Effects of HRG Gas Addition on Performance and Emissions of a SI Engine Fuelled with Liquefied Petroleum Gas

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The present contribution describes the results of an experimental research where LPG-air mixture was enriched with a Hydrogen Rich Gas (HRG) produced by the electrical dissociation of water. Experiments were carried out at engine light and mid load condition. Detailed results are shown, namely engine torque and efficiency, exhaust emissions (NO_x , CO, CO_2 , HC) and cyclic variability, related to combustion characteristics.Some possibilities are emphasized to improving engine performance and emissions in correlation with the amount of HRG, the equivalence air-fuel ratio and the engine operating condition.

Keywords: LPG, hydrogen, HRG, combustion characteristics, emissions

The perspective of oil resources depletion and the increasing severity of regulations on exhaust emissions have stimulated nowadays interest in promotion of alternative fuels for internal combustion engines. Hydrogen is considered an alternative fuel of the future, being long-turn renewable and "clean" burning. In the absence of carbon, major pollutants, typical for petroleum based fuels like CO and CO_2, unburned hydrocarbons (HC) and smoke, are avoided. Nitric oxides (NO_x) are the only pollutants generated by hydrogen, eventually increased by higher combustion temperature.

As an energy medium, hydrogen has some combustion characteristics which are adequate for the spark ignition (SI) engine, especially: limits of flammability in air (2.96 …75%) much larger than methane, propane or gasoline, high research octane number (RON=130), high maximum ignition energy (0.02 mJ) about an order of magnitude lower than for other fuels and a high auto ignition temperature (828K). The operation of SI engines on pure hydrogen is considered at present a long term option, due to economic and technical reasons. The use of hydrogen as an additive to the conventional fuels has appeared instead as a good opportunity to join the main advantages of both fuels.

Extensive studies carried out with gasoline as main fuel has shown a beneficial influence of relatively small amounts of hydrogen in shortening the first phase of combustion, resulting in an improved combustion. All experiments with gasoline-air enrichment with hydrogen have confirmed an extended range of engine stable operation towards lean limits and the extension of the dilution limit of the fuel-air mixture by exhaust gas recirculation (EGR). With regards to emission, CO decreases significantly by hydrogen addition to leaner mixtures. NO_x emissions tend to increase at low excess air. If making use of extended stable lean limit obtained by hydrogen addition, NO_x can be lower; even better results can be obtained by using the improved EGR tolerance, instead of dilution with air. The hydrogen – enriched, EGR dilute operation appears as an attractive alternative to the stoichiometric conventional fuel, with higher engine efficiency and lower NO_x emission [1-6].

Important limitations for the use of hydrogen, especially for automotive engines, are related to certain issues such us on-board storage and safety, as well as the lack of infrastructure distribution. Different strategies were thus approached for on-board production of hydrogen.

A hydrogen-rich gas was obtained by processing a certain fraction of gasoline in a partially oxidative reformer (Plasmatron), through the reaction.

$$C_mH_n + \frac{m}{2}O_2 \rightarrow mCO + \frac{n}{2}H_2$$

A typical composition of the gas is (by vol.): 21% H_2, 24% CO and 55% N_2 [7].

Another continuous on-board production of hydrogen can be obtained by water electrolysis, using directly or indirectly the engine output as a source of energy. Reduction of the energy consumption is thus a main of water electrolysis.

The Hydrogen Rich Gas (HRG) has been developed by Hydrogen Applications Inc. from Clearwater, Florida USA. The new gas would be obtained by a special alkaline dynamic electrolysis of water, with an improved efficiency of process. Compared with similar types of gas, like Brown Gas or Rhode Gas, the composition of the HRG gas would be different. The claimed chemical analysis would consist of 64…67% (vol) hydrogen, 31…33% oxygen and 0…5% some other chemical constituents of hydrogen with oxygen - OH, H_2O_2, H_2O [8]. Its chemical analysis is still a matter of dispute.

HRG obtained with an electrolyser produced under license by ROKURA Inc. in Romania has shown a lower chemical reactivity than the H_2 – O_2 stoichiometric mixture. The laminar flame speed based on experiments made in a combustion cell, at 2 bar and 298 K as initial conditions was 5% lower than in H_2 – O_2 stoichiometric mixture. The auto ignition temperature found in the combustion cell externally heated, with the same initial condition was 743.6 K [9, 10].

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The present study was conducted to determine the effect of adding HRG gas to the Liquefied Petroleum Gas (LPG). There are limited data assessing the effect of hydrogen addition to a LPG fuelled a SI engine. In the paper by Choi et al. [11] experiments were conducted with an one-cylinder engine operated at full load, 1400 rpm and minimum spark advance for best torque (MBT). Two different concentration of H_2 in the mixture with LPG, calculated to maintain equal heating value, were compared with pure LPG. The relative air-fuel ratio λ was also varied from 0.8 to 1.5, with the ignition timing maintained at MBT. No merits of the hydrogen enriched LPG for brake mean effective pressure (BMEP) and brake thermal efficiency (BTE) were found. Hydrogen addition is an advantage in reducing HC emissions; while NO_x emissions are higher compared with the pure LPG fuel, with a peak at around λ = 1.2. CO emission is not influenced by H_2 addition.

Different conclusions have resulted in a study carried out by engine simulation with the AVL Boost software [12]. Significant effects of addition a mixture of H_2 and O_2 in a ratio of 2/1 by volume (supposed to correspond to the water electrolysis), were found for the engine operating at full load: the shortening of the combustion duration, with the consequent improvement of BTE; an increase of NO_x and CO emissions within λ=0.8 … 1.4 domain.

The authors of the present paper had previously explored the potentialities of the LPG enrichment with HRG gas. Experiments carried out on an automotive SI engine operating with LPG and different concentrations of HRG had shown a beneficial influence of HRG gas, at lean mixtures, in improving BTE and BMEP and the abatement of CO, CO_2 and HC emissions; NO_x were generally higher [13].

The present work presents the results of a systematic investigation on performance and emissions of SI engine fueled with LPG enriched with HRG gas. For calculation necessities, only molecular hydrogen 66.5% and oxygen 33.5% were considered as components of HRG gas.

Experimental part

The experiments were carried out on a four stroke car, SI engine. Main specifications of the engine are: 4 cylinders, 76 x 77 mm bore x stroke, 1397 cm^3 displaced volume, 9.5 compression ratio.

LPG and HRG gas were individually supplied to the engine: the first was introduced in the original carburetor, adequately modified, the second upstream the carburetor (fig 1).

HRG gas was delivered by the electrolyser produced by ROKURA, provided with a system to control the gas flow rate. Absolute pressure of HRG gas at the entry in the engine inlet system was 1.2 bar. The pressure in the inlet manifold was kept the same as in the situation of engine fuelled with pure LPG, by adequately changing the throttle position.

The experimental test bed was correspondingly equipped in order to collect and acquire as much as possible of relevant parameters characterizing the electrolyser state and the engine operating condition.

In this sense, the electrolyser was equipped with instrumentation for measuring its electrical energy consumption, the temperature and pressure inside the gas circuit and the gas flow rate delivered to the engine. The instrumentation was adequately selected to ensure safety operation and monitoring of the engine fuelled with LPG and HRG gas. The HRG gas line was thus provided with flame arrestors, electro-valve and unidirectional vent.

Concerning the engine operation parameters, the instant torque and speed were measured and controlled by an eddy current dynamometer. The exhaust emissions (CO, CO_2, NO_x and HC) were measured by a gas analyzer AVL DiGas 4000. A system with pressure transducer Kistler 601 A, charge amplifier Kistler 5001 C, data acquisition card AVL Indimeter 617 and crank angle encoder AVL 364 was used to measure the in-cylinder pressure. For each operating point during the test program in-cylinder pressure for 200 consecutive cycles have been registered; oil temperature, coolant temperature, exhaust temperature, inlet pressure were measured with different sensors.

Test conditions were light load, 1600 rpm, considered as representative for the city traffic, and mid-load, 2500 rpm, representative for the inter-city traffic; the load was identified by the depression in the inlet manifold: p_{ca} = 540 mbar for light load, p_{ca} = 370 mbar for mid-load. Pure LPG was firstly delivered to reach a certain relative air-fuel ratio λ. HRG was then gradually introduced and LPG adequately reduced, to reach the same λ. By a similar manner, the relative air-fuel ratio was progressively increased to about λ = 1.3 at light load, and λ = 1.7 at mid-load. Tests with gasoline at various λ values were also conducted for comparison.

The ignition timing was also varied for each operational condition of the engine, to find the minimum spark advance for best torque (MBT). As a general trend, the MBT ignition timing was retarded towards TDC when HRG concentration increased. Final data comparisons concerning the effects of HRG addition, at various λ and engine speed and load, were made at MBT.

Brake thermal efficiency was calculated with the equation.

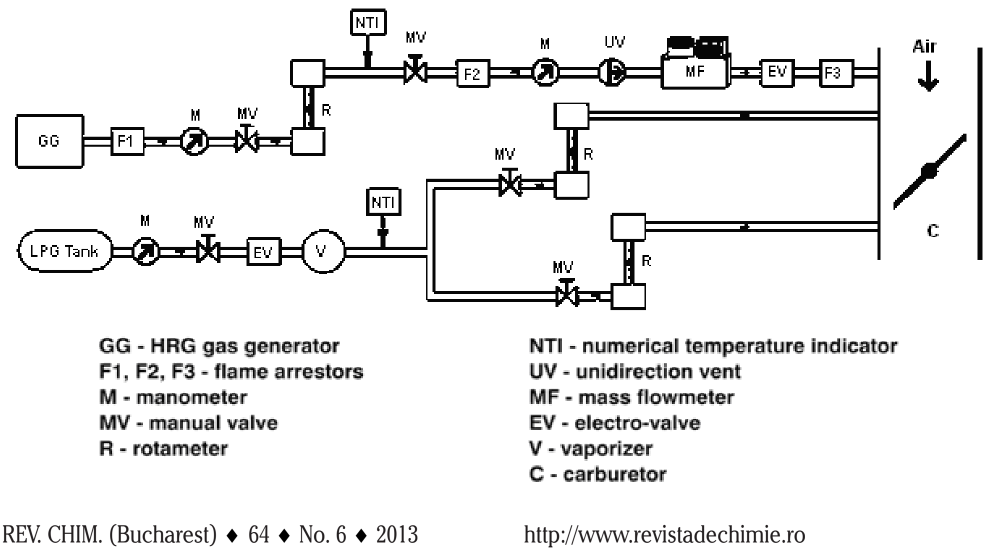

Fig. 1 Schematic of the fuelling system

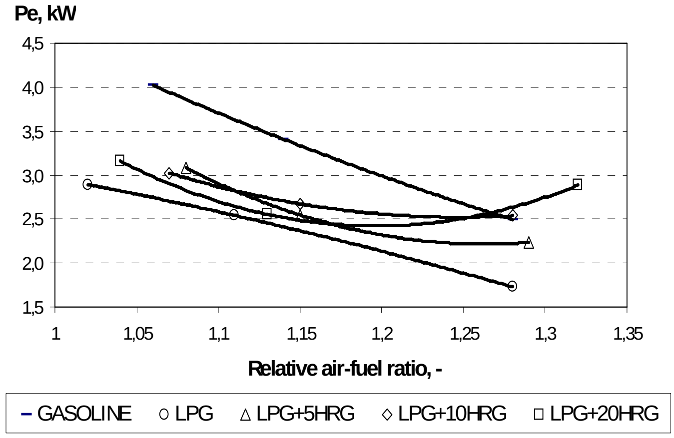

Fig 2. Variation of corrected brake power with relative air-fuel ratio and HRG flow rates (L/h) at 1600 rpm, p_{ca} = 540 mbar, and MBT spark advance.

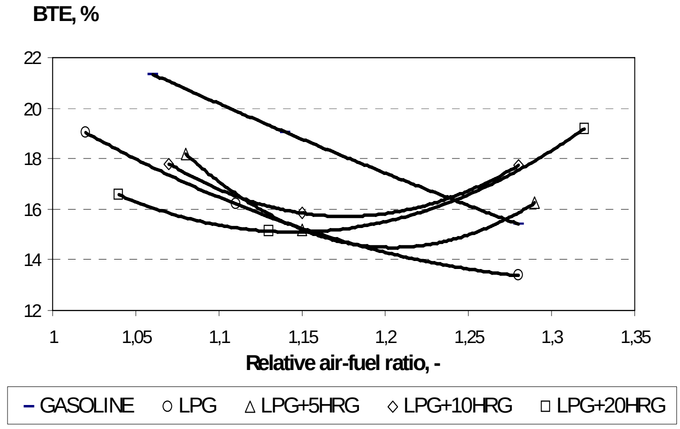

Fig. 3. Variation of BTE with relative air-fuel ratio and HRG flow rate (l/min) at 1600 rpm, p_{ca} = 540 mbar and MBT spark advance

$$BTE = P_{ec} \times 3600 / (C_{LPG} \times LHV_{LPG} + C_{AF}LHV_{AD})$$

with P_{ec} – corrected brake power, kw; C_{LPG}, C_{AF} – mass consumption of LPG and additional fuel (hydrogen from HRG) kg/h; LHV_{LPG}, LHV_{AD} – lower heating value for LPG and additional fuel, respectively, kJ/kg.

The addition of HRG was quantified by the gas flow rate of the electrolyser (5, 10 or 20 L/min) or by the mass percentage Xa of HRG substitution.

Results and discussions

Performance and combustion characteristics

Figure 2 shows the corrected brake power at 1600 rpm, p_{ca} = 540 mbar for various λ and HRG flow rates and MBT spark advance. Substitution of gasoline by LPG results in the decrease of brake power at all tested λ as a result of reduced energy content of the mixture trapped in the cylinder and a reduced BTE. At λ = 1.07, the power with LPG is by 30 % lower then with gasoline, and the difference is maintained up to λ = 1.25. The addition of HRG has a beneficial effect: power is increased, but remains lower compared to the gasoline alternative for lightly diluted fuel-air mixtures. The same trend is found at 2500 rpm, p_{ca} = 370 mbar.

The decrease of the brake power with the substitution of gasoline by LPG is related to a corresponding decrease of BTE by a function f(BTE/λ). At 1600 rpm, p_{ca} = 540 mbar and λ = 1.07, BTE is 16.5 % lower, by 18.5 % than with gasoline; the HRG presence has eventually a negative influence on BTE. A positive effect of HRG addition is noticeable only at more diluted fuel-air mixtures.

With 10 L/min HRG, BTE exceeds at λ=1.25 the corresponding value for gasoline and becomes higher than the gasoline alternative by about 15 % at λ =1.28 (fig. 3). A similar trend is found at 2500 rpm and p_{ca} = 370 mbar; at λ =1.15, the best BTE reached with gasoline is higher by about 20% compared with GPL with 20 L/min HRG. The effect of HRG addition to LPG becomes positive for mixtures leaner than λ =1.28. At λ =1.52 BTE for the same concentration of HRG is higher by about 21% compared with pure LPG.

Combustion characteristics based on cylinder pressure registrations averaged over 200 consecutive cycles, show some specific effects of HRG addition.

The duration of the first phase of combustion, accepted as the crank angle between the spark discharge (av.) and the time when 5 % of the chemical energy has been released (alfa 5 %) [14, 15] is significantly decreased by HRG addition.

At n = 2500 rpm, p_{ca} = 370 mbar and λ = 1.15, the first phase duration (Δα5% = av – alfa 5%) is 28° CA for pure LPG and 20° CA by 15.3% HRG addition; Δα5% is 30° CA for gasoline. At λ =1.28, the influence of HRG is stronger: Δα5% is 32° CA for pure LPG which compares to 21° CA by HRG addition and to 40°CA for gasoline. (fig 4, with conventional negative values for angles before TDC).

As it is known, the duration of the first phase, the stage of ignition and flame-development stage, is influenced by parameters acting in the same sense as for the laminar flame speed; the effect of this duration shortening is attributable thus to the presence of hydrogen. Its laminar flame speed is 3.85 reported to propane at λ =1.15, and the reported value is increasing for leaner fuel-air mixtures. It also explains, at least partially, the smaller MBT spark advances with higher concentrations of HRG in the mixture and the better combustion stability.

In the main phase of combustion, characterized by the leading influence of the turbulence intensity, a relative weak effect of HRG addition was to be expected. The effect actually found is weak: the moment of 90 % release of the chemical energy (alfa 90 %) is slightly different with HRG addition, compared with pure LPG.

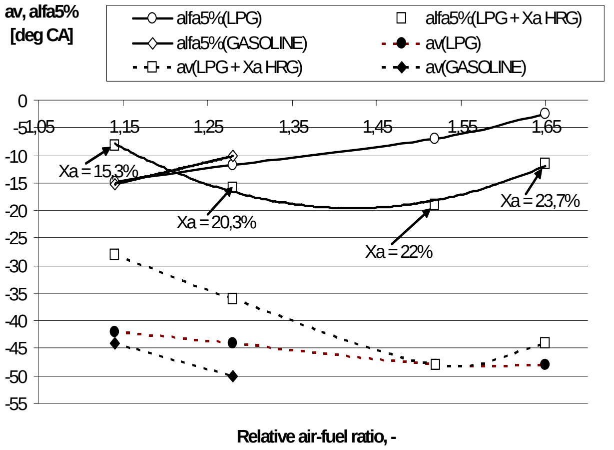

Fig. 4. Variation of MBT spark advance (av.) and the moment of 5 % heat release (alfa 5 %)°CA, with λ - relative air-fuel ratio and HRG (mass fraction) at 2500 rpm, p_{ca} = 370 mbar, MBT spark advance

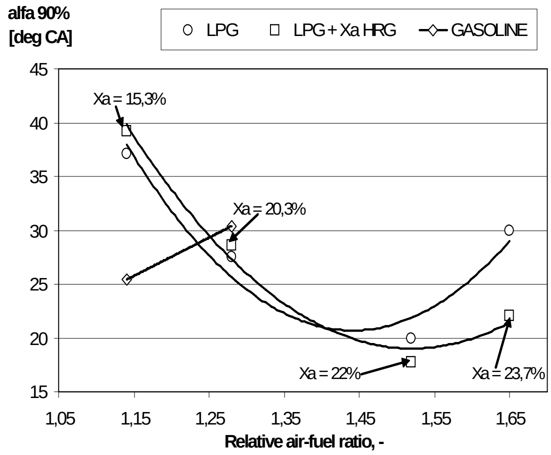

Fig. 5. Variation of the moment of 90 % heat release (alfa 90 %), °CA, with λ - relative air-fuel ratio and HRG (mass fraction) at 2500 rpm, p_{ca} = 370 mbar, MBT spark advance

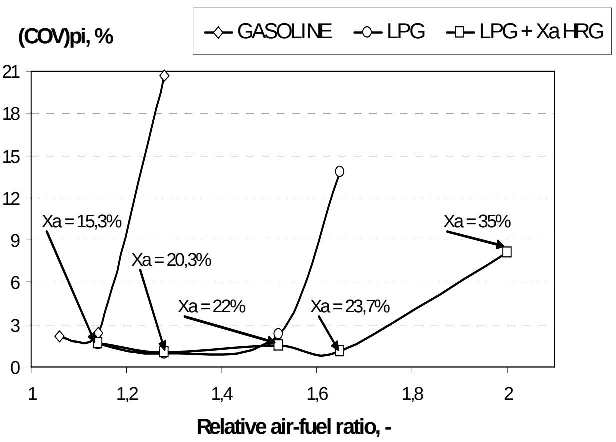

Fig. 6. Variations of COV_{pi} with relative air-fuel ratio and HRG (mass fraction) at 2500rpm, p_{ca} = 370 mbar, MBT spark advance

At λ =1.15, alfa 90 % is 37°CA for pure LPG and 39°CA with 15.3% HRG and 25°CA for gasoline. The duration of the main phase of combustion, considered between 5 % and 90 % heat release ($\Delta\alpha_{5\text{-}90}$ =alfa 90% - alfa 5%) results 52°CA for pure LPG and 47°CA for 15.3% HRG. The slight but still positive influence of hydrogen corresponds to the weak influence of the laminar flame speed on the turbulent flame speed and on the rate of heat release within the thick turbulent flame. In the case of gasoline, with λ =1.15,

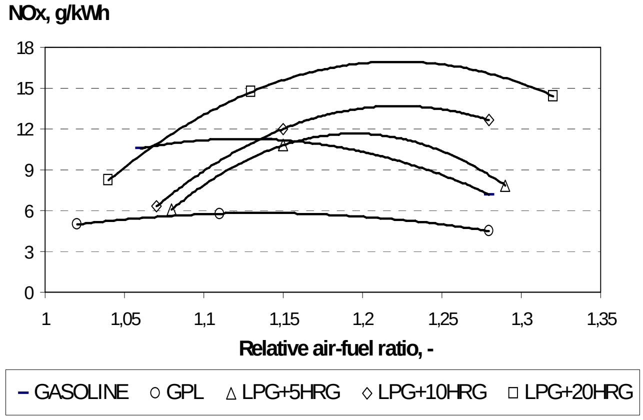

Fig. 7. Variation of NO_x with relative air-fuel ratio and HRG flow rate (L/min) at 1600 rpm, p_{ca}= 540 mbar, MBT spark advance

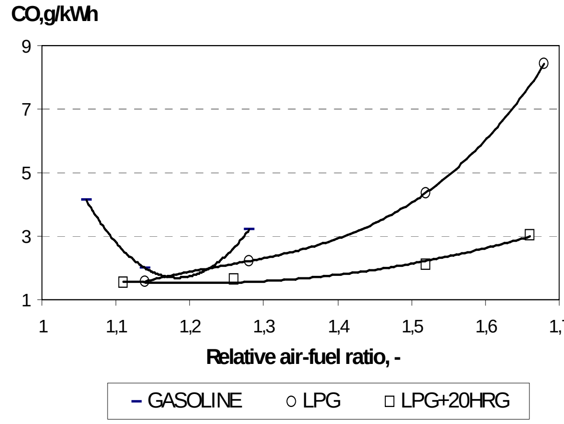

Fig. 8. Variation of CO with relative air-fuel ratio and HRG flow rate (L/min) at 2500 rpm, p_{ca}= 370 mbar, MBT spark advance.

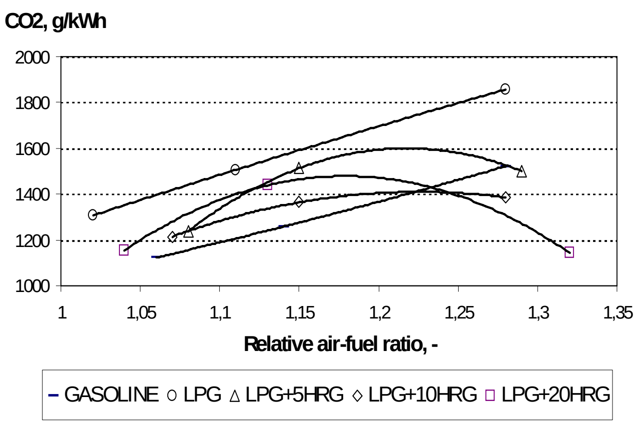

Fig. 9. Variation of CO_2 with relative air-fuel ratio and HRG flow rate (L/min), at 1600 rpm, p_{ca} = 540 mbar, MBT spark advance.

the duration of the main phase of combustion is but the shortest, $\Delta\alpha_{5\text{-}90}$ = 40°CA, which can be correlated with the corresponding higher value found for BTE. An explanation for the shortest duration for gasoline is unclear.

As was already mentioned, the first phase duration $\Delta\alpha_{0\text{-}5}$ is tightly related to the cycle-by-cycle variations, which can be defined in terms of in cylinder pressure variations between successive cycles. A common measure of cycle variability, based on pressure data, is the coefficient of variation in indicated mean effective pressure, defining the cyclic variability in indicated work per cycle. It is calculated as the standard deviation in indicated mean effective pressure σ_{pi} divided by the average (arithmetic mean)

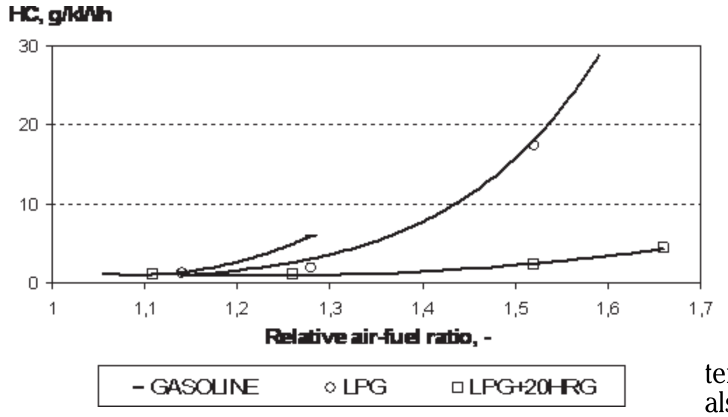

Fig. 10. Variation of HC emission with relative fuel-air mixture and HRG flow rate (L/min) addition at 2500 rpm, p_{ca}= 370 mbar, MBT spark advance.

indicated mean effective pressure, p_i, usually expressed in percent:

$$COV_{pi} = (\sigma pi / p_i) \times 100 \ [\%]$$

A value of 10 percent for COV_{pi} is usually considered a limit to avoid vehicle drive ability problems.

Figure 6 shows COV_{pi} in relationship with λ and the mass fraction of HRG in the mixture with LPG. The effect of HRG addition in extending the stable combustion to leaner mixtures is well illustrated: the value of 10 % for COV_{pi} is reached for gasoline at about λ = 1.2; LPG with a shorter first phase of combustion appears, on the same condition for COV_{pi} with a lean limit of about λ = 1.6. With an addition of 35 % (mass fraction) of HRG, this limit is shifted beyond λ = 2.0.

Emissions

Oxides of nitrogen

Emission of nitrogen oxides are increased by enrichment with HRG. At 1600 rpm, p_{ca} = 540 mbar and λ = 1.1, NO_x is higher by 30 % with 5 L/min addition of HRG, by 50 % with 10 L/min HRG and by 116 % with 20 L/min HRG. The NO_x increase becomes much higher at λ = 1.2: 100% increase with 5 L/min HRG, 132 % increase with 10 L/min HRG and 210 % with 20 L/min HRG. Emissions of NO_x for gasoline, generally higher compared with pure GPL, are eventually surpassed by enrichment of LPG with HRG (fig. 7). The same trend was found at 2500 rpm and p_{ca}= 370 mbar.

Higher NOx emissions are generally attributed to higher gas temperatures. Calculation of conventional temperatures, based on the general law of gases, has confirmed higher temperatures for HRG enriched GPL, at least between the start of combustion and the occurrence of peak cylinder pressure, when about all of NO forms [14]. The presence of hydrogen can also contribute significantly to NO formation, according to the "extended" Zeldovich kinetic mechanism.

Carbon monoxide

The emission of CO is expected to decrease by addition of HRG to LPG, since the carbon concentration is the mixture of both fuels is correspondingly lower. A second positive effect of the presence of hydrogen in HRG results as a participant in the CO oxidation kinetics reaction which is also enhanced by effect of higher gas temperatures.

The addition of 20 L/min HRG has actually no effect on CO emission at 2500 rpm, p_{ca} = 370 mbar and λ = 1.15 but has a positive effect for leaner fuel-air mixtures: the difference in CO emission is 20% compared with pure LPG at λ = 1.2, 43 % at λ = 1.4 and 64 % at λ = 1.65. In both cases, pure LPG and LPG enriched with HRG, CO emission is increasing with λ and the corresponding smaller temperatures. CO emission reported to power increases also with λ, as an effect of brake power decrease (fig. 8).

A rapid increase of CO emission for gasoline – air mixtures leaner than λ = 1.2 or pure LPG – air mixtures leaner than λ = 1.6 (close to the lean limit) is due to the slow burning and the increasing incidence of cycles with partial burning. Experiments at 1600 rpm, p_{ca}= 540 mbar showed the same trend.

Carbon dioxide

The emission of CO_2 is strictly related to the carbon content of the fuel and to BTE. The complex influence of HRG addition to LPG seems to have the dominant effect.

Figure 9 shows the influence of HRG addition on CO2 emission at 1600 rpm and p_{ca} = 540 mbar. The correlation of CO_2 emission with BTE is evidently noticeable for fuel-air mixtures leaner than about λ = 1.15, at different concentrations of HRG added to LPG. Gasoline, having higher BTE, has also correspondingly lower CO_2 emission, although has the constituent carbon in a bigger proportion. At λ = 1.07, CO_2 emission for LPG with 20 L/min flow rate HRG is but lower by 9 % compared with pure LPG, while the corresponding BTE is also lower by 8.7%, and an explanation is unclear, Gasoline, with the highest BTE at light lean mixture, continues to have smaller CO_2 emission. The same trend is found at 2500 rpm, p_{ca}= 370 mbar.

Total unburned hydrocarbons

The unburned hydrocarbons emission (HC), as well as CO emission, is the result of finally uncompleted oxidation reaction, ending late in the exhaust process. Temperature and residence time in the exhaust system are critical factors controlling these oxidation reactions. Engine operating conditions that give the highest operating temperatures (stoichiometric fuel-air mixtures, higher speeds or retarded spark timings) and longer residence time give higher final reductions in HC emission. Incomplete HC late oxidation contributes to higher CO emission [15]. The close relationship between HC and CO emissions is thus apparent. As in the case of CO, a lower HC emission by HRG addition to LPG, or the increase of emission for leaner mixtures is thus to be expected.

Figure 10 illustrates the influence of HRG addition and the relative fuel-air mixture at 2500 rpm and Pca = 370 mbar. The figure is quite similar to figure 8, referring to CO emission. With 20 L /h HRG addition, HC emission is the same as far pure LPG, but becomes lower for leaner fuel-air mixtures: the difference is 40 % at λ = 1.2, 77 % at λ = 1.4 and 90 % at λ = 1.65. HC emission by operation with gasoline is higher than with pure LPG for fuel-air mixtures leaner than λ ≈ 1.15. Similar trends were found at 1600 rpm and p_{ca} = 540 mbar.

Conclusions

A SI car engine fuelled with lean mixtures of LPG and various concentrations of HRG was operated at light load, 1600 rpm and mid-load, 2500 rpm, with MBT spark timing. The required HRG gas was generated by water electrolyses.

Blending LPG with HRG increases the brake power, by an increase of the energy content of the mixture trapped in the cylinder, which remains but lower than by fuelling with gasoline. For slightly lean mixtures, BTE has also the higher values for gasoline, while HRG addition to LPG has even a negative influence. The situation is reversed for leaner mixtures, $\lambda \approx 1.25$.

The MBT spark timing is retarded towards TDC by addition of HRG, in relationship with the shortening of the first phase of combustion. The stability of combustion is thus improved, the lean limits for COV_{pi} below 10% is shifted to leaner mixtures.

A conclusive effect of LPG enrichment with HRG on the main duration of main phase of combustion was not found. The shortest duration resulted for gasoline, a result which correlates with the corresponding higher BTE.

The addition of HRG to LPG results in lower CO, CO_2 and HC emissions at low load, 1600 rpm and mid-load, 2500 rpm and this effect becomes significant for mixtures leaner than $\lambda \approx 1.15$.

NOx emission is significantly increased with HRG addition at both operation conditions.

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