PERFORMANCE COMPARISON BETWEEN HYDROGEN AND GASOLINE FUELLED S.I. ENGINE

by

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Due to its combustion properties, the hydrogen has a great potential in energetic improvement and emission performance of spark ignition (SI) engine. In this respect, the paper presents comparative results of the experimental researches carried on SI single cylinder engine fuelled with gasoline or only hydrogen, at some engine speeds and full load. Direct injection hydrogen fuelled engine power is greater with almost 30% comparative to gasoline engine due to cycle heat release increasing. The hydrogen direct injection method in the engine cylinder at the beginning of the compression stroke after the intake valve closed has been chosen to avoid reducing the power output per litre. Using this fuelling method was possible to avoid the uncontrolled burning process for all engine operating regimes. Hydrogen supply system used is original and offers great flexibility in operation to establish the adjustments.

The obtained results show that the engine fuelled with hydrogen offers the possibility of qualitative load adjustment using for the engine performance improvement especially at partial loads. The paper presents a strategy for combining qualitative and quantitative setting adjustment in order to optimize engine operation at all regimens.

Key words: *hydrogen, combustion, emissions, efficiency, engine fueling*

1. Introduction

Hydrogen, with unlimited producing resources, is considered a privileged alternative fuel due to its properties, table 1, which make it the cleanest fuel [1, 2]. The power output of the hydrogen-fuelled internal combustion engines, depending on fuelling method, can be up to 20% greater than gasoline engines [3, 4]. The experimental researches carried out on spark ignition engines fuelled with hydrogen have highlighted certain aspects of the combustion comparative to gasoline: higher maximum pressure of gas inside engine cylinder; higher pressure increasing rate due to the higher combustion rate of hydrogen compared to other fuels [5, 6, 7, 8]; spontaneous ignition followed by backfire (the uncontrolled ignition occurring at hydrogen fuelled engines can be caused by the hot elements existing in the inlet system or even in the cylinder); in-cylinder pre-ignition followed by rapid pressure increase during the compression stroke that leads to a loss of the engine efficiency; at excess air ratio $\lambda=1$, the mixture air-hydrogen requires an ignition energy 10 to 30 times less than the majority of air-hydrocarbons mixtures; [5, 6, 7]. The aspects of abnormal combustion are frequently present at the stoichiometric air-fuel ratio when the ignition delay is reduced and the combustion rate is high. At lean mixtures ($\lambda=1.5-2.0$) these aspects disappear, but in this case the engine power per

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litre significantly decreases considering also the fact that hydrogen participation at stoichiometric dosage is ~30 % vol. (versus only 1.8 % for gasoline), [6, 7, 8]. To avoid the engine power per litre decreasing due to the fact that hydrogen displaces about 30% from the cylinder volume, the authors have used the in-cylinder mixing formation method, the hydrogen being admitted after the intake valve is closed, figure 1. Using this fuelling method it was possible to avoid the uncontrolled burning process for all engines operating regimes and the reduction of the admitted air quantity.

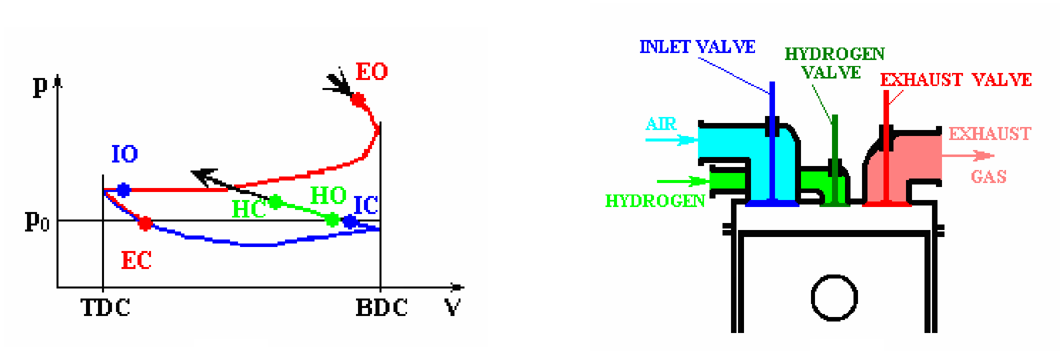
Table 1 Properties of hydrogen and gasoline

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 °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 °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 combustion heat release is about 24% greater than in the case of gasoline fuelled engine and by about 43% greater than in the case of hydrogen-air mixture outside cylinder formation [9, 10]. The hydrogen admission after the intake valve closing allows also the cooling of the cylinder by air; the air is subsequently used for the combustion, preventing the uncontrolled ignition and the return of the flame in the intake system [9, 10].

Because the laminar burning velocity of the hydrogen is about twenty times greater than of the gasoline laminar burning velocity [11], the combustion time duration at the hydrogen engine is shorter than of the gasoline engine, the hydrogen burning approach to constant volume combustion and engine thermal efficiency increases [12]. The wide flammability of hydrogen also permits hydrogen engine fuelled to operate at lean and very lean mixtures and to obtain an improvement in engine thermal efficiency [13, 14], without an important cyclic variation.

For an engine running on hydrogen the exhaust gases contain carbon dioxide, carbon monoxide, small concentrations of hydrocarbons because of oil combustion inside the combustion chamber. Nitrogen oxides exist in exhaust gases because of a higher burning temperature inside the



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b

Figure 1: a)-Direct injection of hydrogen inside the cylinder through a valve in the combustion chamber; b)-The duration of hydrogen valve opening on the compression stroke

cylinder.The NO_x concentration is much higher comparative to the gasoline engine operation with stoichiometric dosage, when the burning temperature increases. At λ=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 NO_x emissions level pronounces decreases at leaner mixtures, λ>2, engine operation being possible due to hydrogen large flammability limits (λ=0.14–10.12), [8, 15, 16]. This particularity allows the use of the qualitative load adjustment for spark ignition engine, leading to a better engine indicate efficiency at engine partial loads comparative to the load quantitative adjustment. The main objectives of this paper are: showing the advantages of the hydrogen fuelled method, the engine energetic performance and pollutant improvement at hydrogen fuelled engine.

2. Experimental investigations

The experimental research was carried out on an experimental single cylinder engine derived from a serial automotive engine with the technical specifications mentioned in table 2.

The specifications of the test engine are given in table 2.

Table 2 Test engine specifications

Engine type	**810-99 modified**
Cylinders	1
Displacement	0.322 litre
Bore	73 mm
Stroke	77 mm
Conrod length	128 mm
Compression Ratio	8.5
Fuelling	Modified carburettor

The hydrogen fuelling of the engine is achieved through a valve at the beginning of the compression stroke after the intake valve closes when a cooling effect for the engine cylinder's hot parts was made by previously aspirated air to avoid the power per litre decrease, spontaneous ignition and the back fire. The pressure in the hydrogen fuelling system is relative low (~ 0.2-0.5 MPa). A special design hydrogen valve, fig.2a, is placed in the engine cylinder head between the intake and exhaust valves. Hydrogen intake valve, separately actuated from the standard engine's valve system, allows 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 fuelling pressure [13, 17]. The hydrogen fuelling valve is actuated by a high flexibility hydraulic system which provides the possibility of adjusting the valve opening duration and the valve opening timing, figure 2b. With this fuelling method it was possible to avoid the uncontrolled burning process for all operating regimes, even for stoichiometric dosage mixtures. In this aspect the temperature regulation of oil and cooling liquid at 80 -90^{o}C was also important.

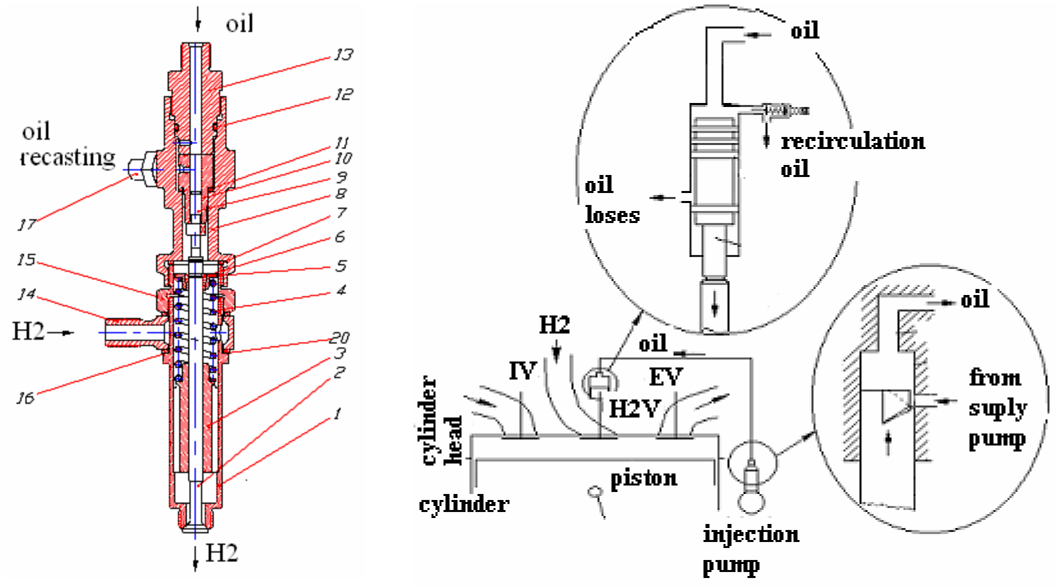

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Figure 2: a-Hydrogen valve assembly: 1-inferior housing; 2- hydrogen valve; 3- perforated dish; 4- valve spring; 5- dish; 6-ring; 7- gasket; 8- superior housing; 9- actuator piston; 10- actuator cylinder; 11- gasket; 12- Oaring; 13- recasting oil connection pipe; 14- hydrogen fueling joint; 15-threaded sleeve; 16- gasket; 17- one-way valve; **b-Hydrogen valve acting schema:** IV-intake valve, EV-exhaust valve, H2V-hydrogen valve

Figure 3 presents the test bed schema. The test bed was equipped with appropriate instrumentation in order to acquire all the parameters of high interest.

The engine is loaded by a Steinbeck B4 hydraulically dynamometer. Gasoline flow rate is measured by an OPTIMAS fuel mass flow meter. The air and hydrogen quantities flow rates are measured by two KROHNE flow meters. The engine was equipped with a quartz piezoelectric pressure transducer Kistler 601 A mounted in the cylinder head for in-cylinder pressure measurement. The crankshaft angle was measured with an incremental transducer Kubler. For each operating

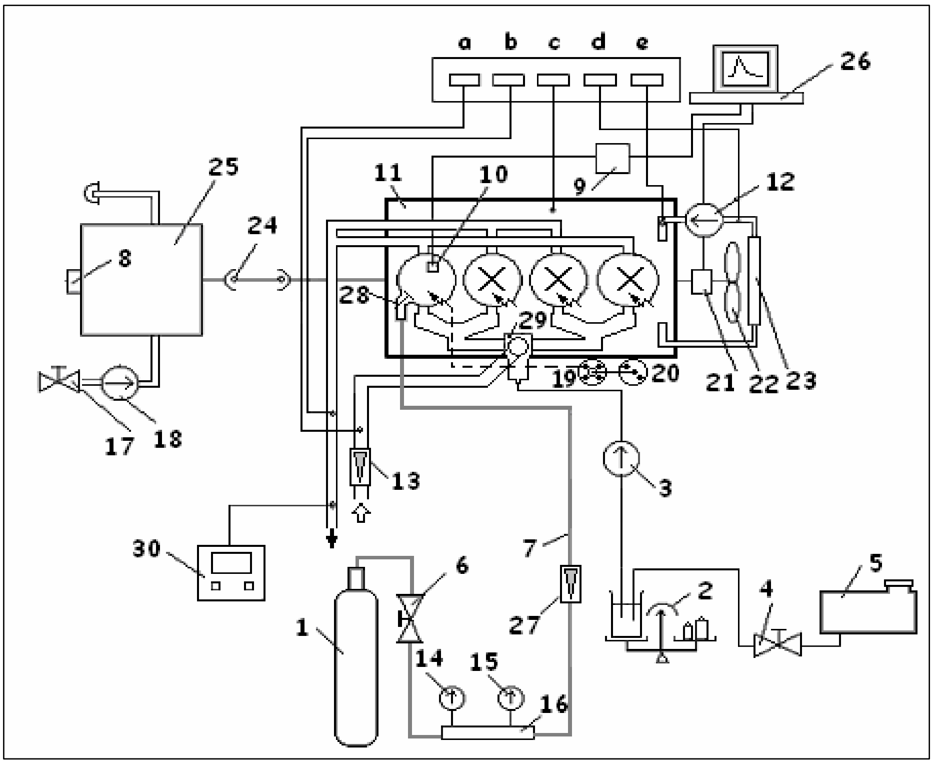

Figure 3 - Engine test bed schema. 1. Hydrogen bottle; 2.Gasoline mass flow meter; 3. Gasoline fuel pump; 4. Gasoline consumption tap; 5. Gasoline tank; 6. Hydrogen consumption tap; 7. Hydrogen fueling pipe; 8. Speed transducer; 9. Kistler charge amplifier; 10. Kistler piezoelectric pressure transducer; 11. SI engine (the suspended cylinders are noted with X); 12. Engine water pump; 13. Air flow meter; 14. H_2 bottle pressure manometer; 15. H_2 engine fuelling pressure manometer; 16. Pressure reducer; 17. Water network tap; 18. Hydraulic dynamometer water pump; 19. Distribuitor; 20. Ignition coil; 21. Kubler speed incremental transducer; 22. Cooling fan; 23. Cooler; 24. Coupling. 25. Schönebeck B4 hydraulic dynamometer; 26. PC + chipboard; 27. Hydrogen flow meter; 28. Hydrogen intake valve; 29. Carburettor; 30. AVL Digas 4000 gas analyzer

condition, 100 consecutive cycles of cylinder pressure data were acquired and averaged by on a PC equipped with AVL acquisition board. The exhaust emissions of NOx, HC, CO and CO_2 are measured by an AVL DiCom 4000 gas analyzer. All instrumentations were prior calibrated to the engine testing. During the experimental investigations, the coolant water and lubricant oil temperatures were strictly kept between 80 and 90 ^{0}C. Hydrogen supply was provided by a bottle at 15 MPa pressure, using two step pressure reductors in order to achieve the fuelling pressure: the first step (for high pressure circuit), the hydrogen pressure from the bottle is reduced at 1 MPa and the second step (for low pressure circuit) the pressure decreases up to the fuelling pressure value, adjusted in the area of 0.1-1 MPa. The spark ignition timing was set at the optimal value for each operating regime.

3. Results and discussions

In figure 4 there are shown the in-cylinder pressure diagrams for gasoline and hydrogen at different dosages. The operating regimes were carried on wide open throttle, at 3000 rpm. Spark ignition timing was adjusted for each operating regime for maximum power. In case of hydrogen fuelling the optimum spark ignition timing is smaller comparative to classic solution due to a much higher burning rate of the hydrogen. Note that if hydrogen supply is at dosages of λ=1-1.5 the curves of pressure variation in the cylinder have a steeper increase than for gasoline operation. At low dosages, $\lambda>1.5$ the curves of pressure variation in the cylinder has a smoother variation.

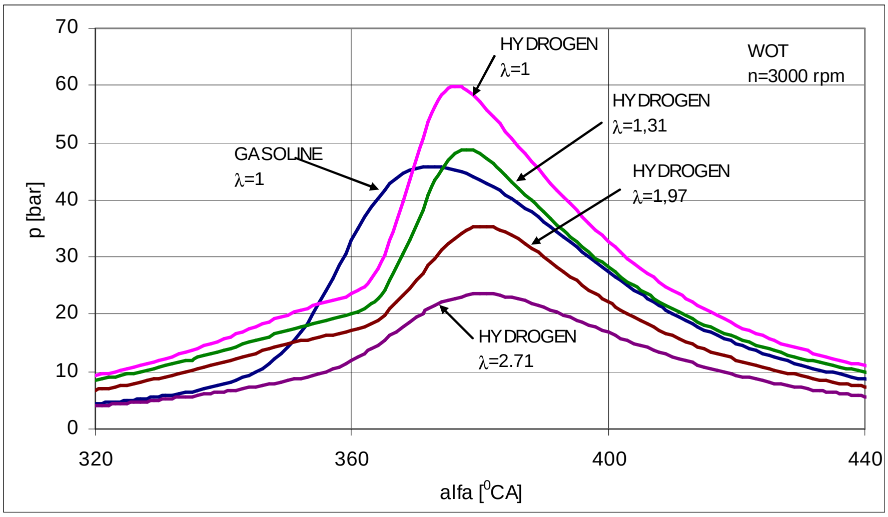

Figure 4 - Pressure diagrams at full engine load and 3000 rpm

In figures 5-12 there are presented the dosage 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 gasoline engine, figure 5. This fact confirms the result of thermodynamic calculus, because hydrogen burning rate is greater to gasoline and for hydrogen directs injection method the cycle heat release increases with almost 24%. The increase of maximum pressure value does not affect the engine reliability, because hydrogen fuelled engine will operate with $\lambda>1.5$ when the maximum pressure is the same to gasoline engine. Same IMEP value of gasoline (λ=1) has been obtained for hydrogen at λ=1.5, fig. 8. The maximum pressure, p_{max}, and maximum pressure rise rate, $(dp/d\alpha)_{max}$, have same values for these dosages, 4.5MPa, respectively 0.22 MPa/^{0}CA, but the indicate specific fuel consumption, ISFC, of hydrogen fuelled SI engine (8950 kJ/kWh for λ=1.5) is lower than of gasoline fuelled SI engine (10500 kJ/kWh for λ=1). This advantage supports the operation of the engine control strategy proposed. One attenuation factor of the maximum pressure and pressure rate increase (the pressure rise rate depends of the combustion rate and of the maximum pressure) 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.

The maximum pressure rise rate, $(dp/d\alpha)_{max}$, for stoichiometric dosage, is higher comparative to gasoline engine, figure 6, due to a greater burning rate and shorter combustion duration for hydrogen, figure 7. For hydrogen fuelling the maximum pressure rise rate values do not exceed significantly the classical values at leaner mixture ($\lambda>1.3$).

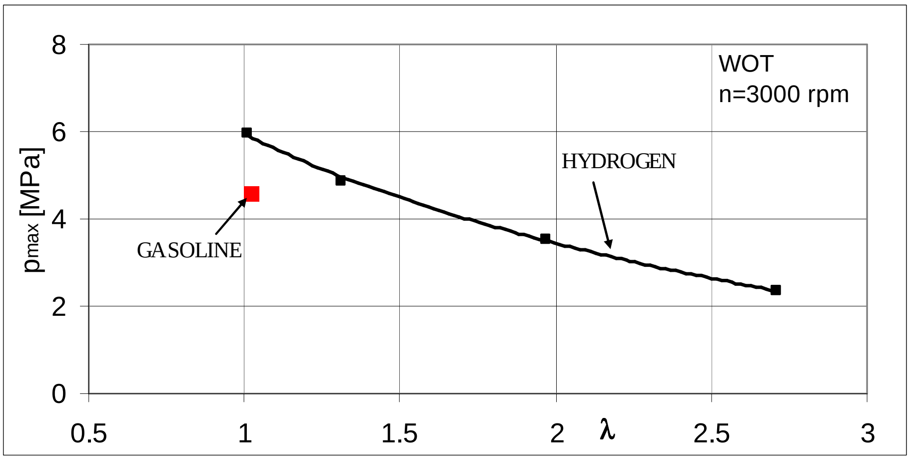

Figure 5 - Maximum pressure versus excess air ratio at full load and 3000 rpm

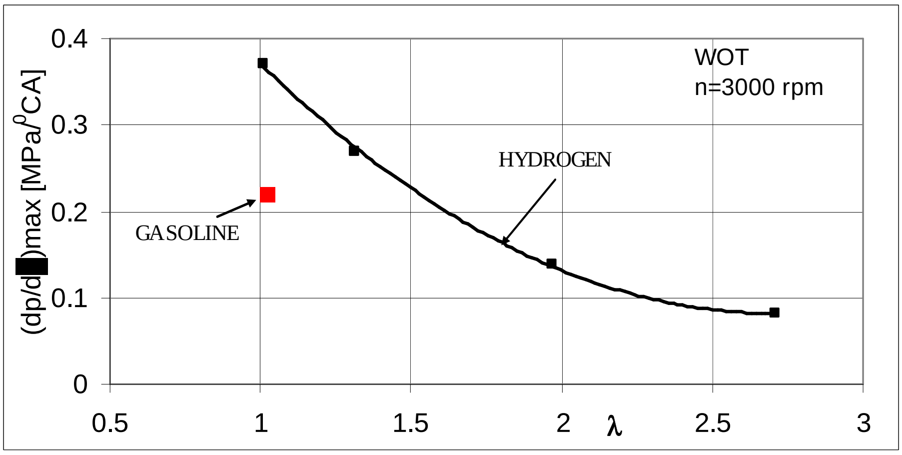

Figure 6 - Maximum pressure rise rate versus excess air ratio at full load and 3000 rpm

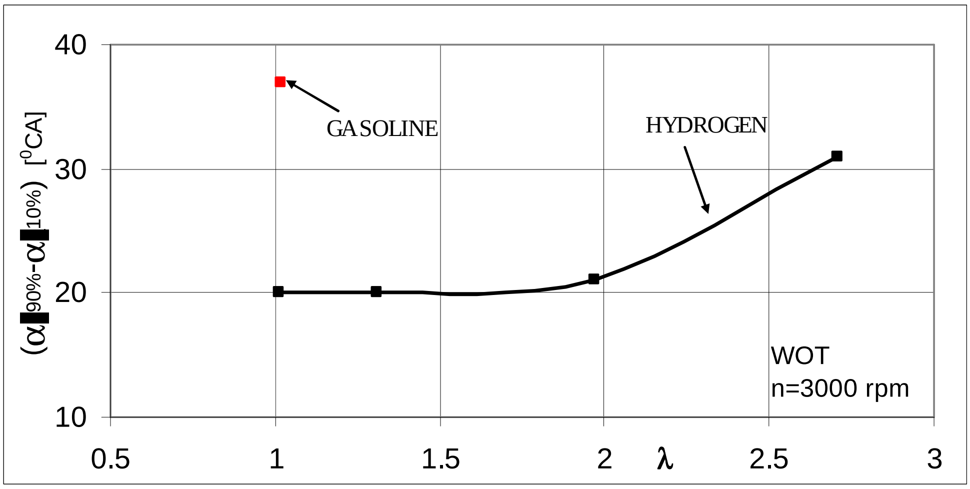

Figure 7 - Combustion time period versus excess air ratio at full load and 3000 rpm

The qualitative load adjustment was applied for hydrogen operating engine. At stoichiometric dosage the indicate mean effective pressure increases with ~25% , figure 8, due to combustion improvement and cycle burning release heat and heat release rate increasing, figure 9. For leaner mixtures λ=1-2.71, the indicate mean effective pressure, IMEP, decreases from 1.32 MPa to 0. 6 MPa, figure 8, fact directly related with load variation between the range χ=100%...45%. At very lean mixtures usage (λ>3), the combustion duration increases, engine efficiency decreases, the combustion instability and unburned hydrogen in exhausts gases appear. To avoid these combustion aspects an adjustment of the quantity load of engine at small loads (χ<45%) is recommended, the excess air ratio being maintained in the area of 2.5-3, [21]. Thus, the hydrogen engine fuelling has a great advantage offering the possibility of a supple load control strategy, [18 and 19].

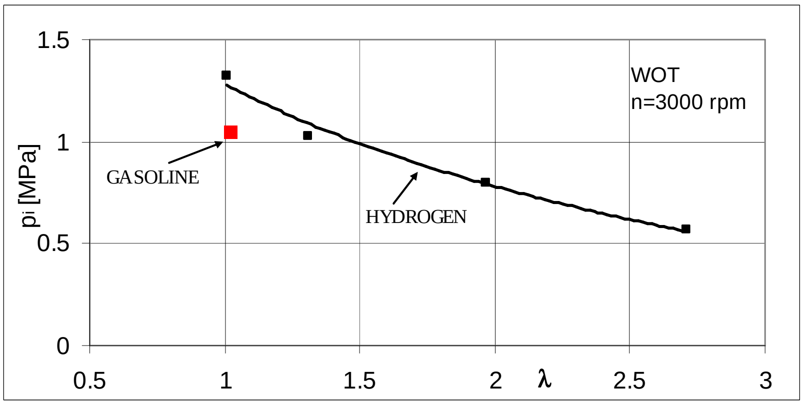

Figure 8 - IMEP versus excess air ratio at full load and 3000 rpm

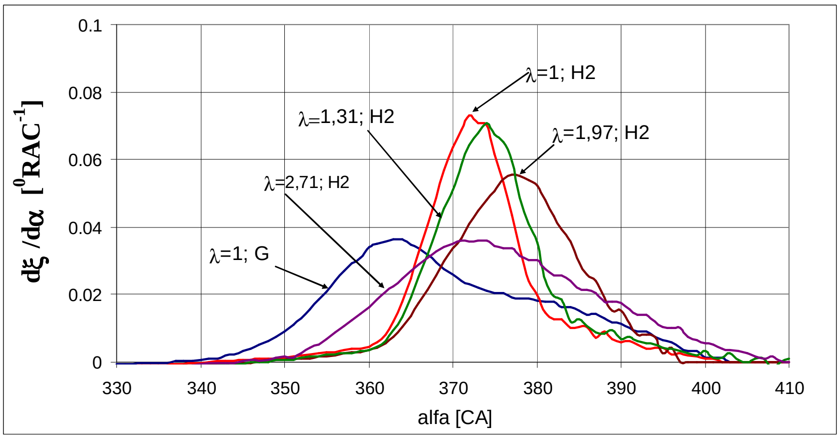

Figure 9 - Heat release rate versus crankshaft angle

The hydrogen properties which provide a high efficiency engine running at partial loads when the qualitative load adjustment can be use are a much higher burning rate, flammability lower limit and lower ignition energy [21]. At stoichiometric dosage the ISFC decreases with ~10% for hydrogen comparative to gasoline, figure 10, because of its higher burning velocity and approaching to constant volume combustion, figure 4. Engine efficiency increases when the mixture becomes leaner up to λ~2.7 due to hydrogen adequate burning properties and due to heat loses reduction. For much leaner mixtures the ISFC increases because the burning duration also increases, [21].

Figure 11 shows the relative NOx emission level as a function of excess air ratio, at full engine load. The NO_x emission level is much higher comparative to the gasoline engine for λ=1-1.5, because the burning temperature increases. For lean hydrogen-air mixtures with excess air ratio λ>1.5 the combustion temperature decreases and, of course, at much leaner dosages λ>1.5, nitrogen oxides emission level decreases very much (for λ>2 maximum temperature is approximately 2100 K and NOx emissions level is virtually zero, [15]). In order to reduce NO_x concentration from exhaust gases at hydrogen fuelling for λ=1-1.5, different NO_x neutralisation methods can be applied by gas passive treatment (e.g. the use of a conventional three way catalyst -TWC), [12]. The stoichiometric dosage engine operation is necessary in order to achieve high power and torque output, the throttle remaining wide open. The mixtures dosages area with λ < 1.5 must be avoided in order to limit the NO_X emissions level, [20]. The engine power decrease is achieved by a throttle easy closing and by the hydrogen consumption reduction in order to maintain the stoichiometric dosage. In this area the quantitative adjustment is applied until the corresponding engine power on gasoline engine at the full load is obtained. At the engine hydrogen fuelling, in the mixtures dosages area λ >1.5, the throttle is wide open and by leaning of the mixtures, corresponding engine power partial loads is obtained. Such,

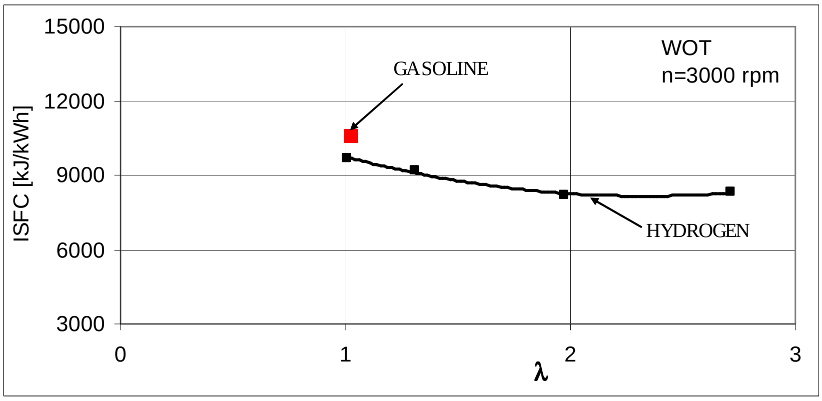

Figure 10 - ISFC versus excess air ratio at full load and 3000 rpm

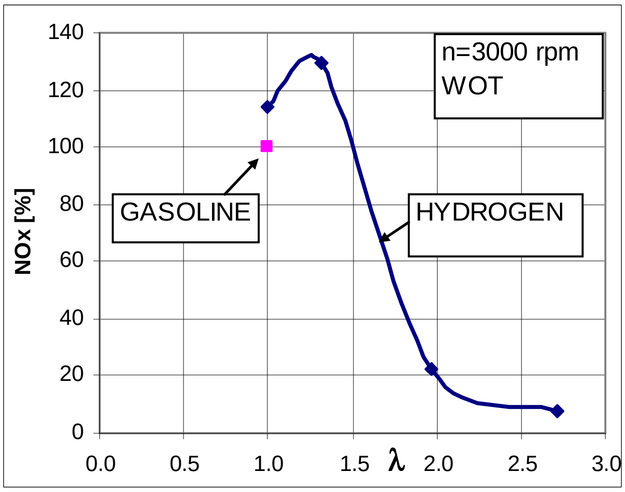

Figure 11 - Relative NO_x emissions versus excess air ratio at full load and 3000 rpm

engine efficiency is higher than that for gasoline (the pump loses are small), but with very low NO_x emissions level. The engine load control strategy is easily applied through the proposed fuelling method.

In order to have a general view on hydrogen engine energetic performance, figure 12 presents the variation of brake effective pressure versus engine speed for wide open throttle. The maximum brake effective pressure increases with ~30% due to the fuelling method used: hydrogen direct injection at the beginning of compression stroke. Comparative to gasoline classic engine BSFC is smaller for hydrogen fuelling at stoichiometric dosage, figure 13; 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 for λ=1. But for leaner mixtures the hydrogen engine efficiency is clearly superior to gasoline engine. For gasoline fuelling the short flammability limits of gasoline cannot provide engine running for dosage values over λ=1.3. For hydrogen fuelling and at the load qualitative adjustment use for dosage values up to λ~5.5 engine efficiency decreases insignificantly,

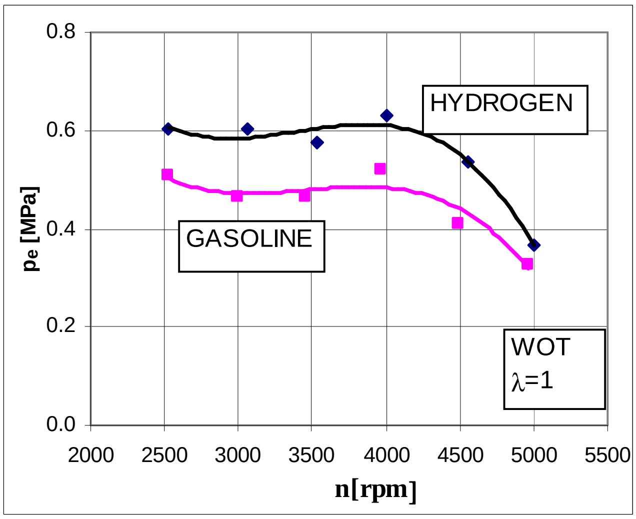

Figure 12 Brake mean pressure versus engine speed at full load

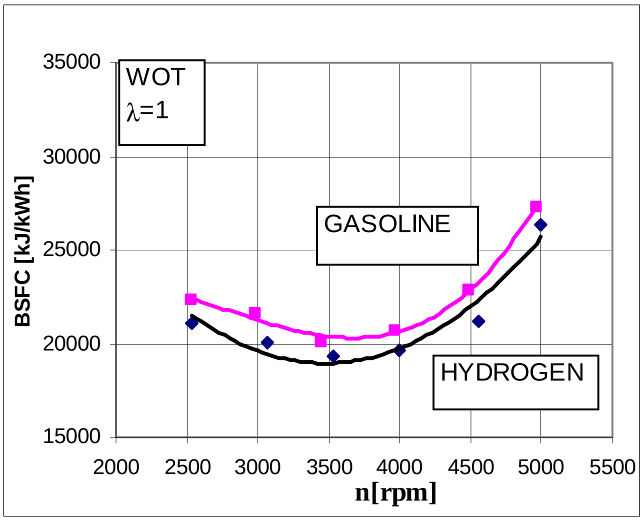

Figure 13 Brake specific fuel consumption versus engine speed at full load

the best results were obtained for λ=2-3, figure 10. For this dosages area, λ=2-4, efficiency improvement is explained by shorter burning duration, figure 7, and heat loses decrease due to a lower combustion temperature. For leaner mixtures, λ>3, the increasing of combustion duration, figure 7, explains the indicate specific fuel consumption ISFC increase, figure 10 (until λ ~ 4 the combustion of the lean H_2-air mixtures may be stable because of the wide ignition limits, [15]).

4. Conclusions

This paper has presented the advantages of using hydrogen as fuel at SI engine.

Direct injection hydrogen fuelled engine power is greater with almost 30% comparative to gasoline engine due to cycle heat release increasing. At the hydrogen fuelled engine ISFC is smaller compared to gasoline engine, especially at partial loads operating, due to improvement of the combustion process. The mixtures dosages area with λ <1.5 must be avoided to limit the NO_X emissions level. The engine power decrease is achieved by the throttle easy closing and by the hydrogen consumption reduction to maintain stoichiometric dosage. The quantitative adjustment is applied in this area until is obtained the corresponding engine power on gasoline engine at the full load. At the engine hydrogen fuelling, in the mixtures dosages area λ>1.5, the throttle is wide open and by leaning the mixtures is obtained the corresponding engine power at partial loads. Thus engine efficiency is higher than for gasoline (the pump loses are small), but with very low NO_x emissions level. Hydrogen fuelled engine does not produce, like petrol engine, 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.

Hydrogen supply system used is original and offers great flexibility in operation to establish the engine adjustments.

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