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EXPERIMENTAL STUDY OF A SPARK IGNITION ENGINE FUELED WITH GASOLINE AND HYDROGEN IN ADDITION

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Hydrogen is a fuel that enables high efficiencies and low emissions of NOx (oxides of nitrogen) for spark ignition engine. However, there are lasting issues concerning its production, storage and distribution. Because gasoline has narrow flammability limits compared with that of hydrogen the engine fuelled only with gasoline could suffer a partial burning or misfire at lean mixtures burning. Hydrogen addition is an effective way for improving the performance of spark-ignited (SI) engines at stoichiometric dosage but also at lean mixture. The paper presents experimentally results regarding the effect of hydrogen addition on the performance of a gasoline engine while studying parameters like effective power, BSFC and emissions (NO_x, HC). The experiment was carried out on a single-cylinder, gasoline engine which was modified by adding a special valve mounted into the engine cylinder head between the intake and exhaust valves. Engine tests were conducted at different operating conditions and different air-fuel ratios. The hydrogen was injected in to the engine cylinder. Hydrogen addition was defined as an energetically fraction from the whole fuel quantity on a cycle.

Keywords: hydrogen, combustion, emissions, engine, thermal efficiency

1. Introduction

During the last years SI-engines have been further improved. Engine development has focused on the reduction of tailpipe emissions, better fuel economy and higher engine performance as well as reduction of system costs.

In order to meet new requirements for emission reduction and fuel economy a variety of concepts are available for gasoline engines. In the recent past new ways have been found using alternative fuels and fuel combinations to reduce costs of engine operation and fuel consumption.

The presented concept for a SI-engine consists of combined injection of gasoline and hydrogen. Hydrogen is being injected additional to gasoline inside the engine through a separate injection system.

Hydrogen has many attractive intrinsic properties that make it a promising fuel.

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Table. 1

Hydrogen properties

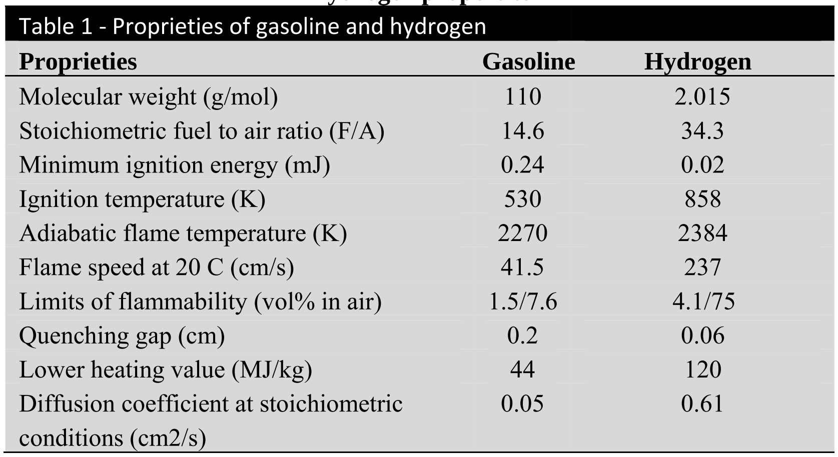

Table 1 - Proprieties of gasoline and hydrogen

Proprieties	Gasoline	Hydrogen
Molecular weight (g/mol)	110	2.015
Stoichiometric fuel to air ratio (F/A)	14.6	34.3
Minimum ignition energy (mJ)	0.24	0.02
Ignition temperature (K)	530	858
Adiabatic flame temperature (K)	2270	2384
Flame speed at 20 C (cm/s)	41.5	237
Limits of flammability (vol% in air)	1.5/7.6	4.1/75
Quenching gap (cm)	0.2	0.06
Lower heating value (MJ/kg)	44	120
Diffusion coefficient at stoichiometric conditions (cm2/s)	0.05	0.61

Main elements that make hydrogen a promising fuel are:

-Due to the lower minimum ignition energy of hydrogen a more stable ignition can be obtained

-Laminar burning velocity of hydrogen is higher than that of gasoline.

-The combustion duration of the hydrogen engine is shorter than gasoline, the constant volume combustion share increases and engine thermal efficiency increases [14].

- The higher diffusion coefficient of hydrogen may enhance the mixing process, which also can increase the engine efficiency and help to produce less unburned hydrocarbons.

- Moreover, adding hydrogen will extend the lean limit due to its lower flammability limit in air.

- Adding hydrogen also produces a higher adiabatic flame temperature in air, which raises concerns over NOx emissions.

Literature review

Comparatively single fuel engines, hybrid hydrogen engines fueled with mixtures of hydrogen and gasoline only consume a limited amount of hydrogen, which not only reduces the concerns about the onboard storage of hydrogen but also reduce the costs for customers. Since hydrogen has many excellent physicochemical and combustion properties, hybrid hydrogen engines tend to achieve better performance than the traditional mono-fuel powered engines [1–7].

There have been many investigations on hybrid hydrogen engines under stoichiometric and lean conditions. Varde et al. [8] investigated the performance of a single-cylinder engine fueled with the hydrogen gasoline mixture. The test results showed that the engine lean burn limit was extended and flame propagation duration was effectively shortened after hydrogen enrichment.

Researchers have investigated the performance of hybrid hydrogen engines under lean conditions. Andrea et al. [9] experimentally studied the performance of a two-cylinder carburetor gasoline engine enriched by hydrogen under various equivalence ratios. The test results showed that the engine torque output was improved and the combustion duration was shortened after hydrogen addition. At lean conditions, hydrogen enrichment was effective on reducing engine cyclic variation. He also concluded from the experiment that the effect of hydrogen addition on improving engine performance was pronounced only when equivalence ratio of the hydrogen–gasoline–air mixture was smaller than 0.85.

Ji et al. [10] investigated the hydrogen hybrid engine combustion and emissions performance at various excess air ratios and hydrogen addition fractions with fixed spark timing. The experimental results demonstrated that the engine brake thermal efficiency was improved for the hybrid hydrogen engine at all excess air ratios. HC and CO2 emissions were decreased whereas NOx emissions were increased with the increase of hydrogen addition level. CO emission was raised at stoichiometric conditions for the HHE, however, the addition of hydrogen was beneficial for reducing CO at lean conditions.

2. Experimental setup and procedure

i) Experimental setup

The experimental research has been carried out on an experimental single cylinder engine derived from a serial automotive engine (S/D =77/73 mm/mm; $\varepsilon = 8.5$). The standard valve system of the engine is maintained. A special valve design is mounted into the engine cylinder head between the intake and exhaust valves. Hydrogen intake valve, actuated separately from the standard valve system of the engine, provides the in-cylinder hydrogen admission at the optimum moments and in different quantities. Hydrogen flow can be adjusted by changing the valve opening time duration or by changing the fueling pressure. The hydrogen fueling valve is actuated by a high flexibility hydraulic system which provides the possibility of adjusting the valve opening duration and timing.

The hydrogen valve is actuated by a hydraulic system that allows the valve timing. The design of this system contains a command pump, which has a piston with a profiled head getting motioned by a cam located on the pump camshaft which at its turn is directly motioned by the crankshaft (by 1/2 ratio).

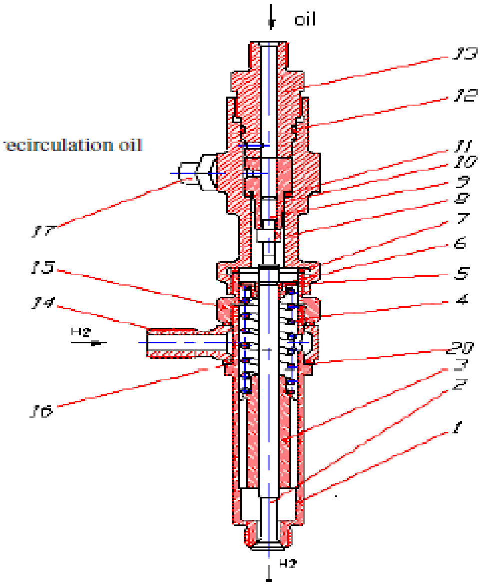

Fig. 1: Hydrogen valve assembly
1-Inferior housing; 2-hydrogen valve; 3-perforated dish; 4-valve spring; 5-dish; 6-ring; 7-gasket; 8-superior housing; 9-actuator piston; 10-actuator cylinder; 11-gasket; 12-ring; 13-recirculation oil connection pipe; 14-hydrogen fueling joint; 15-threaded sleeve; 16-gasket;17-one-way valve.

For the fuelling system a modified carburetor with a control system of the fuel jet section has been used. Both gasoline and hydrogen fuelling systems present a higher working flexibility. Thus the hydrogen and gasoline flows can be adjusted separately in order to obtain different hydrogen addition percents and different air-fuel ratios.

The engine was equipped with:

- Quartz piezoelectric pressure transducer Kistler 601 A mounted in the cylinder head to measure cylinder pressure.
- Incremental transducer Kubler for crankshaft angle measure.
- Cylinder pressure data were acquired and averaged by a PC equipped with AVL acquisition board.
- Air consumption was measured by the diaphragm method, and the hydrogen consumption was measured with flow meter KROHNE.
- Gases analysis was made by the AVL DiCom 4000 gas analyzer.

ii) Experimental procedure

The experiment was started when the engine was fully warmed up. During the tests, the coolant and lubricant oil temperatures were kept around 90 and 95

°C, respectively to minimize their negative effects on the tests results. The purpose of this paper is to investigate the effect of hydrogen enrichment to the performance of a gasoline engine.

The experimental investigations were carried first on the fuelled engine with gasoline and then with gasoline and hydrogen addition, at full load and 3000 rpm (±50 rpm) engine speed. Spark ignition timing was adjusted for each operating regime at optimum value. When adding hydrogen the optimum spark ignition timing is smaller comparative to gasoline SI engine due to much higher burning rate of hydrogen.

Hydrogen flow rate was adjusted by hydrogen injection duration and fuelling pressure. Hydrogen fraction (energetically) was kept up to 20%. The excess air-fuel ratio was kept between 0.8 and 1.7, respectively.

3. Results and discussion

Effective power

Figure 2 shows the effective power variation versus air-fuel ratio - λ. It can be seen a significant increase of power with the addition of hydrogen. When excess air ratio is increased it can be seen a decrease in effective power but still higher than the power of the standard engine. Higher engine effective power obtained by hydrogen addition is due to better combustion properties of hydrogen, due to shorter duration of combustion, cycle burning release heat, and also because of an increase of the heat release rate.

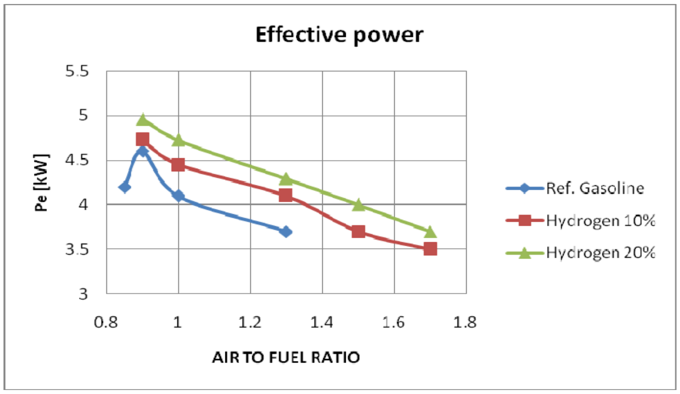

Fig. 2 Effective power vs air to fuel ratio at 10% and 20% hydrogen

Energetic brake specific fuel consumption

Fig. 3 presents the values obtained for the energetic brake specific fuel consumption at 3000 rpm v.s. air-fuel ratio. The influence of hydrogen addition results in a decrease of the specific fuel consumption. Comparative to gasoline engine EBSFC is smaller for hydrogen fuelling due to combustion improvement (better quality of the air-fuel mixture and better burning properties). Gasoline engine operation with higher air-fuel ratios than 1.3 is almost impossible but, by hydrogen addition its operation becomes possible in the very lean mixtures domain (up to 1.7).

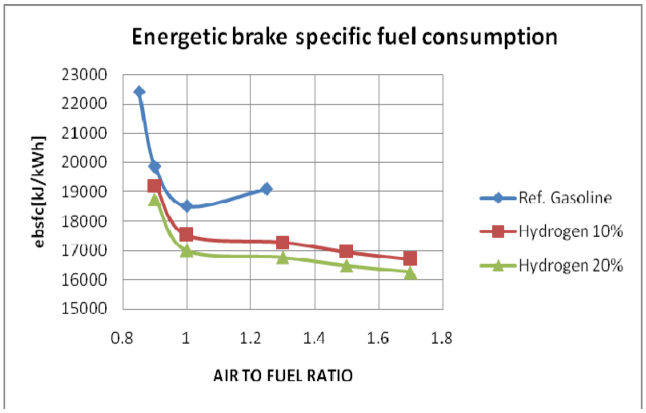

Fig. 3. EBSFC vs air to fuel ratio at 10% and 20% hydrogen

Combustion duration

Fig.4. presents the combustion duration v.s. hydrogen procentage. It can be seen that during the combustion process the combustion duration decreases with the increase of the amount of hydrogen in the cylinder. This property is due to hydrogen burning at stoichiometric dosages up to 20 times faster than conventional fuels.

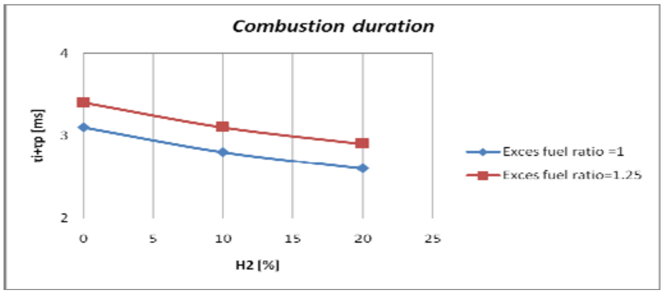

Fig.4. Combustion duration vs H_2 , 3000 rpm.

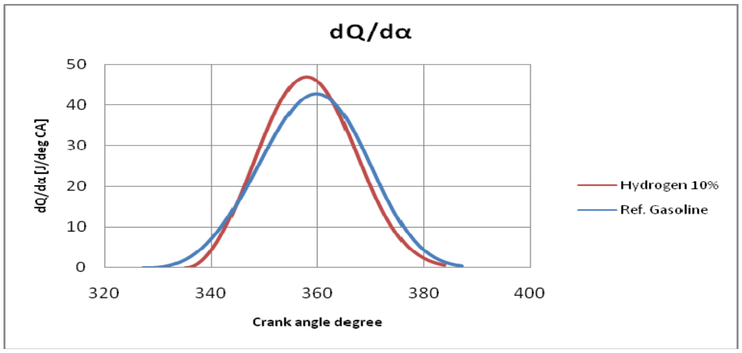

Fig. 5. Rate of heat relase vs crank angle degree 3000 rpm, λ=1.

Hydrogen has a much higher burning velocity than gasoline. Therefore, combustion duration of the hydrogen–gasoline mixture is shorter than pure gasoline, and the reduced combustion period symbolizes the decreased post-combustion duration of the hydrogen-enriched engine and consequently causes the increased specific heat ratio during expansion stroke [15]. The reduced post-combustion duration also means less heat is released but at a higher burning velocity when the piston is moving downward, which results in the reduced cooling losses and exhaust losses.

CO_2 emission

Investigation of pollutants emissions has always been an important goal in the automotive industry. Improving mixture formation is used as a mean to reduce exhaust emissions. Using hydrogen in addition the quality of the air-fuel mixture is better comparative with the gasoline engine and moreover the better hydrogen combustion properties improve the combustion process. As seen in Figure 6, CO_2 emission levels are smaller at the engine fuelled with hydrogen addition than the gasoline engine. The CO_2 emission level reduction is more pronounced at lean mixtures use.

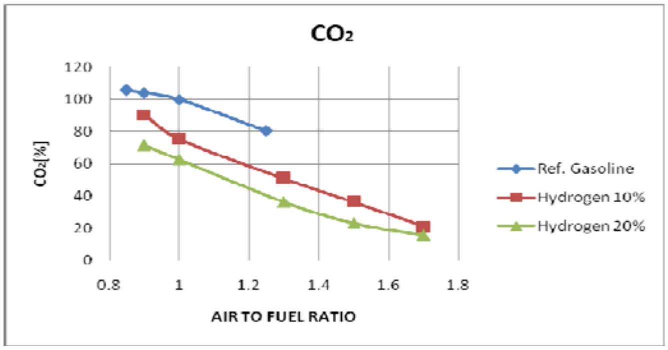

Fig. 6 CO_2 vs air to fuel ratio at 10% and 20% hydrogen

NO_x emissions

Figure 7 shows the variation of NO_x emission which is increased by hydrogen addition. For λ= 1-1.4 range NO_x levels are highest due to the highest peak fire temperatures. For lean hydrogen mixture with excess air ratio (λ>1.4) the combustion temperature decreases and of course NOx emission level decreases very much. In order to reduce NO_x emission level at hydrogen fuelling for λ=1 – 1.4 different neutralization method can be applied by gas passive treatment. More easily is to use the engine qualitative load adjustment which allows the engine operation at lean dosage.

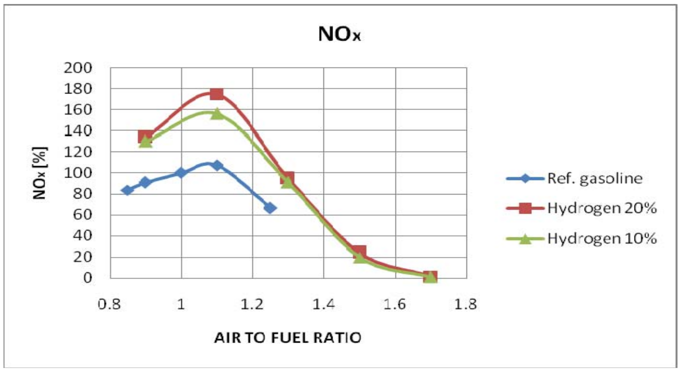

Fig. 7 NO_x vs air to fuel ratio at 10% and 20% hydrogen

HC emissions

An improvement of the combustion process takes place at the use of hydrogen addition so the HC emission decreases [11], [12], [13] Fig. 8.

Reduction of this emissions level is more pronounced at the use of lean mixtures.

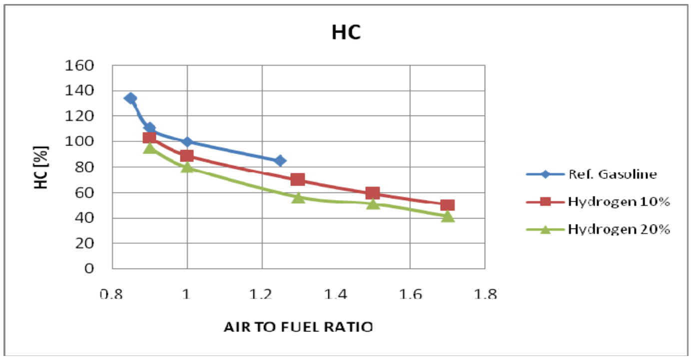

Fig. 8 HC vs air to fuel ratio at 10% and 20% hydrogen

4. **Conclusions**

From the analysis of experimental results obtained by hydrogen additiony, the following conclusions can be reported:

The stable engine operation at lean mixtures comparative to the gasoline engine.

The increase of engine output by hydrogen addition in comparison with normal gasoline operation.

A pronounced reduction of EBSFC comparative to the gasoline engine.

HC and CO emissions level are obviously reduced comparative to the gasoline engine.

NO_x level is higher for λ=1 -1.4 comparative to the gasoline engine. By applying the quality adjustment of the engine load (an efficient load control) the NO_x emission level is obviously reduced.

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