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ASPECTS OF USING HYDROGEN IN SI ENGINE

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The paper presents the results of research's carried on the SI engine, fuelled with hydrogen by direct injection method. Using this fuelling method are avoided the abnormally hydrogen combustion phenomena's, achieving ~30 % engine power increase. Hydrogen engine runs with engine load qualitative adjustment. This provides a higher engine efficiency at low loads, the best results was obtained for λ=2…4. Are presented the influences of the mixture quality on burning process, on polluting and energetically engine performance. Because of the higher combustion temperature the NOx emission level is higher for λ=1…2 comparative to gasoline fuelled engine, but decrease a lot for λ>2.

Keywords: hydrogen, lean mixture, qualitative adjustment, direct injection

1. Introduction

Fossil fuel supply reduction and environment protection preoccupations bring in front for the last years, more than ever, ways to find alternative fuels for internal combustion engines use in order to reduce the exhaust gas emissions.

In order to reduce the pollutant substances emissions and also the substances with green house effect the fossil fuel with high carbon content are replaced in burning process. Into transportation field the dependency of fossil fuels in very high and in order to reduce the internal combustion engine exhaust emissions the researchers act directly to improve engines and fuels.

Among the alternative fuel, hydrogen is considered as an ideal fuel of the future. Hydrogen energetically cycle is much shorter comparative to fossil fuels energetically cycles.

A development of hydrogen technology into the transportation domain is a high cost process and requires solutions for many issues, like:

- a low cost of hydrogen production process
- hydrogen safety storage conditions on the vehicle and in sufficient quantities in order to maintain the automotive autonomy

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- hydrogen infrastructure implementation and the effects on the environment
- the use with high efficiency for the replacement of the hydrocarbons into the combustion processes

Hydrogen physical-chemical properties analysis, table 1, shows suitable characteristics for a high efficiency burning process: a burning rate higher comparative to other hydrocarbons fuels, wide flammability limits, very low ignition energy – properties which provides a stable combustion process for lean and very lean mixtures, encouraging the wide scale hydrogen use as fuel for engines.

Table 1

Properties of hydrogen and gasoline

Property		Gasoline	Hydrogen
Molecular mass, [kg/kmol]		114	2.016
Theoretical air-fuel ratio, [kg/kg comb]		14.5	34.32
Density, at 0°C and 760 mmHg, [kg/m^3]		0.735-0.760	0.0899
Flammability limits in air, at 20 ^{o}C and 760 mm Hg	% vol.	1.48-2.3	4.1-75.6
	λ	1.1-0.709	10.12-0.136
Flame velocity in air (λ=1), at 20 ^{o}C and 760 mm Hg [m/s]		0.12	2.37
Octane Number		90-98	>130
Min. ignition energy in air [mJ]		0.2-0.3	0.018
Autoignition temperature, [K]		753-823	848-853
Lower Heating Value (gas at 0°C and 760mmHg)	stoichiometric fuel-air mixture [kJ/m^3]	3 661	3 178
	[kJ/kg]	42 690	119 600

The researches for using hydrogen as fuel for engines was initiated many years ago, since the third decade of the last century, [1, 2] but for the last two decades this issues becomes important aspects for university researchers and world wide prestige firms [3,…21].

2. Hydrogen combustion particularities

The research's regarding hydrogen use as fuel for engines where especially developed for spark ignitions engines. Were developed two research ways:

- a partial gasoline substitution with hydrogen;
- a total gasoline substitution with hydrogen.

If the hydrogen is used as additional fuel, it can be improved the engine running at lean mixtures in order to decrease the pollutant emissions; this it happens due to a better burning process, more efficient one, for partial loads, knowing that hydrogen has an wide range of ignitability. For this purpose small hydrogen quantities are used, in addition, the gasoline substitution percent being around 10%. This process is easy to imply, because the small hydrogen quantities admitted into the engine inlet don't produce any abnormal combustion phenomena's. In this case the engine modifications are minimal and the hydrogen tank or the hydrogen producing devices on the vehicle board are easy to equipped, due to a small hydrogen quantity required by the engine.

This process can be considered a step forward for a hydrogen total fuelled engine; in that case the advantages of the exhaust emissions decrease are obvious. Hydrogen doesn't pollute. For an engine running only with hydrogen the exhaust gases don't contain: carbon oxides, hydrocarbons, particles and lead compounds; all this excluding the unburned hydrocarbons or the carbon oxides provided by oil burning inside the combustion chamber. Nitrogen oxides are still exists in exhaust gases because of a higher burning temperature inside the cylinder. The NO_x concentration is much higher comparative to the petrol engine runs with stoichiometric dosage, when the burning temperature increases, but the concentration decreases a lot for leaner mixtures, $\lambda>2$, mixture conditions very easy to imply due to hydrogen large flammability limits ($\lambda = 0.14...10.12$), [10, 20, 21]. This particularity allows the use of qualitative load adjustment for spark ignition engine, leading to a better engine indicate efficiency for partial loads comparative to the load adjustment classic process of intake shuttering by throttle.

Running with stoichiometric mixture becomes necessary option in order to attenuate the litre power decrease, knowing that at this dosage hydrogen fill up (occupies) almost 30% from the mixture volume. To avoid this power decrease the supercharging or hydrogen direct injection method can be use, avoiding thus the reduction of admission air quantity. At $\lambda=1...2$ different methods can be applied in order to reduce the exhaust NO_x emission concentration: catalytic converters use, ignition timing tuning, cooled exhaust gas recirculation.

The control of the running of the hydrogen fuelled engine is made it in a first step by a qualitative load adjustment until $\lambda=3.5…4$, after that a quantitative load adjustment is required in a second step, in order to prevent the engine efficiency decrease because of the combustion duration increase, increasing caused by an excessive lean mixture, $\lambda>4$, [10].

Theoretically the methods used for the engine fuelling with gaseous fuels can be applied for hydrogen too, but considering some particularity issues. The research's regarding the hydrogen use in engines shows specific burning process aspects:

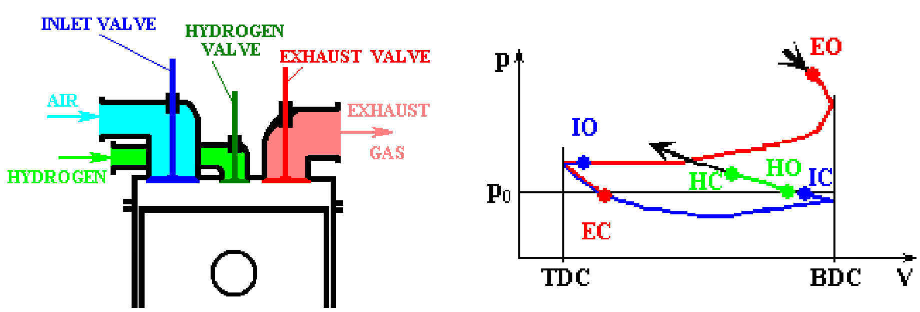
- spontaneous ignition followed by intake misfire ("back fire") or the pre-ignition phenomena followed by a higher in-cylinder pressure increase, with negative effect on the engine performance (brutally engine running, the efficiency and power decreases), all because of hydrogen large flammability limits and because of a lower ignition energy of the hydrogen-air mixtures;

- in-cylinder high pressure rise rate because of higher burning rate.

This specific burning phenomenon's appears with a maximum intensity at stoichiometric mixtures, for maximum burning rate and minimum ignition energy. In order to assure the control of the running of the hydrogen fuelled engine is important to take special precautions in order to eliminate this phenomena's:

- uncontrolled ignition sources elimination thru design solutions regarding cylinder head, valves, ignition system, piston and piston rings;
- using an adequate mixture forming process in order to avoid inflammable mixtures forming in areas when the ignition may occurs from the sources;
- burning rate control in order to decrease the in-cylinder pressure rate.

Hydrogen use as fuel for engines implies fuelling system and safety issues and combustion process control issues. In order to avoid litre power decrease because of the reduction of the inlet air quantity, hydrogen is admitted inside the cylinder after the inlet valve closing, figure 1, achieving in this way inside cylinder mixture forming. Thus is avoided the inlet air quantity reduction, and the cycle mixture mass, the cycle release heat increases with almost 24 % comparative to classic engine and with almost 43% comparative to solution when



a) b)

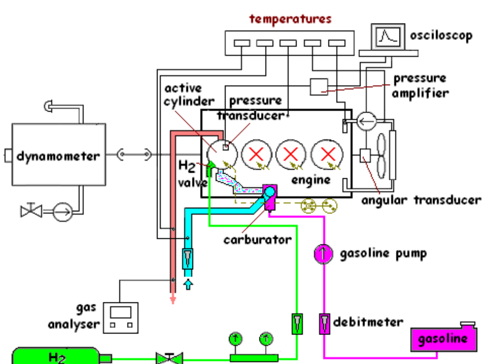
Fig. 1. a)-Direct injection of hydrogen inside the cylinder thru a valve in the combustion chamber. b)-The duration of hydrogen valve open on the compression stroke.

the air-hydrogen mixture forming is made it outside the cylinder. Also this hydrogen fuelling method, after the inlet valve closing at the beginning of the compression stroke, allows cylinder cooling with air and eliminates the uncontrolled burning process or intake back fire.

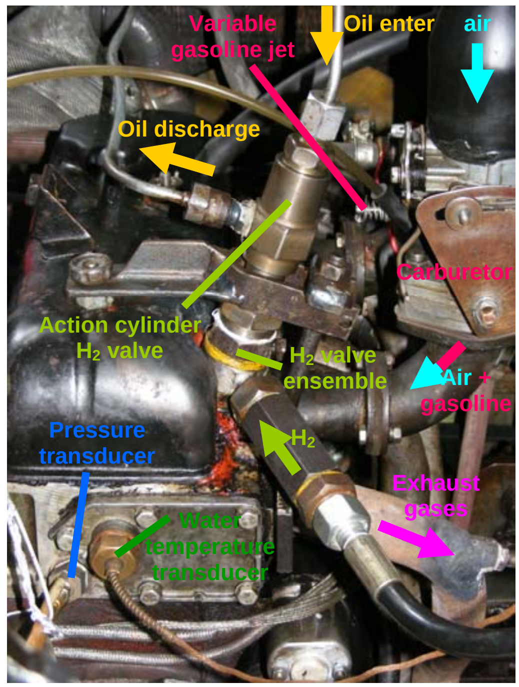
3. Experimental investigations and results

Investigations carried on the experimental single cylinder engine derived from a 4 stroke automotive SI engine, with following the characteristics: bore

D=73 mm, stroke S=77 mm, compression ratio ε=8.5, liquid cooled, normal admission, speed n=5000 rpm; three valves: one for admission, one for hydrogen supply, one for exhaust; ignition system with central spark plug. Hydrogen valve is actuated by a hydraulic system with the adjustment possibility for opening timing or the opening duration of the valve. Hydrogen flow rate is controlled by valve opening duration or by the fuelling pressure.



a)



b)

Fig. 2 a)-The engine test bed schema; b)-The test bed picture

Figure 2**a** presents engine test bed and a detail image for cylinder head, figure 2**b**. The test bed devices and instrumentations allow to determinate the following engine operating parameters: torque, speed, temperatures, pressures, air and hydrogen flow rate and for p-α diagram acquisition was used a Kistler pressure transducer, and an AVL acquisition system. Crank angle position is given by a Kubler incremental transducer. Hydrogen supply is provided by a bottle at 15 MPa pressure, using two step pressure reductor's in order to achieve the fuelling pressure: on the first step (for high pressure circuit), the hydrogen pressure from the bottle is reduced at 1 MPa and on the second step (for low pressure circuit) the pressure decrease till the fuelling pressure value, adjusted in the area of 0.1…1 MPa.

For a normal operating regime, without knocking process or in-cylinder higher pressure rise rate, the engine spark timing was adjusted. The operating regimes were carried on wide open throttle. Spark ignition timing was adjusted for each operating regime for maximum power. In case of hydrogen fuelling the spark ignition timing was reduced comparative to classic solution due to much higher burning rate of hydrogen.

In figs. 3…8 is presented the mixtures quality influence on some cycle characteristics parameters. The maximum pressure, p_{max}, takes higher values at the same dosage, λ=1, for hydrogen fuelling comparative to petrol engine figure 3. This fact confirms the results of thermodynamic calculus, because hydrogen burning rate is superior to gasoline and for hydrogen direct injection method the cycle heat release increases with almost 24%. The increase of maximum pressure value (~ 30 %) doesn't affect the engine reliability. One reduction factor for maximum pressure rise rate increase is represented by molar chemical shrinking at hydrogen combustion.

For stoichiometric dosage the molar chemical shrinking coefficient at hydrogen combustion is 0.85, and at gasoline burning a molar expansion process takes place, the molar coefficient being 1.05.

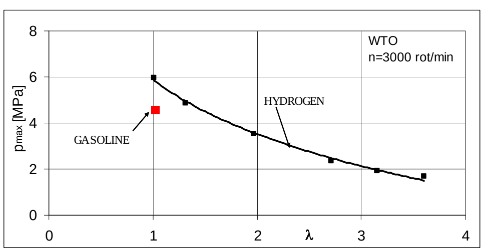


Fig.3. Maximum pressure versus λ

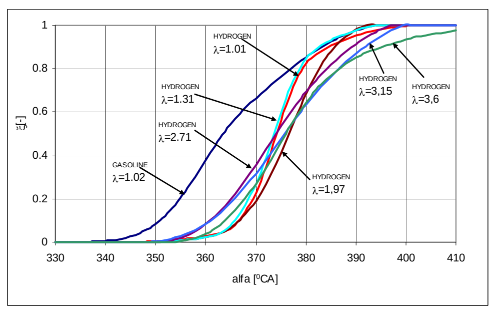


Fig. 5. Heat release versus crankshaft angle

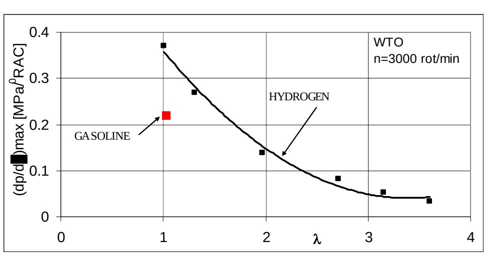


Fig.4. Maximum pressure rate versus λ

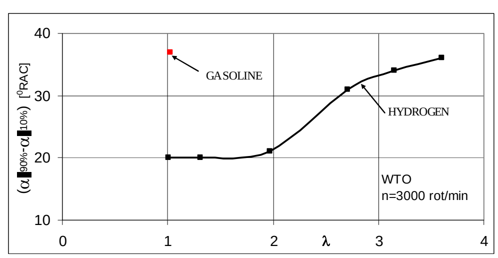


Fig. 6. Burning combustion duration versus λ

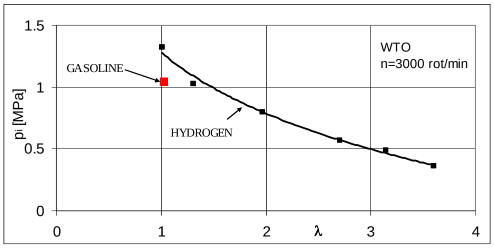


Fig. 7. Indicated mean pressure versus λ

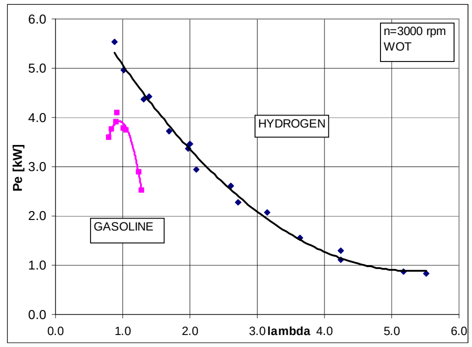


Fig.9. Engine power versus λ

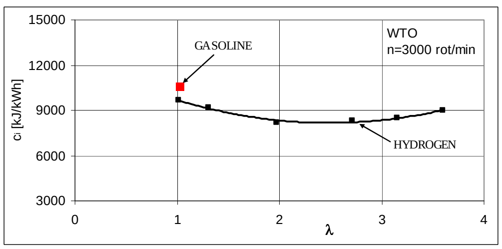


Fig. 8. ISFC, c_i, versus λ

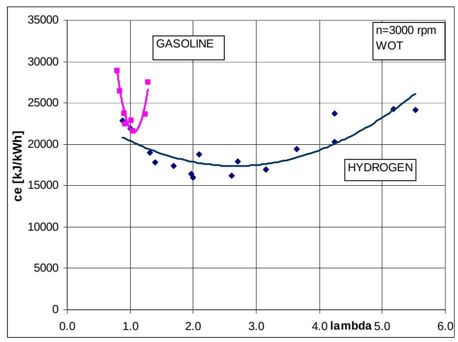


Fig.10. BSFC versus λ

The maximum pressure rise rate, $(dp/d\alpha)_{max}$, for stoichiometric dosage, is higher comparative to petrol engine, figure 4, due to a superior burning rate and shorter combustion duration for hydrogen, figures 5, 6. For hydrogen fuelling the maximum pressure rise rate values don’t exceed significantly the classic values, but they can be controlled by spark ignition timing adjustment. The maximum pressure rise rate takes lower values for lean dosages $\lambda>2$, with a lower pressure rise rate during combustion.

For hydrogen operating engine the qualitative load adjustment was applied. For leaner mixtures $\lambda=1….3.6$, the IMEP, p_i, decreases from 1.32 MPa to 0.36 MPa, figure 7, fact which is directly related with load variation between the range $\chi=100\%...25\%$. At stoichiometric dosage the indicate pressure increases with ~25% due to combustion improvement and cycle burning heat increase.

A much higher burning rate, flammability lower limit for very lean dosages, $\lambda_i=10.12$ and lower ignition energy, all this hydrogen qualities provides efficiency engine running at partial loads when the qualitative load adjustment is used. At stoichiometric dosage the ISFC, c_i, decreases with ~10% for hydrogen comparative to gasoline, figure 8. Engine efficiency increases when the mixture becomes leaner till λ~3.2 due to hydrogen suitable burning properties and due to the reduction of heat loses. For much leaner mixtures the ISFC increases because the burning duration also increases, figures 5, 6.

4. Energetic and polluting performance

In order to have a general view on hydrogen engine energetic performance figure 9 presents the variation of effective power versus volumetric efficiency for wide open throttle conditions at 3000 rpm engine speed. For each operating regime the spark ignition timing was set at optimal value. The maximum power increases with ~30% due to the fuelling method used: hydrogen direct injection at the beginning of compression stroke. Load qualitative adjustment was used for hydrogen running engine. Comparative to petrol classic engine the engine efficiency is improved for hydrogen fuelling at stoichiometric dosages, figure 10. This advantage appears due to better hydrogen burning properties, but as a disadvantage appears the increase of heat loses caused by a much higher burning temperature. But for leaner mixtures the hydrogen engine efficiency is clearly superior to petrol engine. For gasoline fuelling the short flammability limits of gasoline can't provide engine running for dosage values over λ=1.3. For hydrogen fuelling and load qualitative adjustment use for dosage values till λ~5.5 engine efficiency decreases insignificantly, the best results where obtained for λ=2…4, figure 10. For this dosage area, λ=2…3.2, efficiency improvement is explained by shorter burning duration and heat loses decrease due to a lower combustion temperature. For mixtures leaner to excess, λ > 3.2, the increasing of combustion duration, figure 5, explains brake specific fuel consumption BSFC increase, figure 10.

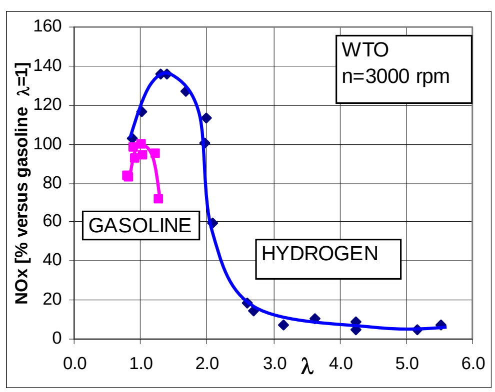


Fig.11. Relative NO_x emissions versus excess air ratio at full load and 3000 rpm

Hydrogen fuelled engine don't produce like petrol engines a lots of polluting substances as, CO, HC, particles and lead compounds and CO_2

emission. Excluding the unburned hydrocarbons or the carbon oxides provided by oil burning inside the combustion chamber, the only polluting substances are nitrogen oxides because of a higher burning temperature inside the cylinder. The NO_x emission level is much higher comparative to the petrol engine for λ=1-2, figure 11, because the burning temperature increases. At much leaner dosages, λ>2, nitrogen oxides emission level decreases very much, figure 11. In order to reduce NO_x concentration from exhaust gases at hydrogen fuelling for λ=1-2, different neutralisation methods can be use, such as NO_x catalytic converters.

5. Conclusions

From the research results analysis, the following conclusions can be formulated:

1. Hydrogen fuelled engine efficiency is superior to gasoline engine, especially at small partial loads operating conditions, due to a better combustion process and load qualitative adjustment method.
2. The level of pollutant emissions decreases at the hydrogen fuelling. The exhaust gases don't contains CO_2 or lots of polluting substances provided by classic engines such as CO, HC, particles and lead compounds. Excluding the unburned hydrocarbons or the carbon oxides provided by oil burning inside the combustion chamber, nitrogen oxides emission level is the only issue. NO_x exists in exhaust gases because of a higher burning temperature inside the cylinder reached at λ=1-2. In order to resolve these issue different methods can be applied like: cooled exhaust gas recirculation, ignition timing optimization for this purpose and/or catalytic converters use.
3. The solution of hydrogen direct injection at the beginning of the compression stroke provides engine running, at stoichiometric dosage, without abnormal burning phenomena's.
4. Direct injection hydrogen fuelled engine power is bigger with almost 30% comparative to gasoline engine, due to avoiding of the inlet air quantity reduction.

On medium term hydrogen application in use can be developed in order to replace the fossil fuels into engine combustion processes. This becomes an efficient solution for pollutant emissions level decrease and hydrocarbons fuels dependency reduction.

Due to its properties hydrogen has proved to be an excellent fuel for internal combustion engines and signifies a reliable option to the fossil fuels replacement, providing also the benefit of maintaining the main principles of the existing engines design.

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