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Effects of Gasoline-Air Enrichment with HRG Gas on Efficiency and Emissions of a SI Engine

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ABSTRACT

The addition of hydrogen to the gasoline-air mixture may contribute significantly towards accelerating the combustion process, with the beneficial effects on engine performance and emissions.

The present contribution describes the results of an experimental research where gasoline-air mixture was enriched with a Hydrogen Rich Gas (HRG) produced by the electrical dissociation of water. The HRG analysis shows the presence of hydrogen and oxygen together with some additional species.

Experiments were carried out at engine light and partial load. Detailed results of the measurements are shown, namely engine torque and efficiency, exhaust emissions, cyclic variability, heat release rates and combustion duration. The possibilities of improving engine performance and emissions in correlation with the amount of HRG, the equivalence ratio and the engine operating condition are thus outlined.

INTRODUCTION

The use of hydrogen (H2) as an additional fuel to gasoline has been considered, since the early 70', as an attractive possibility to join the major advantages given by both fuels [1], [2]. Due to the high laminar velocity of combustion and the wide flammability limits of hydrogen, its addition is utilized as a method to shift stable engine operation to leaner mixtures, with positive effects on emissions and thermal efficiency. The use of hydrogen as an additive was also considered as a solution to enhance the combustion rates of some fuels like methane [3]. On the other hand, the use of hydrogen as an additive in relatively small concentrations to the main fuel appeared to be rational, considering the storage difficulties in a vehicle. A great amount of hydrogen stored on-board in a tank would dictate a significant increase of the vehicle weight, which is detrimental to the fuel consumption and vehicle autonomy.

Extensive studies have shown a significant shortening of the initial flame development stage, as well as of the rapid burning stage, when relatively small amounts of hydrogen (up to 10% by mass) were used with gasoline [4]…[8]. A combustion stability benefit when using gasoline was also emphasized, at different throttle openings. Influence of hydrogen addition to the cycle-to-cycle variability can be correlated with the influence on the initial stage of combustion. All experiments with hydrogen addition have confirmed an extended range of the engine stable operation towards the lean limits and the extension of the dilution limit by EGR. Both, experiments and simulations have shown the possibility of a significant gasoline fuel consumption reduction obtained from hydrogen addition. The total efficiency improvement can be considered as the result of several effects: the partial dethrottling because the hydrogen, which has a low density, decreases the amount of air filling the cylinder; the faster combustion, thus approaching the ideal Otto cycle; the possibility to increase the compression ratio due to a higher resistance to knock. The reduced engine knock tendency, by hydrogen addition, is due to the reduction of burning duration and by slowing autoignition chemistry [9]. With regards to the HC emissions, a significant decrease results by hydrogen addition with leaner mixtures. The NO_X emissions tend to increase with respect to pure gasoline fueling, because of higher adiabatic flame temperature, at low excess air. If making use of extended lean limit produced by hydrogen, NO_X emissions can decrease; and even more favorable effect can be obtained by using the wider EGR tolerance instead of the dilution with air [7], [10], [15].

One of the main limitations in using the hydrogen is its generation and portability. To avoid the storage problems in the last years, the possibilities to produce hydrogen continuously on board were investigated. The partial oxidation in air of a certain fraction of gasoline can thus be used to produce a hydrogen, carbon monoxide and nitrogen mixture. Several types of gasoline partial oxidation reformer systems have been developed and the opportunities offered by the reformer gas for combustion improvement were explored. A significant thermal increase enough to compensate the energy losses occurring in the on-board reformer, as well as, near zero emission in terms of HC and NO_X has been observed. H_2 and CO are also effective in lengthening the ignition delay, thus reducing the knock susceptibility [11]… [15].

Hydrogen production by the electrolysis of water, using directly or indirectly the engine output as a source for the energy needed, was the alternative also studied. It was found that the presence of oxygen as a product of water electrolysis would not produce a significant change in the engine performance, and the overall effect of the production of hydrogen was found energetically to be not viable over much of the engine operating range [16], [17].

The experiments have been conducted using the HRG produced by a new type of water electrolyzer with high efficiency of gas generation. The technology licensed to Rokura Aplicatii Industriale SRL from Romania produces the HRG who's composition includes not only the conventional mixture of hydrogen and oxygen but also, OH, HO_2, traces of H_2O, and some additional species [18].

The present contribution presents the results of a first investigation, for a spark ignition engine operating with HRG enriched gasoline. The study was focused on the influence assessment of the percentage addition on combustion characteristics, engine brake specific fuel consumption and brake emissions.

EXPERIMENTAL DETAILS

Experiments were performed on a four stroke engine (Table 1), coupled to an eddy current dynamometer. The original carburetor was modified for an open loop control of the relative air-fuel ratio.

Table 1: Engine specifications

Number of cylinders	4
Displaced volume, dm^3	1.397
Bore × Stroke, mm	76 × 77
Compression ratio	9.5
Combustion chamber geometry	Wedge

The HRG gas delivered by an electrolyzer was introduced in the mixing chamber through a manual control system provided with pressure regulators, thermal resistors and flow meters, in order to obtain the specified pressures, temperatures and gas flow rates: the HRG absolute pressure at the entry in the carburetor was 2 bar. The throttle position was adequately modified, in order to keep the same pressure in the intake manifold as in the case of pure gasoline fueling.

The fuel consumption measurement was made with a flow meter Fisher Rosemount Flo-Tron 10E, 1…100 kg/h, and the air consumption with a standardized plate orifice mounted on an air tank. The parameters of the electric discharge and the spark advance were measured and registered with a high voltage probe Tektronix P 6015, a current probe P 6021 and an oscilloscope TDS 320. The composition of the exhaust gases was determined with a gas analyzer AVL DiGas 4000, and the corresponding relative air-fuel ratio was checked by an UEGO sensor, NTK TC 6110C. The cylinder pressure was measured too, using an indicating system including a pressure transducer Kistler 601A, a charge amplifier Kistler 5001 C, a data acquisition card AVL Indimeter 617, a crank angle encoder AVL 365.

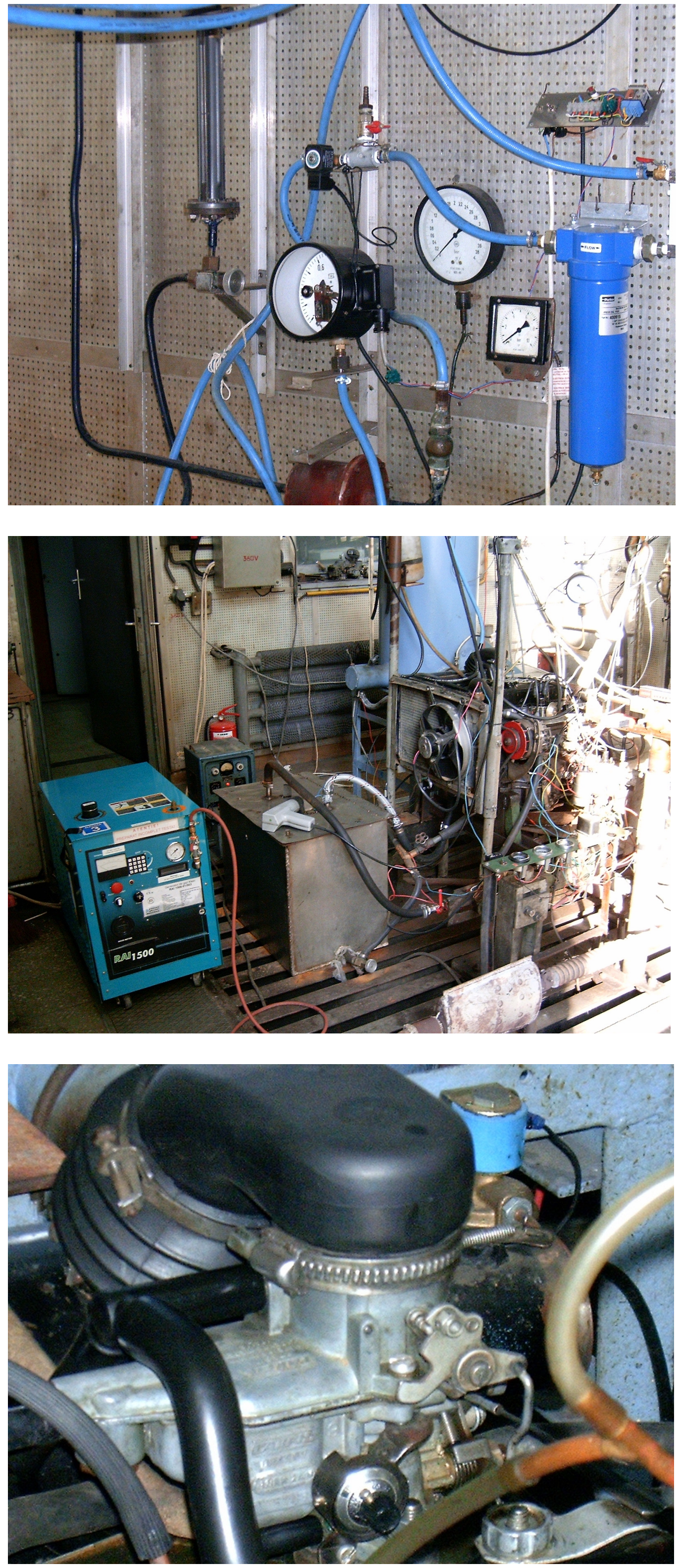

Fig. 1 Experimental equipment

The engine operating conditions were chosen as follows: a light load (about 3 bar NIMEP) and a mid-load (about 6 bar NIMEP) at two speeds 1600 rpm and 2500 rpm. The first load is thus representative by its highest sensitivity to the fuel-air ratio, while the second load is representative of typical engine operation. Experiments were carried out close to stoichiometric conditions and at lambda (relative air-fuel ratio) of 1.2 the HRG-gasoline ratio being a research variable. The ignition timing was also varied, in view of defining MBT spark timings for each set of operating parameters. The following data were collected for each set of operating conditions, at MBT spark timing: engine performance parameters, in-cylinder pressure for 500 consecutive cycles, registered with a resolution of 0.2 ºCA, HRG and gasoline flow, air flow, CO, CO_2, HC and NO_X emissions concentrations.

RESULTS AND DISCUSSIONS

The first group of tests was carried out at light load and at 1600 rpm with, lambda of 0.92 – 0.94 (the contribution in O_2 of the HRG included). Figure 2 shows the brake thermal efficiency (BTE) versus spark advance, with different HRG flow rates (l/h). The data corresponding to the MBT spark timings are plotted in figure 3 versus the hydrogen percent volumetric fractions in the fuel calculated for 65.03% H_2 volumetric fraction in HRG. BTE was calculated with the equation:

$$BTE=P_{ec}\times 3600/(C_g\times LHV_g+C_{H_2}\times LHV_{H_2})\times 100$$

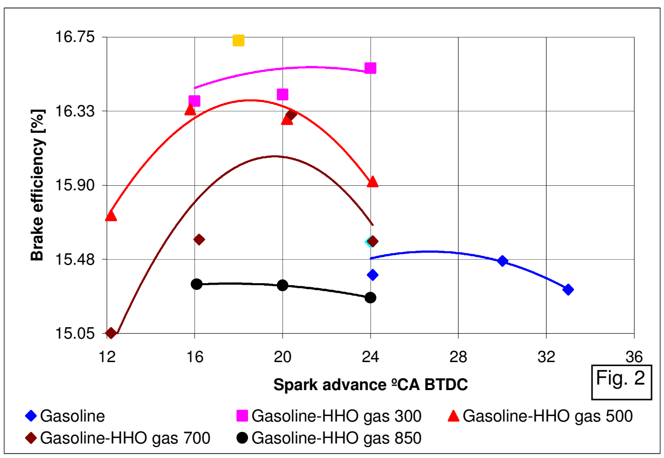

Fig. 2 HRG addition influence on brake thermal efficiency, for different spark timings, light load, 1600 rpm, lambda of 0.92 – 0.94

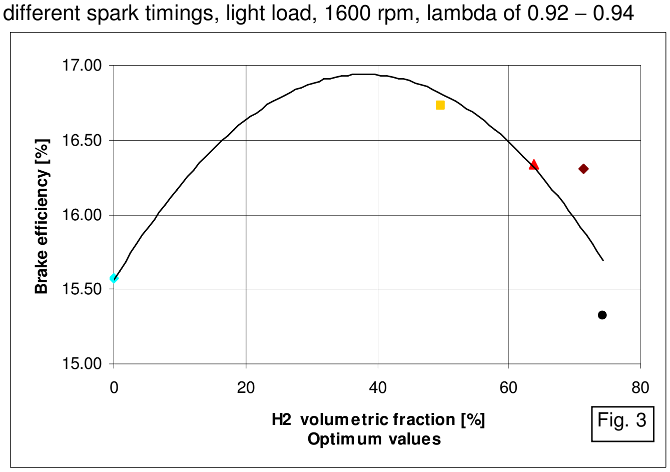

Fig. 3 H2 volumetric fraction influence on the brake thermal efficiency, light load, lambda of 0.92 – 0.94, MBT spark timings

One can notice that the MBT values for gasoline and optimum gasoline-HRG-mixture has slightly modified color symbols in Figure 2. This convention is respected for best comparison, starting with Figure 3.

As the HRG flow rate is increased the brake efficiency increases, reaches a peak and starts decreasing relatively rapidly. The peak break thermal efficiency was reached with about 50% hydrogen correspondingly to 300 l/h HRG gas flow rate, and is around 7.4% higher than a straight gasoline conditions; the corresponding increase on the net indicated mean effective pressure (NIMEP) is of 5.6% (Fig. 4).

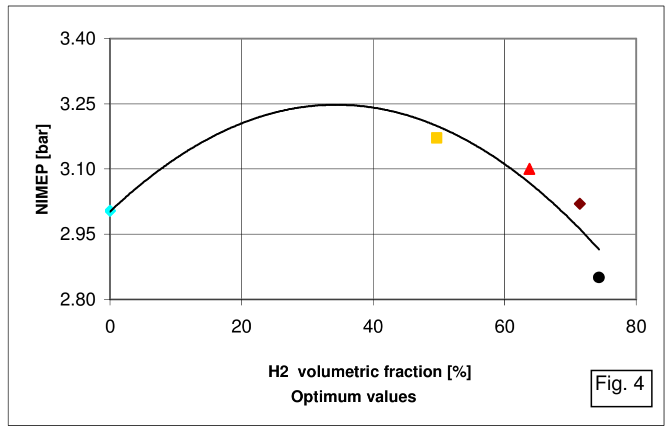

Fig. 4 H2 volumetric fraction influence on NIMEP, light load, 1600 rpm, lambda of 0.92 – 0.94, MBT spark timings

Figure 5 shows the effect of the HRG addition, expressed as hydrogen percent volumetric fraction in the fuel, with MBT spark timings, on the cyclic variability coefficient of NIMEP "$(COV)_{NIMEP}$".

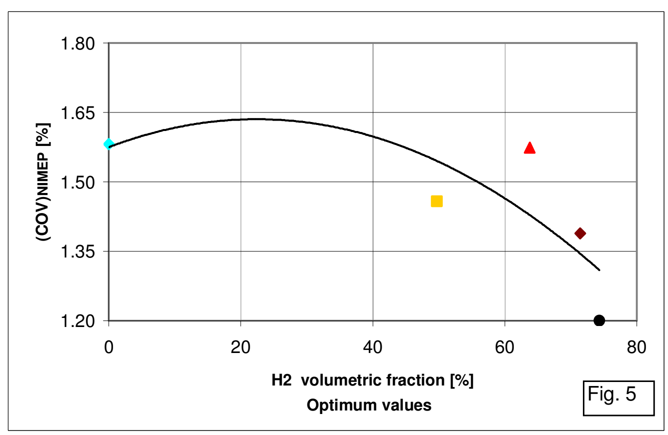

Fig. 5 H2 volumetric fraction influence on cycle-by-cycle variability, light load, 1600 rpm, lambda 0.92 – 0.94, MBT spark timings

The level of $(COV)_{NIMEP}$ is typically low for a fuel-air mixture slightly rich, but by addition of HRG the cyclic variability can be still lowered. A complex behavior of hydrogen in the domain of very small concentrations is also suggested. This positive effect can be correlated with the influence of the initiation stage of combustion.

Figure 6 reports the combustion initiation stage duration DAI 0-10%, corresponding to burning 10% of the charge mass, and the rapid burning stage duration DAI 10-90% necessary to burn 10 to 90% of the charge.

The benefit of hydrogen addition by the HRG in shortening the first stage of combustion is evident, and it correlates with the decrease of the $(COV)_{NIMEP}$ previously noticed.

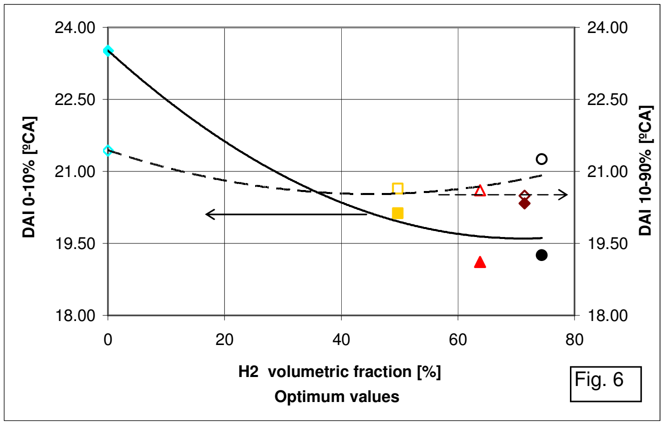

Fig. 6 H2 volumetric fraction effect on initiation and rapid burning stage durations, light load, 1600 rpm, lambda of 0.92 – 0.94, MBT spark timings

However differences in the domain of big values of hydrogen volumetric fractions become insignificant. The effect on the rapid burning stage duration by HRG addition is generally insignificant. The overall burning duration appears lower by HRG addition and this effect, combined with the smaller cyclic variability expressed the combustion enhancement and can thus explain the positive influence on NIMEP and BTE, previously shown for moderate proportions of HRG.

The improved BTE by HRG addition is reflected in a corresponding decrease of the CO_2 emission, while the CO emission in condition of relatively lack of oxygen keeps practically unchanged (Fig. 7). This behavior is unexpected, since CO emission should have also decreased if combustion efficiency increased.

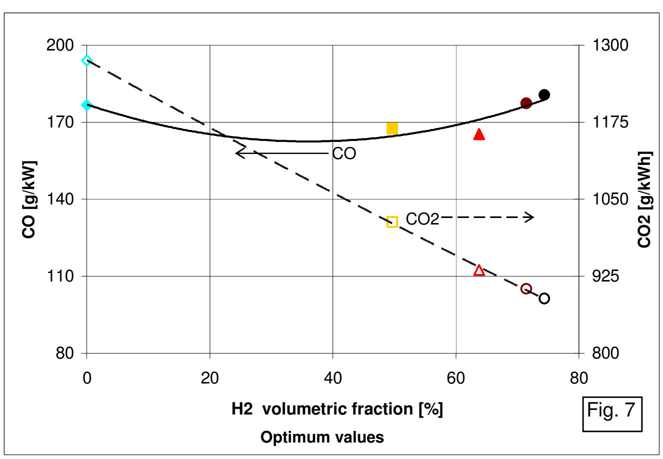

Fig. 7 H2 volumetric fraction influence on CO and CO_2 emissions concentration, light load, 1600 rpm, lambda of 0.92 – 0.94, MBT spark timings

The effect of HRG on NO_X emissions is also negligible (Fig. 8). An effect of HRG addition on HC emission concentration can but be noticed: the light increasing above volume fractions of 40% may be due to the higher burn temperatures.

The typical decreasing trend for higher HRG proportions could be associated with the similar trend in combustion variability.

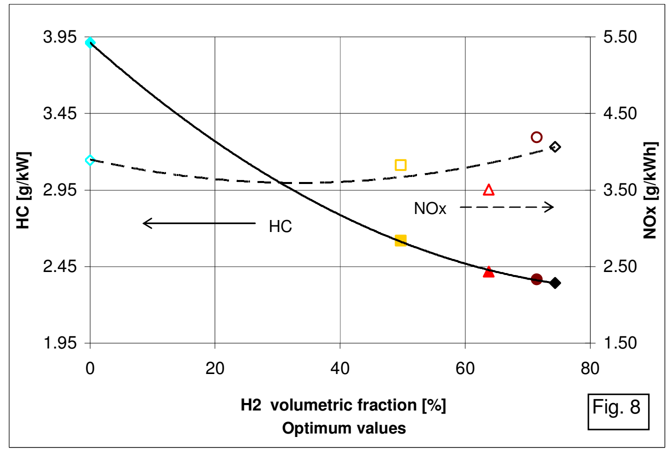

Fig. 8 H2 volumetric fraction influence on HC and NO_X emissions concentration, light load, 1600 rpm, lambda of 0.92 – 0.94, MBT spark timings

A stronger impact of the HRG addition is to be expected at the tests performed at the same engine load and speed, when the fuel-air mixture is leaned out, with a lambda of 1.18 – 1.20; relatively close to the lean normal operational limit the effect of combustion enhancement by addition of hydrogen in HRG ought to be more pronounced. Brake thermal efficiency shows indeed a rise of about 23% by 50% volumetric fraction of hydrogen (Fig. 9 and Fig. 10) with a corresponding 10% increase of NIMEP (Fig. 11)

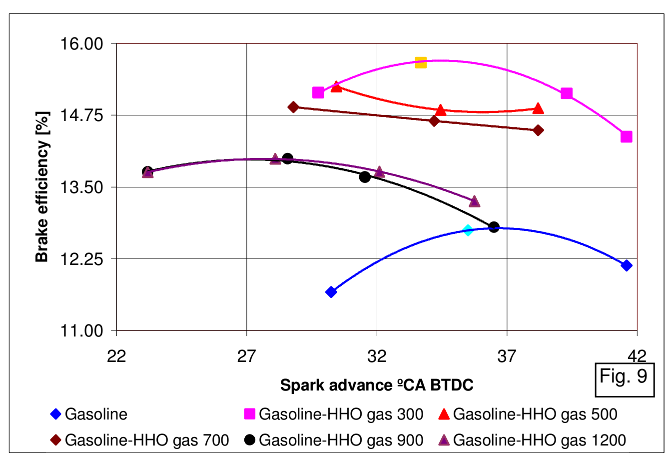

Fig. 9 HRG addition influence on brake thermal efficiency for different spark timings, light load, 1600 rpm, lambda of 1.18 – 1.20

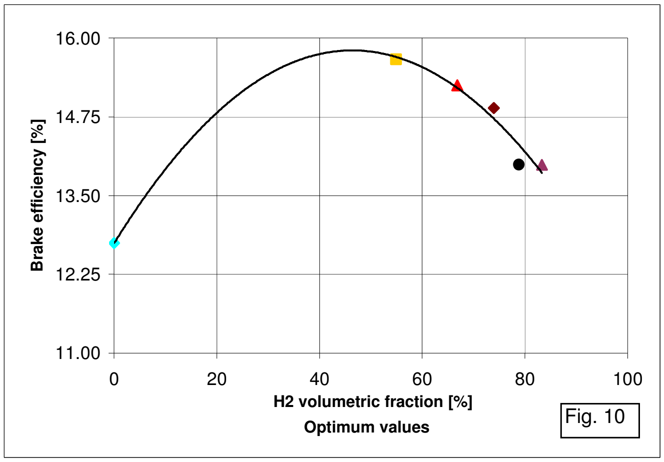

Fig. 10 H2 volumetric fraction influence on brake thermal efficiency, light load, 1600 rpm, lambda of 1.18 – 1.20, MBT spark timings

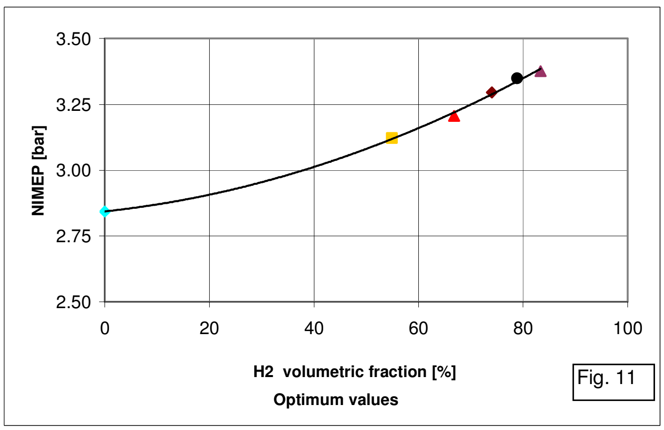

Fig. 11 H2 volumetric fraction influence on NIMEP, light load, 1600 rpm, lambda of 1.18 – 1.20, MBT spark timings

The cycle-by-cycle variability is quite high for that lean mixture ($(COV)_{NIMEP}$=25.7%) when the engine is operated with gasoline only.

A well marked improvement results by addition of the HRG, and this effect is extended up to about a hydrogen volumetric fraction of 70%: for 50% hydrogen in the fuel $(COV)_{NIMEP}$ drops to an acceptable level of 9.3% (Fig. 12).

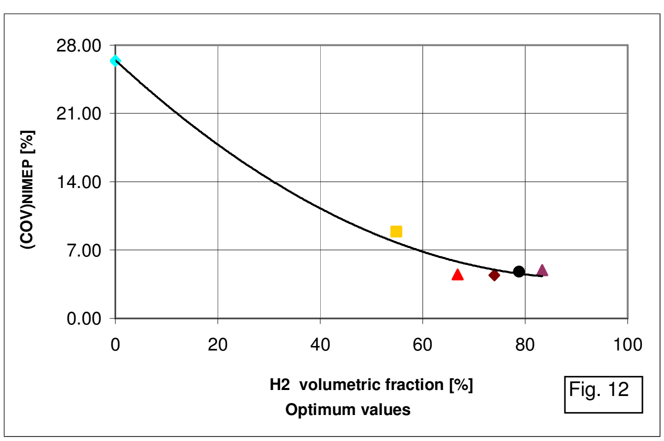

Fig. 12 H2 volumetric fraction effect on cycle-by-cycle variability, light load, 1600 rpm, lambda of 1.18 – 1.20, MBT spark timings

The effect of HRG addition expressed by hydrogen fraction increasing on both combustion durations is also very strong and continuous over the whole range investigated of H_2 fractions: at 50% hydrogen volumetric fraction, DAI 0-10% is lower by 33%, and DAI 10-90% by 31.5% (Fig. 13).

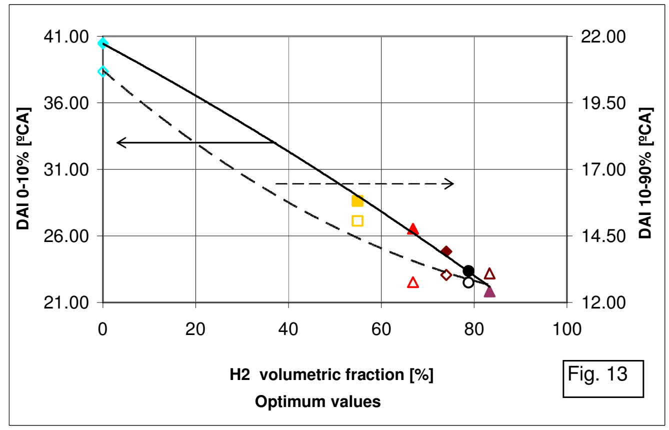

Fig. 13 H2 volumetric fraction effect on combustion stages durations, light load, 1600 rpm, lambda of 1.18 ÷ 1.20, MBT spark timings

The important shortening of combustion duration, associated with the much lower cyclic variability can explain the effects afore-mentioned on BTE and NIMEP. The beneficial influence on BTE is also reflected in the smaller concentrations of CO_2 emissions in the engine exhaust (Fig. 14). CO emission concentrations are also substantially decreased by enriching the fuel with HRG. In lean mixtures, the presence of hydrogen acting as a catalyst in the CO oxidation kinetics is made evident in full extent.

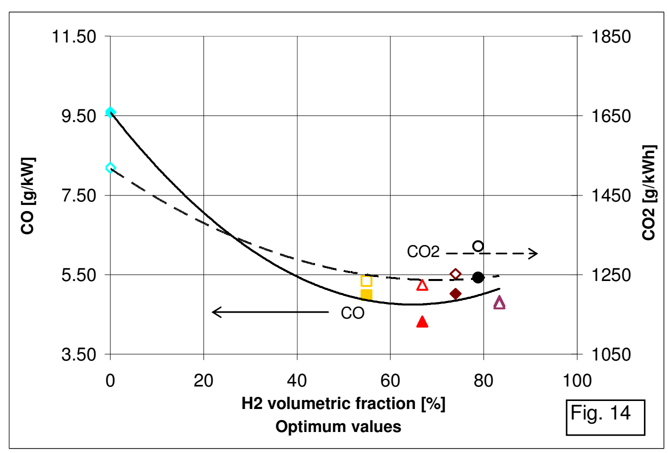

Fig. 14 H2 volumetric fraction effect on CO and CO_2 emissions concentration, light load, 1600 rpm, lambda of 1.18 – 1.20, MBT spark timings

A similar trend is found for HC emissions (Fig. 15). For lean mixtures and light loads, the HRG addition appears as very efficient in HC emissions reduction and this effect could result from the improved combustion variability, by eliminating, or at least decreasing the incomplete combustion phenomenon. The overall level of the HC emission concentrations is anyway higher than for rich mixtures (Fig. 8) with burned gases of generally lower temperature and accordingly a HC final oxidation less intense.

Hydrogen addition is expected to produce an increase of NO_X emissions with respect to pure gasoline fueling because the higher adiabatic flame temperature produced by hydrogen combustion favors the NO_X formation, in the domain of small excess of air. The results (Fig. 15) confirm the expectations.

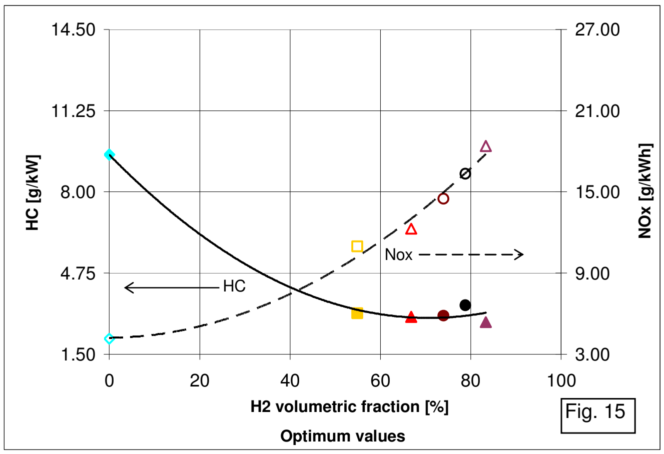

Fig. 15 H2 volumetric fraction influence on HC and NO_X emissions concentration, light load, 1600 rpm, lambda of 1.18 – 1.20, MBT spark timings

Similar experiments performed at other operation conditions have confirmed the general trends already presented. At mid-load in conditions of higher temperature, pressure and turbulence intensity the influence of HRG addition appears but attenuated (Figs. 16 -18)., the role of hydrogen on combustion enhancement being less important.

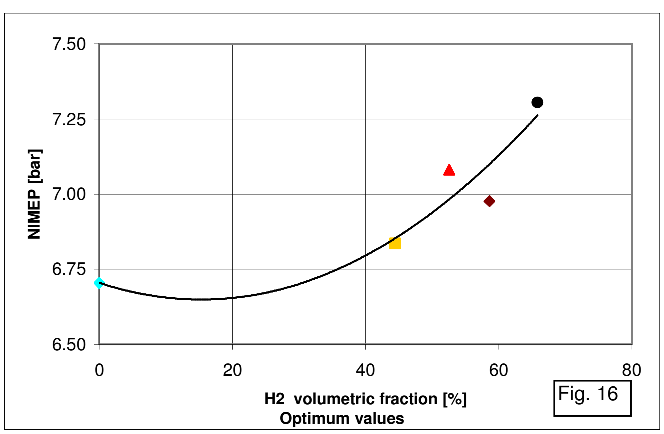

Fig. 16 H2 volumetric fraction effect on NIMEP, mid-load, 2500 rpm lambda of 1.18 – 1.20, MBT spark timings

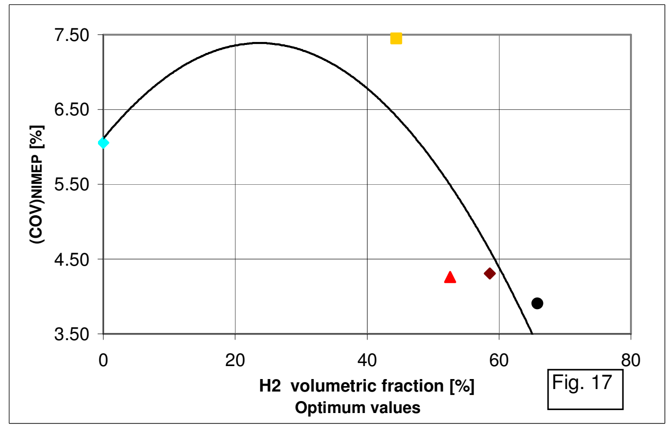

Fig. 17 H2 volumetric fraction effect on cycle-by-cycle variability, mid-load, 2500 rpm, lambda of 1.18 – 1.20, MBT spark timings

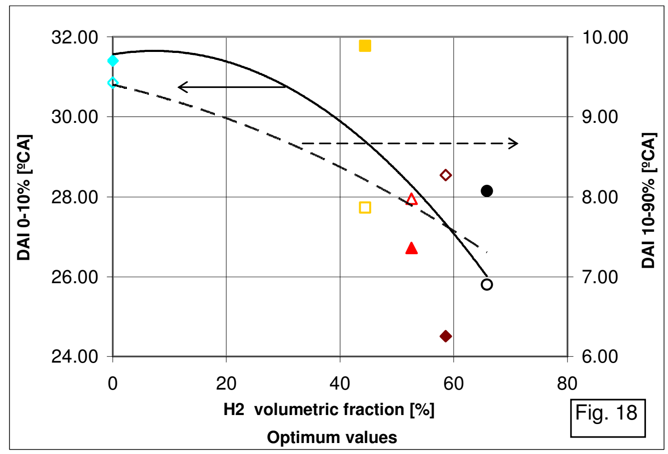

Fig. 18 H2 volumetric fraction influence on combustion stages durations, mid-load, 2500 rpm, lambda of 1.18 – 1.20, MBT spark timings

On the whole, the effects of HRG addition emphasized by the experiments were attributed to the presence of hydrogen, the main component of the gas. These effects are actually close to those previously found in studies performed with hydrogen-enriched gasoline [5], [7], [17]. It was not possible to isolate a special effect of other species present in HRG. The problem of a possible specific influence of the molecular oxygen and other components identified in the HRG will be addressed in a next study.

CONCLUSIONS

The effect of additions of HRG on gasoline combustion has been experimentally investigated in a passenger car engine. It was shown that:

The addition of HRG has a positive effect of combustion process enhancement. BTE, NIMEP, and $(COV)_{NIMEP}$ are improved, in connection with the combustion duration shortening. HC and eventually CO emissions concentrations are also reduced, while NO_X is generally increased. The maximum lambda value (1.20) was a limit imposed by engine running stability.

• The effect of HRG addition is most apparent at light load with leaned mixtures.

• The effect of HRG addition was explained in terms of well known influence of hydrogen, the main component of HRG. A possible influence of other species existing in the gas was yet not identified.

• Hydrogen and oxygen mixtures are very reactive and represent a potential hazard of pre-ignition, if an ignition source is present (static electricity). In this sense, experiments are continuing with the HRG direct injection in the cylinder.

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DEFINITIONS, ACRONYMS, ABBREVIATIONS

BTE	Break thermal efficiency
BTDC	Before top death center
C_{H2}	Gravimetric hydrogen consumption
C_g	Gravimetric gasoline consumption
COV	Coefficient of variability of the NIMEP
ºCA	Crank angle degree
DAI 0-10%	Combustion initiation stage duration
DAI 10-90%	Combustion rapid stage duration
HC	Unburned hydrocarbons
HRG	Hydrogen Rich Gas
LHV_{H2}	Hydrogen low heating value
LHV_g	Gasoline low heating value
MBT	Maximum brake torque
NIMEP	Net indicated mean effective pressure
P_{ec}	Brake power, corrected