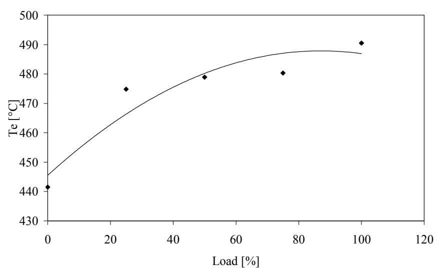


Figure 3: NOx values versus temperature.

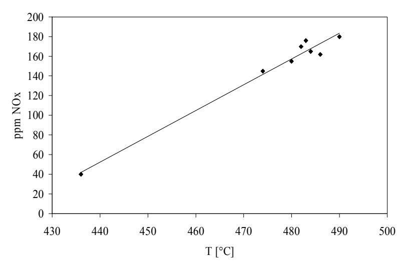
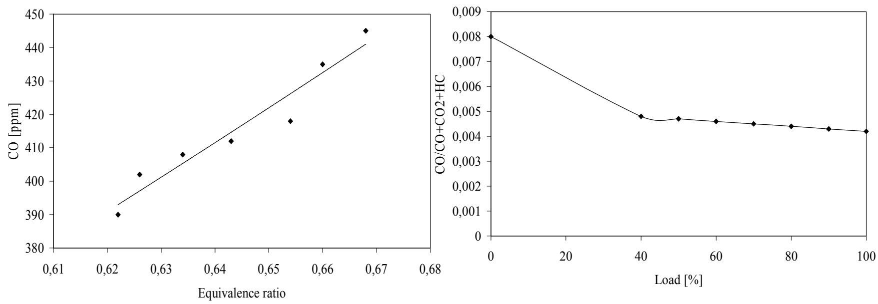


Figure 4: Temperature of exhaust gas values versus temperature.

reach a plateau from 50% load. NOx formation is highly dependent on temperature. It is clear that the engine load has the effect of increasing gas temperatures and consequently the production of NOx.

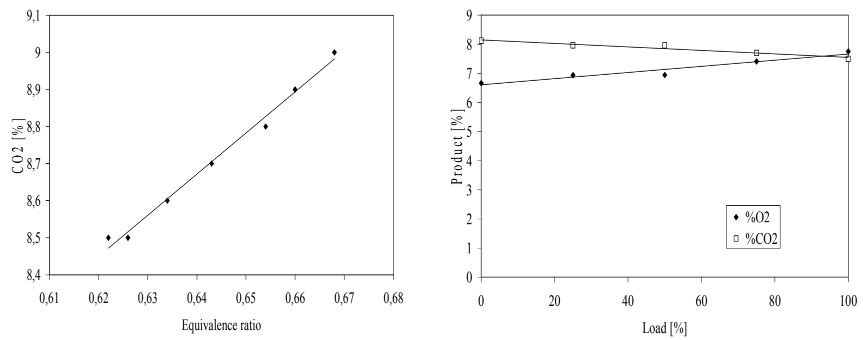
The formation of CO acts as an essential intermediate step in the process of oxidation of hydrocarbons leads to the final product CO_2: the rate of oxidation of fuel depends on the concentration of available oxygen, the gas temperature and time left available to the reactions to be accomplished, then the engine speed. Reducing emissions of CO is in improving the uniformity of composition of the mixture and the impoverishment of the mixture at admission. Figure 5a shows the CO according to equivalence ratio in a range of lean (between 0.6 and 0.7). The main parameter governing the emissions of CO is fuel mixture. It is clear that the increase in equivalence ratio, results in a net increase of CO production, but much less than in the rich equivalence ratio where lack of oxygen leads to incomplete combustion.

In Order to compare the combustion efficiency depending on load, it is interesting to study the proportion of CO in the carbon products. Figure 5b shows the CO emissions compared to the amount of other pollutants (CO, CO_2



(a) (b)

Figure 5: CO values versus equivalence ratio and load.



(a) (b)

Figure 6: CO_2 (a) and product (b) values versus equivalence ratio and load.

and HC) as a function of the load. It is clear that behavior in two steps is reported. A sharp decrease between 0 and 40% load. A plate curve followed, indicating a combustion improvement. However we note that the emissions unloaded case is twice as large in full load. There are therefore the proportions of CO decrease significantly when the load increases. This indicates that the fuels are converted into CO_2 at full load and therefore the combustion is better and cleaner. We note also that fuel is unloaded not very clean. The presence or not of carbon monoxide is an indicator of the quality of combustion. The appearance of carbon monoxide implies a decrease in the amount of carbon dioxide. In a complete combustion of all carbon fuels is transformed into water and carbon dioxide, CO_2 is a good indicator of the combustion mixture. Figure 6a represents the evolution of CO_2 as a function of wealth. It is clear that in the studied range of equivalence ratio growth in CO_2 emissions versus equivalence ratio, because the percentage of carbon input directly controls the rate of formation of CO_2, it is logical that the CO_2 emissions increase with equivalence ratio and decreases as the load increases, fig. 6b.

Figure 7 show an increase in the peak values of the average pressure. This is due to the low ignition energy of the NG and its larger flame velocity, fig. 7. The

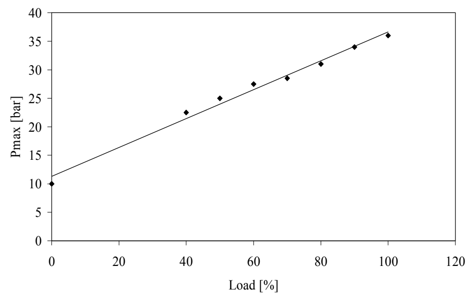
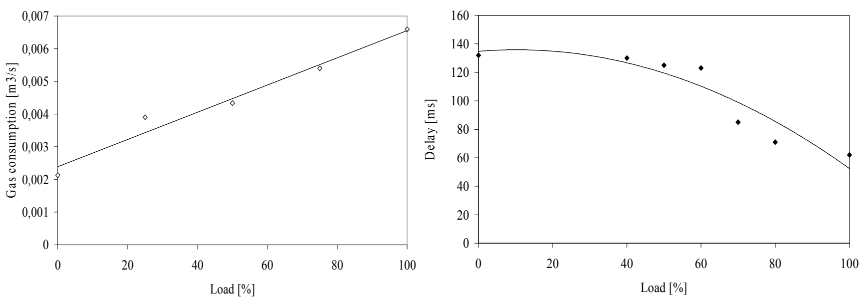


Figure 7: P_{max} values versus load.



(a) (b)

Figure 8: Gas consumption (a) and delay (b) values versus load.

mechanical power increases with the load, the work done must be more important and the maximum pressure.

The results also show the consumption of fuel is clearly illustrated. Indeed, the initial mass fraction of methane decreases in the low load and is completely burned just at high load, fig. 8a. Based on the evolution of the burning time depending on the load, we can say that combustion propagates better at full load. The combustion is better and a higher temperature which reduces emissions of carbon monoxide, CO prevents release of maximum energy, fig. 8.

3.2 Comparison of natural gas, methane and hydrogen methane mixture

The comparison of three fuels namely natural gas, pure methane and methane-hydrogen mixture will be able to enlighten us on the advantages and disadvantages of each. As we compare natural gas, pure methane and hydrogen methane mixture, we can see the influence of all these compounds simultaneously and not one by one. However nitrogen and carbon dioxide being low in quantity compared to the proportions in the injected air, the differences in the properties of methane and natural gas are therefore mainly due to ethane and propane.

On oxides of nitrogen (Figure 10a), pure methane emits a little more than natural gas and much more than the mixture methane/hydrogen. The small difference between natural gas and methane can be explained by the difference in temperature. Indeed the formation of oxides of nitrogen is influenced by the maximum temperature during combustion and the rate of oxygen. This suggests to us that the combustion temperature is higher and the excess of oxygen caused by the formation of carbon monoxide allows nitrogen oxides to form. The reaction mechanisms of hydrogen are different from those of carbon chains, it is likely that the oxidation reaction of hydrogen with concurrent with the forming oxides of nitrogen. The burn gases are waste gases from previous combustion cycle or gas burned intentionally recycled to control NOx emissions. The burn gases play a role in diluting the fuel mixture and the temperature reached after combustion varies inversely with the quantity of gas burned. Therefore, increasing the fraction of burnt gas reduces emissions of NOx. However, it simultaneously reduces the burning rate and a value too large fraction burned brings instability of operation. We find most of unburned carbon in the exhaust gas to the CH_4/H_2 mixture which contains the least fuel-based carbon. We can therefore say that hydrogen tends to promote its combustion at the expense of methane. The unburnt rate is slightly higher for natural gas than for methane, this is probably due to ethane and propane which are more difficult to oxidize, fig.10b.

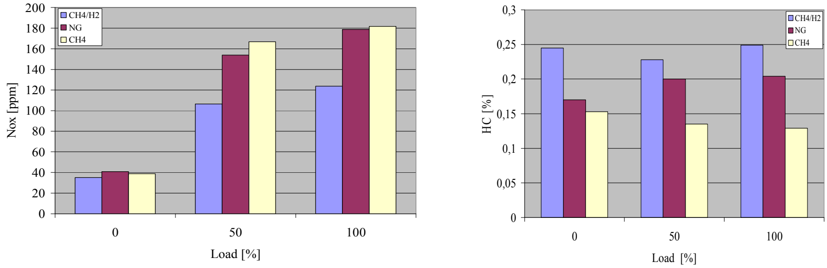
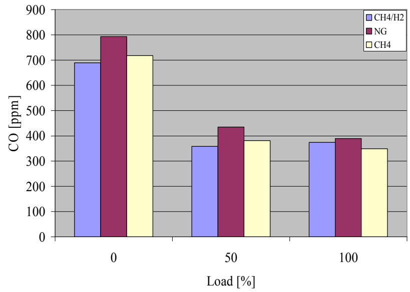
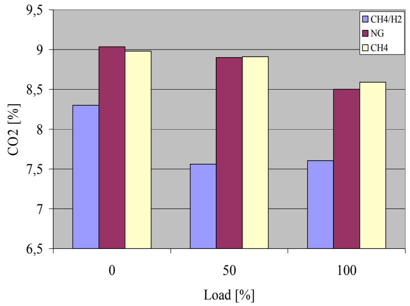


Figure 9: NOx and Hc values versus crank angle.

Emissions of carbon monoxide and carbon dioxide are lower (figure11) for the mixture methane/hydrogen. This is easily explained by the fact that the combustion of hydrogen emits only water, these emissions are due solely to methane that is present only 85%. When comparing the emissions of methane and natural gas, we see carbon dioxide is slightly more present for combustion to natural gas because it has several carbon compounds (ethane, propane) and must therefore form more carbon dioxide. Regarding the pollution of carbon monoxide is much higher for natural gas which can be caused by a greater maximum temperature. The combustion of methane with the addition of propane and ethane is therefore at temperatures greater than that of methane alone. There is therefore from these results that the combustion of methane is less polluting than that of methane with ethane and propane.



(a)



(b)

Figure 10: CO and CO_2 versus load.

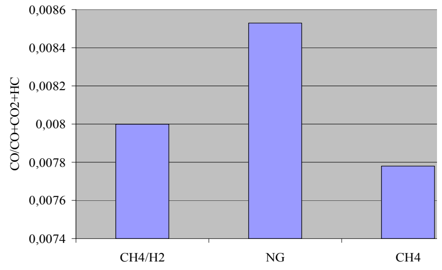


Figure 11: CO for different fuels.

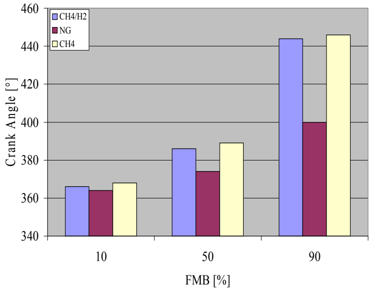


Figure 12: Angle at which 10%, 50% and 90% of the mass fraction is burned.

When we look at the pollution of carbon monoxide for methane and the mixture methane/hydrogen, we find a very small difference. This suggests to us that the 85% methane mixture pollute almost as much as pure methane. To verify this we looked at the proportion of carbon monoxide in the carbon products (i.e. carbon monoxide, carbon dioxide and unburned). That is to see how much carbon methane formed from carbon monoxide.

Figure 12 shows that pollution of natural gas is more important than that of pure methane and hydrogen-methane mixture. Hydrogen thus plays a negative role in the methane combustion. But pollution of the mixture methane/hydrogen remains the lowest. The combustion of natural gas or methane with a small proportion of ethane and propane in turn is the most polluting.

In figure 13 representing the angles for which 10%, 50% and 90% of the mass fraction is burned, it is clear that the natural gas combustion was much faster than the mixture and methane. We can therefore say that the ethane and propane accelerate combustion and reduce the time of self ignition. For the mixture methane/hydrogen and pure methane, we notice that they have the same delay autoignition but the burning mixture is a little faster. The findings should be taken with caution because the uncertainty is greater than the gap between the two gases. We can therefore say that the 15% hydrogen mixture had little or no influence on the progress of the reaction.

4 Conclusion

We analyze the combustion of methane gas mixture of methane and hydrogen. By taking methane as a reference so we could see the influence of one part of the addition of 15% hydrogen and the other from the addition of 5% to 1% ethane and propane. Adding hydrogen aims to reduce polluting emissions, and indeed we have reduced emissions of carbon dioxide because the carbon supply was less important and oxides of nitrogen because the reaction mechanisms of hydrogen are probably those competitors of these oxides. However with the addition of 15% hydrogen, we found an increase in carbon monoxide and unburned carbon. Hydrogen has prevented the proper combustion of methane. Indeed, the methane has a better combustion alone. The addition of hydrogen greatly alters the reaction rate and the time of autoignition, it accelerates only slightly. By cons it greatly increases the maximum pressure. For the addition of ethane and propane, we found that the delay autoignition was lower and the reaction was much faster. This has the effect of increasing emissions of carbon monoxide and slightly those of oxides of nitrogen.

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