IMPROVEMENT OF THE PERFORMANCE OF A SPARK IGNITION ENGINE BY USING HYDROGEN

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Hydrogen can be used as an alternative fuel for S.I. engines due to its excellent combustion properties. The paper presents experimental researches regarding the use of hydrogen in S.I. engines. The pollutant emissions, brake thermal efficiency and effective power are analyzed and compared with the gasoline fuelled engine. The tests were carried out on an experimental mono-cylinder engine with normal admission system, three valves: one air inlet valve, one hydrogen inlet valve and one exhaust valve. From the researches made, hydrogen proves to be an excellent fuel for S.I. engines.

Keywords: hydrogen, internal combustion engine, emissions, experimental research

1. Introduction

Since the late 19^{th} century when the first internal combustion engine was deployed in mobile applications, it is still an indispensable technology for today's road transportation. Over 100 years of research and technological developments have made the internal combustion engine the most reliable and affordable propulsion system. Because the air quality has decreased significantly in the last years, pollution became a major priority for engine developers due to its impact on the planet's atmosphere. There are many solutions to overcome this problem and one of them is the use of the alternative fuels [1]. Among alternative fuels, hydrogen is considered the cleanest fuel for internal combustion engines.

The variety of methods to produce hydrogen as well as the long-term viability of some of them (from fossil fuels, from nuclear power, from renewable energy: biomass, solar, wind, etc.) [2], the variety of methods to produce energy from hydrogen (internal combustion engines, fuel cells and gas turbines), potentially high efficiency and theoretically zero pollutant emissions makes the hydrogen very attractive.

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A recent study shows the fuel per hectare of land used for different biomass derived fuels and for hydrogen from photovoltaic panels or from wind turbines [3]. The results show that the energy production is higher when the land is used to capture the solar or wind energy. The use of hydrogen as an energy carrier has an advantage in terms of volumetric and gravimetric density compared to electricity. Although it offers better autonomy than batteries, its very low density compared to the classical fuels used today limits the autonomy even if the hydrogen is stored in gaseous form at high pressure (700 bar) or in liquefied form. Due to the production of hydrogen which in most cases produces greenhouse gas emissions, care must be taken in the final report between the use of hydrogen and the use of hydrocarbon fuels in terms of CO_2 emissions to ensure that hydrogen offers less pollutant emissions overall [4]. Nevertheless, hydrogen offers significant advantages to study all its possibilities for use in spark ignition engines [5]. Properties of gasoline and hydrogen relevant to their use in internal combustion engines are summarized in Table 1.

Table 1

Properties of gasoline and hydrogen

Property	*Gasoline*	*Hydrogen*
Chemical Formula	Various	H_2
Density at NTP [kg/l]	0.74	0.00008
Lower Heating Value [MJ/kg]	42.9	120
Volumetric Energy Content [MJ/l]	31.7	0,010
Stoichiometric AFR [kg/kg]	14.7	34.2
Energy per Unit mass of air [MJ/kg]	2.95	3.51
Research Octane Number (RON)	95	>130(λ=2.5)
Heat of vaporization [kJ/kg]	180-350	461
Flammability Limits in Air [λ]	0.26-1.60	0.15-10.57
Laminar flame speed at NTP, λ=1 [cm/s]	28	210
Adiabatic Flame Temperature [°C]	2002	2117

Hydrogen is a very flexible fuel when it comes to load control strategy. The very lean operation it is possible due to its wide flammability limits and the high flame speeds of hydrogen mixtures, allowing the qualitative adjustment by using a leaner mixture, reducing the NO_x emissions and increasing the thermal efficiency of the engine [6].

Considering the hydrogen on board storage problems, maximizing the efficiency is very important for hydrogen internal combustion engines. Several papers reported efficiencies and emissions of engines operated on hydrogen. Ford [7, 8 and 9] published the values obtained on a modified spark ignition engine with a compression ratio optimized to take advantage of the high auto-ignition temperature of hydrogen. Tang et all. [7] obtained the maximum brake thermal efficiency of 38% for the relative air fuel ratio of λ=3 at 2000 rpm. The maximum indicated thermal efficiency obtained was for λ=3.3 and engine speed of 5000 rpm. Natkin et alt. [8] obtained similar results with a supercharged engine to increase the power output.

Al-Baghdadi [10] found that the increased compression ratio benefited the power output and thermal efficiency of the hydrogen engine. But when the air-fuel ratio was lower than 1,25, NO_x emissions engine increased significantly. Ganesh et al. [11] claimed that thermal efficiency of the hydrogen engine was about 2% higher than that of the gasoline engine.

BMW [12, 13, 14] reported results from a single-cylinder engine supercharged to 1.8 bar that achieves a 30% increase in specific power output compared to a naturally aspirated gasoline engine. Berckmüller et al. [12] have compared the thermal efficiency for a hydrogen fuelled engine using the port fuel injection at wide open throttle, throttled stoichiometric and supercharged stoichiometric strategies. The indicated thermal efficiency reached 40% at low loads and 32% at high loads. A 2% increase was obtained by using stoichiometric EGR strategy as an alternative to the throttled stoichiometric approach.

The predominant mixture formation strategy at the hydrogen use is the port fuel injection (PFI), but the engine effective power is reduced about 30 % [15, 16, 17]. In order to increase the power output and to avoid combustion anomalies, cryogenic injection and hydrogen direct injection (DI) have been successfully used in spark ignition engines [18].

The thermal efficiency of hydrogen direct injection operation was measured on a single cylinder Ford research engine, achieving the maximum break thermal efficiency of 45 % at an engine speed of 3000 rpm [9]. Even at partial loads hydrogen direct injection can be used for optimizing engine efficiency. A study shows that the combustion duration at low engine loads can be reduced at smaller hydrogen injection timing, and the thermal efficiency increased from 34 % to 39 % [19].

In the laboratories of the internal combustion engines department from Politehnica University of Bucharest was made an experimental single cylinder engine derived from the Dacia engine 810-99. The engine was fueled with hydrogen by direct injection at the beginning of the compression stroke, after the intake valve closes through an original fueling system which allows modification of the start of fuel injection timing, injection duration and pressure of hydrogen fueling. The paper presents results of the experimental investigations of the hydrogen spark ignition engine fueled. The advantages of using hydrogen are highlighted and the qualitative engine load control strategy is presented.

2. The test bed

The experimental engine was mounted on the test bed adequate instrumented for the experimental investigations carried, its schema being presented in fig. 1.

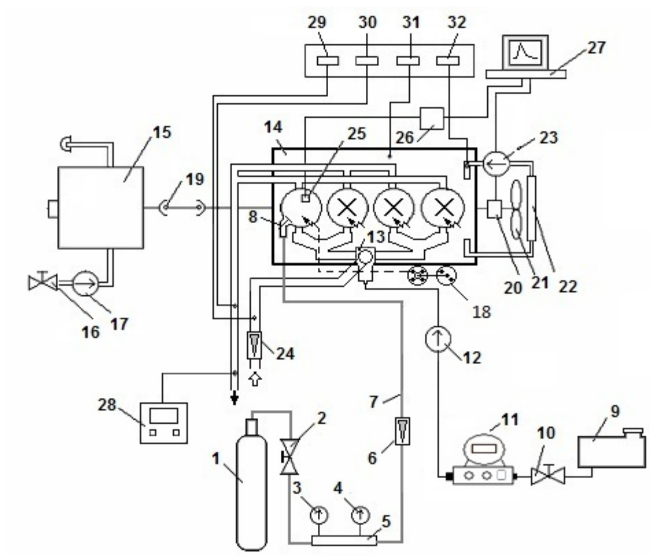

Fig. 1. Test bed schematic

The test bed: 1 - hydrogen tank, 2 - hydrogen consumption tap, 3, 4 - fuelling manometers, 5 - pressure reducer, 6 - hydrogen flow meter, 7 - fuelling pipe, 8 - hydrogen intake valve, 9 - tank, 10 - gasoline consumption tap, 11 - gravimetric fuel flow meter, 12 - gasoline fuel pump, 13 - carburetor, 14 – spark ignition engine, 15 - Schönebeck B4 hydraulic dynamometer, 16 - water network tap, 17 - hydraulic dynamometer water pump, 19 - coupling, 20 - crank angle encoder, 21 - cooling fan, 22 - cooler, 23 - engine water pump, 24 - air flow meter, 25 - piezoelectric Kistler pressure transducer, 26 - Kistler charge amplifier, 27 - PC equipped with AVL acquisition board, 28 - AVL DiCom Analyzer 4000, 29 - inlet air temperature measurement indicator, 30 - exhaust gas temperature measurement indicator, 31 - engine oil temperature measurement indicator, 32 - cooling liquid temperature measurement indicator.

The experimental investigations were carried at full load, at different engine speeds and at different values for the relative air-fuel ratio. Spark ignition timing was adjusted for each operating regime at optimum value. In case of hydrogen fueling the optimum spark ignition timing is smaller comparative to gasoline S.I. engine due to a much higher burning rate of the hydrogen. In this paper are presented experimental investigations results at the full load and 2500 rpm (±50 rpm) engine speed.

First time, were conducted experimental investigations on the gasoline S.I. engine fueled to obtain reference dates and then the engine was fueled only with hydrogen. Hydrogen fuel consumption was measured with a flow meter calibrated at 10 bar pressure.

3. Experimental research results

Effective Power:

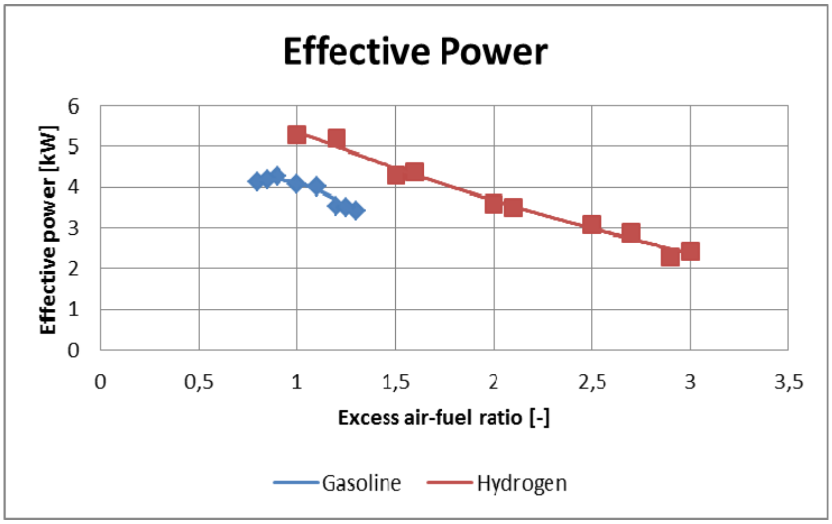

Fig. 2. Effective power vs. Relative air-fuel ratio

The influence of the relative air-fuel ratio has a major impact on the effective power using both fuels. Due to the wide flammability limits of hydrogen, it can be used with good results at lean and very lean air-fuel ratio. Thus while gasoline engine operation is limited at λ approximately 1.25-1.3, hydrogen-powered engine operation is stable up to λ=3 when the power decreased with about 15 %. Using the hydrogen direct injection in the engine cylinder avoids the abnormal burn phenomena [20] and the reduction of the engine power, disadvantages of the hydrogen port-fuel injection. At the use of hydrogen the engine power increased with ~20% for stoichiometric air-fuel ratio comparative to gasoline engine and with ~25% at leaner mixtures (fig. 2) due to combustion improvement and cycle burning release heat and heat release rate increasing.

Energetic Brake Specific Fuel Consumption:

The energetic brake specific fuel consumption has lower values by hydrogen fueling due to better mixture quality and better combustion properties of hydrogen (higher burning velocity than gasoline). The minimum value of the energetic brake specific fuel consumption was obtained at very lean mixtures, λ~2.5 (fig. 3a) due to hydrogen suitable burning properties and due to the reduction of heat loses. For λ>2.5, the energetic brake specific fuel consumption increases due to the combustion duration increase (fig 3b). At λ=3 the EBSFC for hydrogen is lower than the EBSFC at λ-1.2 for gasoline because the heat release duration is smaller due to the higher burning rate of hydrogen. Also, there are other factors that lead to the smaller EBSFC like the lower heat exchange due to the lower combustion temperature for hydrogen at the same dosage.

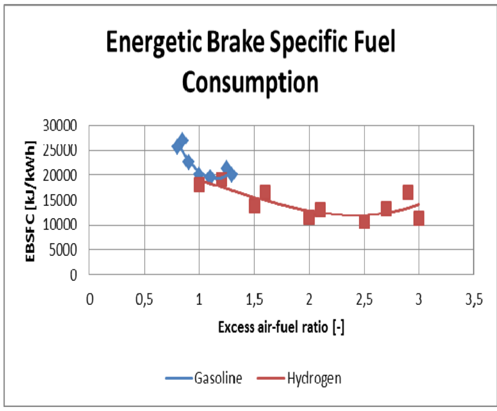

Fig. 3a. EBSFC vs. Relative air-fuel ratio

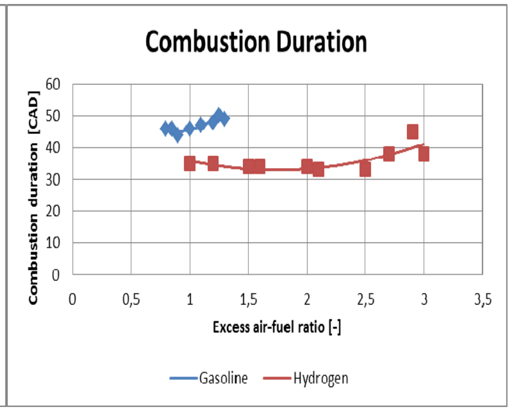

Fig. 3b. Combustion duration vs. Relative air-fuel ratio

Exhaust gases temperature:

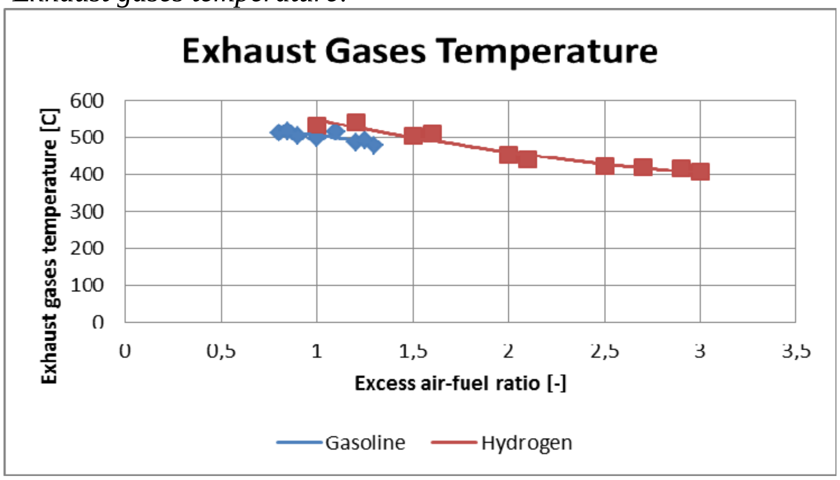

Fig. 4. Exhaust gases temperature vs. Relative air-fuel ratio

Exhaust gases temperature are higher by hydrogen fueling (fig. 4) due to its combustion properties and as the mixture is leaner the temperatures are reduced. The lower combustion temperatures have a direct impact on the NO_x emissions.

NO_x Emissions:

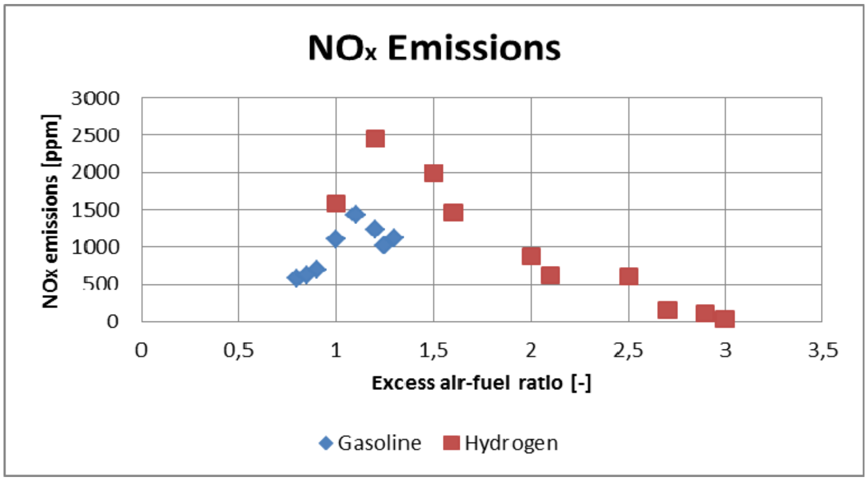

Fig. 5. NO_x emissions vs. Relative air-fuel ratio

NO_x emissions are much higher by hydrogen fueling comparative to gasoline (fig. 5) due to the burning temperature increase at stoichiometric relative air-fuel ratio and until λ=1.8. For leaner mixtures with λ>1.8 the burning temperature decreases and the NO_x levels drops. The air-fuel ratio area between 1 and 1.8 must be avoided for the engine to run with very low NO_x emission level. By using a conventional three way catalyst the NO_x emissions can be reduced at λ between 1 and 1.8 [21].

Engine load qualitative adjustment:

The maximum NO_x emissions value when the engine is running on gasoline is obtained at λ=1.1 and the effective power is 3.7 kW. by hydrogen fueling, at the same air-fuel ratio, the engine power is 5 kW, but the NO_x emissions level is greater. For the hydrogen fuelled engine can be used the qualitative adjustment of the load for operation with lower NO_x emissions level. Thus, keeping the gasoline engine power (3.7 kW), at the use of leaner mixtures on hydrogen engine operation (λ~2), the NO_x emissions level is lower. By increasing the relative air-fuel ratio the NO_x emissions reduces significantly.

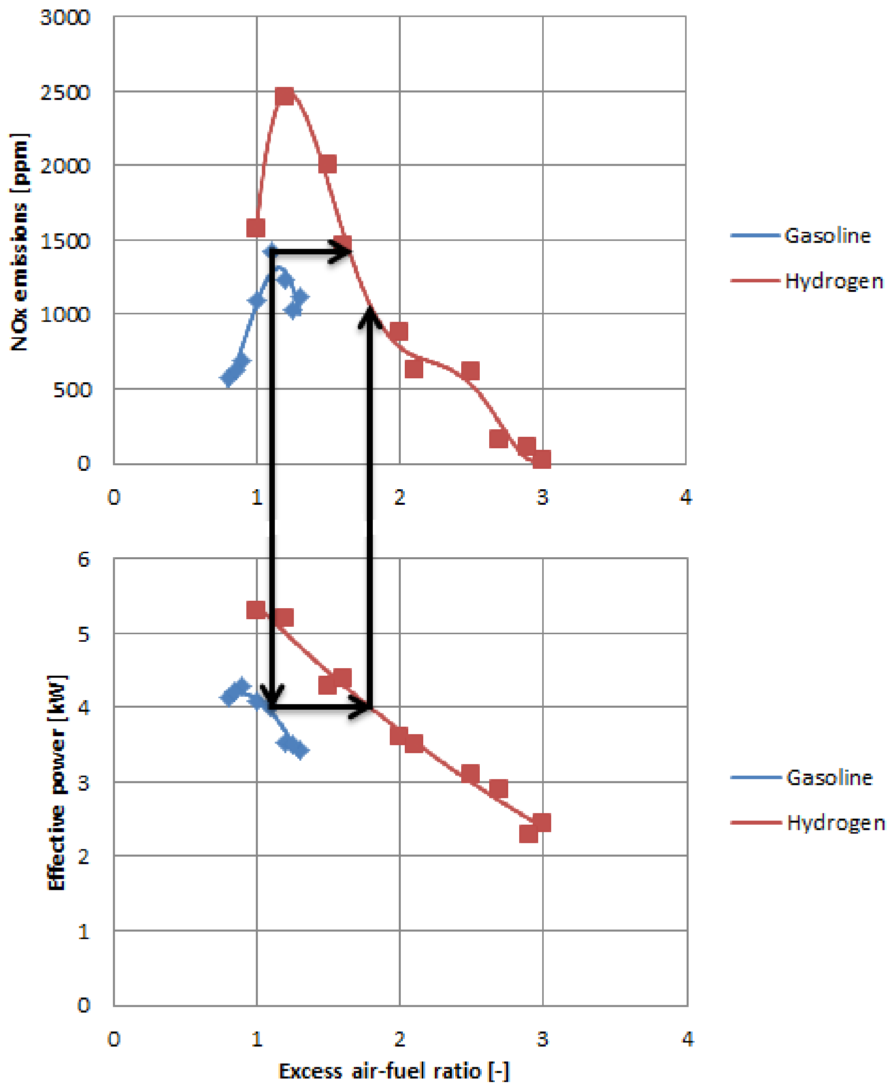

Fig. 6. Qualitative control strategy

4. Conclusions

The effective power by hydrogen fueling is greater with almost 30 % comparative to gasoline at stoichiometric air-fuel ratio. The same effective power of gasoline engine can be obtained at leaner air-fuel ratio at use of hydrogen.

The energetic brake specific fuel consumption is smaller comparative to gasoline due to the improvement of the combustion process.

The NO_x emissions are greater at the use of hydrogen in the mixtures air-fuel ratio area with $\lambda<1.8$ due to the higher combustion temperature but as the mixture is leaner the NO_x emissions levels decrease significantly.

The NO_x emission level decreases by increasing the relative air-fuel ratio (qualitative control), obtaining approximately the same power output to gasoline engine operation.

Hydrocarbons and carbon oxides emissions are every low and appear only from the oil burning inside the combustion chamber.

Acknowledgement

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