A CONTROL STRATEGY OF THE HYDROGEN ENGINE FUELED LOAD

Constantin PANA, Niculae NEGURESCU, Marcel Ginu POPA, Alexandru CERNAT

University Politehnica Bucharest, Romania.

Rezumat. Hidrogenul are un potential important pentru imbunatatirea perfoemantelor energetice si de poluare ale motorului cu aprindere prin scanteie datorita bunelor sale proprietati de ardere. Cercetarile pentru utilizarea hidrogenului drept combustibil pentru motorul cu aprindere prin scanteie sunt dezvoltate pe doua directii: combustibil unic si combustibil de adaos. Lucrarea prezinta rezultate ale investigatiilor experimentale efectuate pe un monocilindru experimental alimentat numai cu hydrogen prin metoda injectiei directe dupa inchiderea supapei de admisie. Prin utilizarea acestei metode de alimentare cu hydrogen sunt evitate atat fenomenele de ardere necontrolata cat si scaderea puterii litrice a motorului la dozaj stoichiometric. Sistemul de alimentare cu hydrogen este original si ofera o mare flexibilitate in functionare la stabilirea reglajelor. Sunt prezentate influente ale calitatii amestecului asupra procesului de ardere si asupra performantelor energetice si de emisii ale motorului alimentat numai cu hydrogen. Este utilizata o stategie pentru controlul sarcinii motorului prin combinarea reglajului cantitativ cu cel calitativ pentru optimizarea performantelor sale la toate regimurile de functionare.
Cuvinte cheie: hidrogen, emisii, ardere, randament.

Abstract. The hydrogen has an important potential for the energetically and emissions performance improving of the SI engine due to its good combustion properties. The researches for using hydrogen as a fuel for spark ignition engines are developed in two ways: a full substitution of gasoline with hydrogen and the partial substitution.The paper presents results of the experimental researches carried on SI single cylinder engine fuelled with only hydrogen by direct injection method after the intake valve closed. Using this fuelling method are avoided so the abnormally hydrogen combustion phenomena's as decrease of the engine power output per liter for stoichiometric dosage operating conditions. Hydrogen fuelling system used is original and offers a great flexibility in operation to establish the adjustments. The influences of the mixture quality on burning process, on emissions and energetically engine performance at the fuelling with hydrogen are presented. Is used a strategy thru combining qualitative and quantitative adjustment in order to optimize engine operation at all regimens.
Keywords: hydrogen, emissions, combustion, efficiency.

1. INTRODUCTION

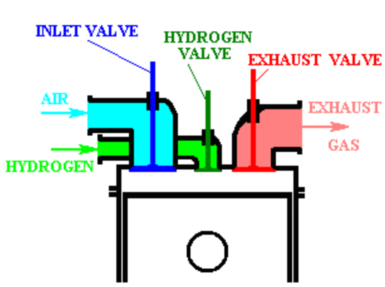
Hydrogen is identified as an clean alternative fuel for SI engines. Hydrogen can provide very low emissions levels at the engine operation [1, 2]. Hydrogen energetically cycle is much shorter comparative to fossil fuels energetically cycles. Hydrogen can be obtained from water, is no toxic and theoretically the water is obtained when is burn it. 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;
- hydrogen infrastructure implementation and the effects on the environment;
- the use with high efficiency for the replacement of the hydrocarbons into the combustion processes;

Due to its physical and chemical properties the use of the hydrogen in SI engines has been developed on two directions:
- The use of hydrogen with gasoline as an addition fuel. Having very wide flammability limits and a high combustion speed, small quantities of hydrogen allow the stability of engine operation at very lean air-fuel mixtures;
- The use of hydrogen as a single fuel. This method will be analyzed in this paper.

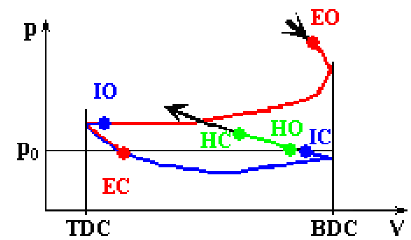
The power output of the hydrogen-fuelled internal combustion engines, depending on fuelling method, can be with until 20% greater than gasoline engines [3, 4]. The experimental researches carried out on spark ignition engines fuelled with hydrogen have highlighted certain specific aspects of the combustion 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 air to fuel ratio λ=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 (λ =1.5...2.0) these aspects disappear, but in this case the engine power per litter 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 litter decrease due to the fact that hydrogen displaces about 30% from the cylinder volume, the authors used the in-cylinder mixing formation method, the hydrogen being admitted after the intake valve is closed, figure 1. With this fuelling method was possible to avoid the uncontrolled burning process for all engines operating regimes and the decrease of the admitted air quantity.

The moment of hydrogen admission inside the cylinder influences the combustion development affecting the mixture homogeneity degree.

The combustion heat release is about 24% greater than in the case of gasoline fueled 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].



a)



b)

Fig. 1. a)-Direct injection of hydrogen inside the cylinder thru a valve in the combustion chamber
b)- Valve timing and duration of the hydrogen valve opening

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

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 limit (λ =0.14....10.12) [8, 15, 16].

This property 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.

2. EXPERIMENTAL INVESTIGATIONS

Some experimental researches were carried out on an experimental single cylinder engine derived from a serial automotive engine with four cylinders, with the compression ratio of 8.5:1, cylinder bore of 73 mm, cylinder stroke of 77 mm.

The hydrogen fueling of the engine is achieved through a valve at the beginning of the compression stroke after the intake valve close when a cooling effect for the engine cylinder's hot parts was made by previously aspirated air and to avoid the power per litter decrease, spontaneous ignition and the back fire. The pressure in the hydrogen fuelling system is relative low (~ 0.15...0.6 MPa). A special design hydrogen valve 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 fueling pressure [13, 17]. The hydrogen fuelling valve is actuated by a high flexibility hydraulic system which provides the possibility of adjusting of the valve opening duration and the valve opening timing.

The hydrogen valve is actuated by a hydraulic system, having a higher working flexibility. 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.

The engine is loaded by a Schoenebeck B4 hydraulically dynamometer. Gasoline flow rate is measured by an OPTIMAS fuel mass flowmeter. The air and hydrogen quantities flow rates are measured by two KROHNE flowmeters.

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 condition, 100 consecutive cycles of cylinder pressure data were acquired and averaged by on a PC equipped with AVL acquisition board. The exhaust emissions are measured by an AVL DiCom 4000 gas analyzer. All instrumentation was 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 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 decreases till the fuelling pressure value, adjusted in the area of 0.1…1 MPa.

For each operating regime the spark ignition timing was set at the optimal value.

3. RESULTS AND DISCUSSIONS

In figure 2 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 supply hydrogen 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, λ>1.5 the curves of pressure variation in the cylinder have a smoother variation.

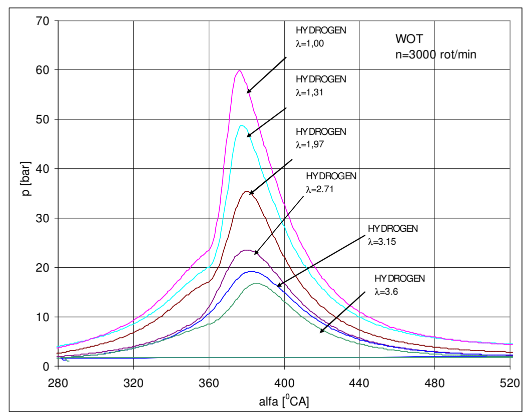


Fig. 2. Pressure diagrams at full load and 3000 rpm

Fig. 3. Maximum pressure versus to air fuel ratio at full load and 3000 rpm

In figures 3…9 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 petrol engine, figure 3.

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 increase with almost 24%.

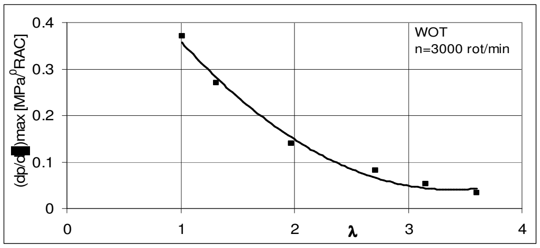


Fig. 4. Maximum pressure rate versus to air fuel ratio at full load and 3000 rpm

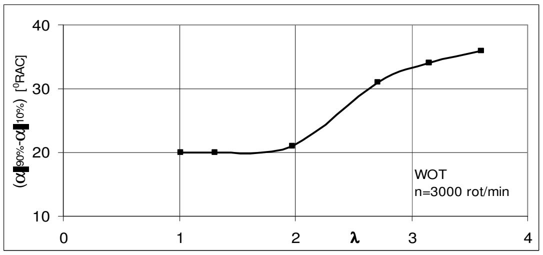


Fig. 5. Combustion time period versus to air fuel ratio at full load and 3000 rpm

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

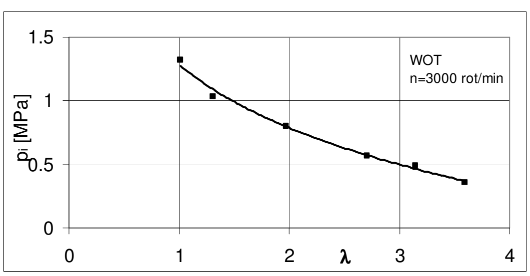


Fig. 6. Indicate mean effective pressure, IMEP, versus air to fuel ratio at full load and 3000 rpm

The increase of maximum pressure value doesn't affect the engine reliability. One reduction factor for maximum pressure 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.

For hydrogen operating engine the qualitative load adjustment was applied. At stoichiometric dosage the indicate mean effective pressure increases with ~25%, due to combustion improvement and cycle burning release heat and heat release increasing, figure 7

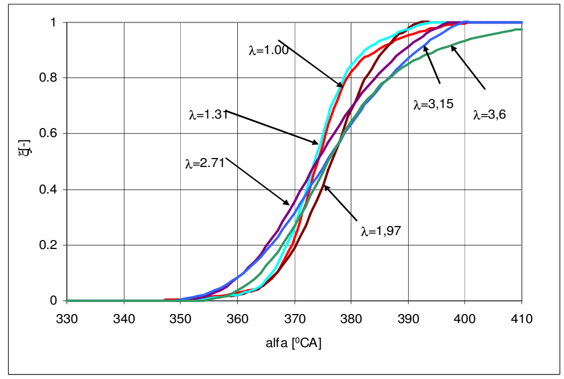


Fig. 7. Heat release versus crankshaft angle at full load and 3000 rpm

For hydrogen operating engine the qualitative load adjustment was applied. At stoichiometric dosage the indicate mean effective pressure increases with ~25%, due to combustion improvement and cycle burning release heat rate and heat release increasing, figure 7. For leader mixtures λ =1….3.6, the in mean effective pressure, IMEP, decreases from 1.42 MPa to 0. 4 MPa, figure 6, fact which is directly related with load variation between the range χ=100%...30%. At very lean mixtures use (λ >3), the combustion duration increases, figure 5, engine ISFC increases, figure 8, appears the combustion instability and unburned hydrogen in exhausts gases. To avoid these combustion aspects the applying of the quantity load adjustment of engine at small loads (χ<30%) is recommended, the air to fuel ratio being maintain in the area of 2.5....3. Thus, the hydrogen engine fuelling has a great advantage to offer the possibility of a supple load control strategy, [18, and 19].

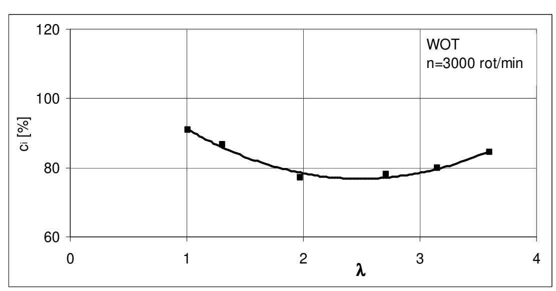


Fig. 8. Indicated specific fuel consumption versus air to fuel ratio at full load and 3000 rpm

The much higher burning rate, flammability lower limit and lower ignition energy are hydrogen qualities which provide a high efficiency engine running at partial loads when the qualitative load adjustment can be use. At stoichiometric dosage the ISFC decreases with ~10% for hydrogen comparative to gasoline because of it higher burning velocity and near constant volume combustion. Engine efficiency increases when the mixture becomes leaner till λ~2.7 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.

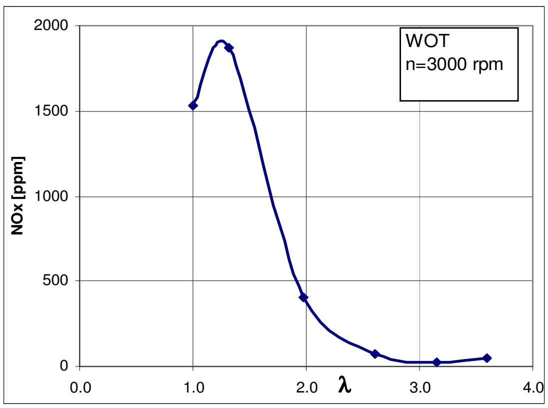


Fig. 9. Relative NO_x emissions versus air to fuel ratio at full load and 3000 rpm

Figure 9 shows the NOx emission level as a function of air to fuel 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. At much leaner dosages, λ>1.5, nitrogen oxides emission level decreases very much. 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 apply 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 aria with λ <1, 5 must be avoided in order to limit the NO_X emissions level. The engine power decreases is achieved by a throttle easy close and by the hydrogen consumption reduces for to maintain the stoichiometric dosage. In this area the quantitative adjustment is applied until is obtained the corresponding engine power on gasoline engine at the full load. At the engine hydrogen fueling, in the mixtures dosages area λ>1.5, the throttle is wide open and by the mixtures leaning is obtained corresponding engine power partial loads. Such, engine efficiency is higher than 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 fueling method.

In order to have a general view on hydrogen engine energetic performances, figure 11 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 12. This advantage appears due to better hydrogen burning properties, but as a disadvantage also 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 gasoline 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 at the load qualitative adjustment use for dosage values till λ~5.5 engine efficiency decreases insignificantly, the best results were obtained for λ=2…3. For this dosages area, λ=2…4, 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, the increasing of combustion duration, explains brake specific fuel consumption BSFC increase.

4. CONCLUSIONS

The used fueling engine method consisting in the admission of hydrogen inside the cylinder at the beginning of the compression stroke does not decrease the air cycle quantity, fact which could lead to an increase of the per liter output with ~20%. The solution has benefits especially for the engines with small and medium displacement to which the power decrease is too significant to be accepted. Hydrogen fuelled engine efficiency is better to gasoline engine, especially at partial loads operating conditions, due to a better combustion process. The mixtures dosages aria with λ <1, 5 must be avoided for to limit the NO_X emissions level. The engine power decreases is achieved by the throttle easy close and by the hydrogen consumption reduces for to maintain stoichiometric dosage. In this area the quantitative adjustment is applied until is obtained the corresponding engine power on gasoline engine at the full load. At the engine hydrogen fueling, in the mixtures dosages area $\lambda>1.5$, the throttle is wide open and by the mixtures leaning is obtained the corresponding engine power at partial loads and the engine efficiency is higher than for gasoline (the pump loses are small), but with very low NO_x emissions level. Hydrogen supply system used is original and offers great flexibility in operation to establish the engine adjustments. The hydrogen fueling method at low pressures – 0,2…0,3 MPa that allows hydrogen admitance inside the cylinder after the end of the admission process avoids the uncontrolled ignition tendencies when the SI engine uses hydrogen-air mixtures at stoichiometric global air fuel ratio. The uncontrolled ignition is avoided by cooling the hot elements existing inside the cylinder before hydrogen admission; the cooling effect is assured by the fresh air which subsequently is used in combustion.

REFERENCES

[1] Rottengruber H, Berckmüller M, Elsässer S, Brehm N, Schwarz C., *A High-efficient Combustion Concept for Direct Injection Hydrogen Internal Combustion Engine*, 15th World Hydrogen Energy Conference, Paper nr. 28j-01, Yokohama, 2004

[2] Subramanian V., Mallikarjuna J., M., Ramesh A., *Improvement of Combustion Stability and Thermal Efficiency of a Hydrogen Fuelled SI Engine at Low Loads by Throttling*, Advances in Energy Research, 2006, www.ese.iitb.ac.in/~aer2006/papers/AR_168.doc

[3] Verhelst S., Sierens R., *A Quasi-dimensional Model for the Power Cycle of a Hydrogen-Fuelled ICE*, International Journal of Hydrogen Energy 32 (2007), 3545 – 3554

[4] Bayer, G., *Hydrogen Storage for Passenger Cars*, 5th International Colloquium Fuels, Esslingen, 2005, pp.407-412

[5] Furuhama S., Yamane K., Combustion Characteristics of *Hydrogen Fueled Spark Ignition Engine*, Bul. of JSAE, nr.6, 1-10, 1974

[6] Grabner P., Wimmer A., Gerbig F., Krohmer A., *Hydrogen as a Fuel for Internal Combustion Engines*, 5th International Colloquium Fuels, Esslingen, 2005, pp. 3-13

[7] Edmondson H., Heap M., P., *The Burning Velocity of Hydrogen-Air Flames, Combustion and Flame*, 16, pp.161-165, 1971

[8] Pischinger P., *Internal Combustion Engines Hydrogen Fuelling*, MTZ, 37, 3, 71-72, 1976

[9] Negurescu N., *Researches related to the SI hydrogen fuelled engines*, PhD Thesis U.P.B., 1980

[10] Negurescu N., ,Pana C., Popa M. G., *Aspects Regarding the Combustion of Hydrogen in Spark Ignition Engine*, SAE 2006-01-0651, in Hydrogen IC Engines SP-2009, pp.51-64

[11] Heywood B., J., Vilchis F., R., Comparison of Flame *Development in a Spark Ignition Engine Fueled with Propane and hydrogen*, Comb. Sci, and Techn., vol. 38, 1984

[12] Shudo T, Nabetani S, Nakajima Y. *Analysis of the degree of constant volume and cooling loss in a spark ignition engine fuel led with hydrogen.* International J ournal Engine, Res 2001; 2:81e92.

[13] Rankin D. D. *Lean combustion technology and control*. 1st ed. London: Elsevier; 2008.

[14] Shudo T, Omori K, Hiyama O. *NOx reduction and NO2 emission characteristics in rich-lean combustion of hydrogen*, International Journal Hydrogen Energy 2008; 33:4689e93

[15] Berger,E., Bock, C.,Fisher, M., Gruber, M., Kiesgen,G., Rottengruber, H., *The New BMW12-cylinder Hydrogen Engine Clean Efficient and Powerful Vehicle Powertrain*, FISITA World Automotive Congress, 2006, YOKOHAMA, paper F2006P114

[16] Verhelst, S., Verstraeten, ST., Sierens, R., *Combustion Strategies and NOx Emissions for Hydrogen Fueled IC Engines*, FISITA World Automotive Congress, 2006, YOKOHAMA, paper F2006092

[17] Pana C., Negurescu N., Popa M. G, , Boboc G., Cernat AL., Soare D, *An Investigation of the Hydrogen Addition Effects to Gasoline Fueled Spark Ignition Engine*, Paper No. 2007-01-1468, SAE World Congress 2007, Detroit, Apr. 16-19, ISSN 0148-7191

[18] Verhelst, S., Maesschalck, P., Rombaut, N., Sierens, R., *Efficiency Comparison Between Hydrogen and Gasoline, on a bi-Fuel Hydrogen/Gasoline Engine*, International Journal of Hydrogen Energy 34 (2009) 2504 – 2510, pp. 2504-2510

[19] Sinclair L., A., Wallance J., S., *Lean Limit Emissions of Hydrogen-fuelled Engines*, International Journal of Hydrogen Energy, Volume 9, Issues 1-2, 1984, pp.123-128