EXPERIMENTAL ASPECTS OF HYDROGEN USE AT DIESEL ENGINE BY DIESEL GAS METHOD

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Abstract

Due to good combustion properties of hydrogen comparative to diesel fuel, it can be used at the automotive diesel engine for improvement of the energy performance and for reduction of the pollutants emissions level. The use of small hydrogen quantities which can be produced on the vehicle board represents another advantage. The paper presents some comparative results of the experimental investigations carried on a truck diesel engine of 10.34 L displacement fuelled with diesel fuel and hydrogen at engine middle loads. The hydrogen was injected in the engine intake manifold at different volume flow rates from 9 $L\cdot min^{-1}$ to 40 $L\cdot min^{-1}$. The general objective of the research is the analysis of the effects of the hydrogen use at the diesel engines on the energy performance and on the pollutant emissions. The engine energy performance, pollutant emissions level and combustion parameters at the hydrogen diesel engine fuelled were analyzed and compared with diesel fuel operation. The researches established the favourable influences of the hydrogen use on the diesel engine operating. The obtained results of the experimental investigations highlight the improving of engine performance at fuelling with hydrogen as addition in air.

Key words: *hydrogen, diesel engine, combustion, maximum pressure, heat release rate, soot emission, nitrogen oxides emission*

1. Introduction

Nowadays, all over the world, a special attention is given to the reduction of the fossil fuel pollutant emissions, in all main areas of technical activities [1], [2]. In the automotive area, the main pollutants appear because of the fuels combustion imperfection in internal combustion engines and the reduction of the exhaust emissions represents an important objective for the researchers in the field [3], [4], [5], [6]. Regarding the impact of pollutant emissions on environmental [1], [2], [3], specials measures are taken in order to reduce as much as possible the pollution produced by diesel engines, especially in the urban areas [3], [4], [5], [6], [7], [8]. Petrovic, [3] explains the negative effect on environment and human health of the pollutant emissions emitted by automotives equipped with diesel engines that transit the urban areas. These issues are under the directives of the European Community and Kyoto Protocol [1], [2], which include new strategy for pollution reduction, and were recently discussed at the C40 Events-C40 Mayors Summit 2016 (in December 2016) and at the 21st Session of the Conference of the Parties (COP21) from the 2015 Paris Climate Conference. After COP21 meeting this pollution issue becomes a priority for some cities capitals (Paris, Madrid, Athens and Mexico City) which want to forbidden the access of diesel engines automotives in metropolises starting with 2020. Moreover, the access will be forbidden in whole France since year of 2025. Also, the gradual

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diminution of the worldwide oil reserves contributes to the necessity of searching of alternative energy from durable and renewable resources, [1], [2]. The most important pollutants emissions of diesel engine are nitrogen oxides (NO_x) and smoke, the carbon dioxide CO_2 being considerate a greenhouse effect gas [3], [4], [5], [6], [7], [8]. In order to limit the pollutants emissions level at diesel engines, especially NO_x and soot, the pollution legislations become more severe, this fact leading to the applying of new active methods for fuels combustion control [3], [4], [5], [6], [7], [8]. Environmental protection requires the limitation of the fossil fuels consumption through the use of alternative fuels also for internal combustion engine [3], [4], [5], [6], [7], [8]. Petrović [3] presents the effect of particles matter (PM) emission from the exhaust of modern diesel engines, showing that the percent of vehicles which emit fine particles (smaller than 0.1 μm) is slightly higher in urban areas with intensive traffic and high frequency of heavy duty and passenger automotives with diesel engines. Petrović [3] shows that these particles might have harmful effects on environment, on humans, being made it from toxic organic and organic materials. Petrović [3] explains the negative impact on human heath like eye irritation and decrease in lung function. Particles are kept in the nose and in the lungs, but particles smaller than 2.5 μm are found deep in the lung, and even in the liver and the brain, affirms Petrović [3]. Many of these pollution issues can be partial eliminated by alternative fuel use at diesel engines, in single or dual fuelling modes [4], [5], [6], [7]. Xiaolu [4] uses dimethyl ether (DME) to fuel a light-duty direct injection diesel engine. Xiaolu [4] uses a separate fuel system to inject the DME into the fuel line of the original engine, in different mass percentages from 13.04% to 7.82%. As results Xiaolu obtains: the smoke emission decreases with 30% comparative to diesel fuelling at medium and high engine [4]. The NOx and HC emissions of the DME-diesel blends are slight lower comparative to diesel fuelling, at all loads. At low engine loads the smoke emissions is almost the same, but at medium and high engine loads the smoke emission decreases with 30% for DME-diesel blends use [4]. Xiaolu [4] studies the effect of DME on autoignition temperature and on engine power outputs. Xiao [5] uses dimethylfuran (DMF) to fuel a modified 4-cylinder medium-duty commercial diesel engine diesel engine and investigates the combustion and emissions characteristic of DMF versus diesel fuel. Xiao [5] tests five types of DMF-diesel blends showing the influence on maximum in-cylinder pressure, autoignition delay and combustion duration. The brake specific fuel consumption (BSFC) increases with the increase of DMF percent in blends with diesel fuel, but the HC emission decreases and the CO increases comparative to classic diesel engine at low loads [5]. The HC and CO emissions levels are very low, but the NOx emissions increases for higher DMF percents, at medium and high loads [5]. Soot emission is significantly reduced comparative to diesel fuel, but Xiao explains the negative effect on engine performance in terms of BSFC and brake thermal efficiency (BTE) [5]. Vellaiyan [6] uses water-diesel emulsions to develop an “eco-friendly diesel fuel” that can be use at diesel engines to reduce the pollution, to protect the environmental and human health. Vellaiyan [6] carries out the experimental investigations on a single cylinder, 4-stroke diesel engine with variable compression ratio. Vellaiyan [6] shows that the increase of water content in blends (WC) with diesel fuel leads to improved engine performance and low NO emissions level. But more than 20% of WC leads to the increase of autoignition delay, combustion duration, HC and CO emissions [6], the in-cylinder pressure rise rate and heat release rate being also affected. Generally, the combustion, engine performance and emission levels were improved for the optimal condition (100% engine load and 18% WC) [6]. The alternative fuels use at internal combustion engines, especially hydrogen, is considerate an efficient strategy for pollutant emissions control [3], [4], [7], [8], [9], [10]. Hydrogen is a privileged alternative fuel for the internal combustion engines due to its properties, presented in tab. 1, which makes it the cleanest fuel and due to its unlimited producing resources [7], [8], [9], [10], [11], [12], [13]. The very high value of hydrogen specific volume represents a disadvantage because it occupies an important volume inside the engine cylinder and so the air quantity admitted inside the engine is reduced. This issue appears when the air-fuel mixture is made outside the cylinder. From this point of view the engine power decreases, the reduction of the inlet air quantity being more significant at the increase of the hydrogen percent in the mixture, at the increase of hydrogen amount in the inlet air admitted inside the engine (at stoichiometric dosage hydrogen occupies almost 30% of mixture volume). Because of its lower density the storing of hydrogen on automotive board in large quantities is difficult, a high pressure system for gas state storing being necessary. Liquid state storing of hydrogen, which will allow storing up high quantities of hydrogen, is difficult because of the very low liquefying temperature of hydrogen and of the technical issues that must be resolved for liquid hydrogen reservoirs, fuelling system etc.

Table 1. Properties of hydrogen and diesel fuel, [14], [18]

Property		**Diesel**	**Hydrogen**
Formula		$C_{14.5}H_{30}$	H_2
Molecular weight [kg·kmol^{-1}]		204	2.016
Density [kg·m^{-3}] at 0 [°C] and 760 [mmHg]		825-870	0.0899
Lower Heating Value [MJ·kg^{-1}]		42.5	119.6
Autoignition temperature [K]		473...493	858
Octane Number Research [-]		30	130
Cetane Number [-]		45-55	-
Flame velocity in air [m·s^{-1}] (λ=1), 20 [˚C], 760 [mmHg]		0.3	2.37
Flammability limits	**$\lambda_i \ldots \lambda_s$**	0.34-1.68	0.136…10.12
	[volume % in air]	0.7-5	4.1-75.6
Theoretical air-fuel ratio, (kg air/kg fuel) [-]		14.76	34.32
Minimum ignition energy in air [mJ]		-	0.018
Quenching gap in NTP air [cm]		-	0.064
Diffusivity in air [cm^2·s^{-1}]		-	0.63
Boiling point [K]		436-672	20.27
Flame temperature in air [K]		2327	2300

For these considerations the use of onboard vehicles hydrogen producing sources is advantageous and represents a viable method when the hydrogen consumption is reduced. The higher hydrogen diffusion speed, defined by the value of the coefficient of diffusion in air which is few times higher comparative to others hydrocarbons, favours the rapid forming of mixture with air, the homogeneous air-hydrogen mixture being aspirated inside the cylinder. Comparative to other fuels based on hydrocarbons, the hydrogen combustion properties (such as wide flammability limits, higher burning velocity and lower ignition energy) represent advantages which assure the improvement of the combustion process and the increase of the engine efficiency. Thus, the very large domain of flammability of hydrogen represents an advantage for its use at internal combustion engines which can operate with lean and very lean mixtures with high efficiency. Hydrogen has the combustion velocity higher with one order of magnitude versus other hydrocarbon fuels and its presence in the air-fuel mixture leads to the increase of hydrocarbons combustion velocity. Another important aspect of hydrogen use at the internal combustion engines fuelling is the easiness of air-hydrogen mixture ignition at contact with hot surfaces or hot gases, the hydrogen minimum ignition energy being 10 times lower comparative to other hydrocarbons fuels. Because of this motive the uncontrolled ignition of air-hydrogen mixture with the return of the flame in the inlet pipe or the in-cylinder ignition and uncontrolled combustion may appear. These phenomena have a reduced probability to appear at the use of lean and very lean air-hydrogen mixtures. Hydrogen is not toxic and doesn't pollute. Due to the absence of carbon and sulphur during the hydrogen combustion a serial of pollutant substances like HC, CO, SO_2, particulate matter (PM), ozone and other carcinogenic compounds are not produced [3], [4], [5], [6], [7], [8]. But because of higher temperatures of the gases at hydrogen combustion, the NO_x emissions level can be greater for air-fuel mixture dosages closer to stoichiometric value comparative to standard engine. This disadvantage can be eliminated through use of lean dosage mixtures [14]. Hydrogen has high resistance to autoignition which prevents its use as single fuel at diesel engine, an ignition source being required [7], [8], [19], [20], [21], [22]. One of the methods of hydrogen use in dual fuelling system recommended for diesel engines is the diesel-gas method. The advantages of diesel-gas method use are: can be easy implemented on the diesel engine; the air-hydrogen mixture has a higher homogeneity being assured all conditions for an economic engine operation. The hydrogen is injected into the intake manifold and the higher homogeneity hydrogen-air mixture is ignited by the flame initiated by autoignition of diesel fuel pilot injected into the engine cylinder. Due to its proprieties it seems very possible to reach homogenous air-fuel mixtures during the pre-formed phase of the air-fuel mixture combustion. So, is possible to decrease the soot emission level by using hydrogen in diesel engine at the same energy level achieved at the engine operation only with diesel fuel. The hydrogen can be easy used in diesel engines, as addition in air, in low substitute energetic percents of the diesel fuel without major design modifications of engine. Its properties made hydrogen to have important effects on in-cylinder combustion with considerable improvements of energy and pollutant performance [3], [7], [8]. The main effects of hydrogen on in-cylinder combustion and on the pollutant emissions are:

Hydrogen effects on in-cylinder pressure. The maximum pressure and maximum pressure rise rate depend on the rate of heat release [22]. The hydrogen affects the heat release rate and the maximum pressure increase when the amount of hydrogen which replaces the diesel fuel increases, due to its better combustion proprieties and due to the higher homogenization of air-fuel mixture [19]. Also, due to better combustion properties of the hydrogen the maximum pressure rise rate increases, but through the decrease of diesel fuel injection timing the maximum pressure and the maximum pressure rise rate can be limited [23].

Hydrogen effects on brake thermal efficiency. Many papers from the specialty literature show that the brake thermal efficiency increases at the hydrogen use in diesel engines due to hydrogen's higher calorific heat and its better burning properties comparative to diesel operate at all engine loads [7], [8], [10], [11], [23]. The greater combustion velocity of the hydrogen comparative to diesel fuel assures the decrease of combustion duration and the increase of engine thermal efficiency, especially at partial engine loads [7], [8], [24], [25].

Hydrogen effects on the brake specific fuel consumption. For brake specific fuel consumption (BSFC) the researchers highlight its decrease at the increase of the hydrogen amount which replaces the diesel fuel due to the increase in brake thermal efficiency (BTE) [23], [24], [25], [26].

Hydrogen effects on pollutant emissions. Pollutant emissions are dependent on engine operating conditions (engine load, engine speed etc), fuel composition, air/fuel equivalence ratio, oxygen content. At use of the hydrogen as addition in inlet air, smoke emission level decreases due to improvement of the combustion and due to lower carbon content in air-fuel mixture [3], [7], [8], [15]. The NO_x emissions level increases with hydrogen addition percent at high engine loads only when the gas temperature is above NO_x formation temperature [3], [7], [8], [24], [27]. Some authors show that the NO_x emissions level decreases at the engine operation with small hydrogen quantities in addition in inlet air (for engine operating regimes of partial loads) [7], [8], [15], [27].

Premkartikkumar [7] uses oxygen enriched hydrogen-HHO gas in addition to fuel a direct injection diesel engine. The gas is aspirated into the cylinder along with intake air, different flow rates between 1-3.3 $L \cdot min^{-1}$ being used. At hydrogen-HHO gas use Premkartikkumar [7] shows the increase of the brake thermal efficiency of the engine with 11.06%, the decrease of carbon monoxide with 15.38% and the reduction of unburned hydrocarbon with 18.18%. At 100% engine load, the emission levels of carbon dioxide and NO were increased with 6.06% and 11.19%, respectively (for 3.3 $L \cdot min^{-1}$ flow rate). At partial loads and 1 $L \cdot min^{-1}$ flow rate the NO emission level decreases with 15.48% [7].

The main objective of the paper is the analysis of the hydrogen use effects on the energy performance and on the pollutant emissions of the diesel engine. The engine energy performance, pollutant emissions level and combustion parameters at the hydrogen fuelled diesel engine were analyzed and compared with diesel fuel operation. To implement a relative simple fuelling method which can be easily applied to new generation of diesel engines and on the old design diesel engines that are still in exploitation in order to improve their pollution performance in order to maintain them in service is also another objective. The novelty of the paper work is assured by the following aspects: hydrogen use at diesel engines in order to reduce the pollutant emissions and the establish of the optimum correlation between engine load-hydrogen cycle quantity, injection timing and exhaust gas temperature in order to control the combustion process and to obtain the best ecological and energy performance of the engine for hydrogen- diesel fuel fuelling.

2. Experimental research of hydrogen use at diesel engine

The experimental research has been carried on the D2156 MTN8 diesel engine at the operating regimes of 40% and 70% engine loads, engine speed of 1400 ±1% min^{-1} and normal thermal regimen (80 °C temperature of cooling agent). The engine power was maintained constant for every load (53 kW (±1%) and 83.5 kW (±1%), respectively). The engine was mounted on a test bench equipped with an eddy-current dynamometer and adequate instrumented with: thermometers, thermocouples, thermoresistances and manometers which assure the monitoring of the engine functional parameters, data acquisition system, air flow meter, hydrogen flow meter, diesel fuel consumption device and exhaust gas analyzer. The scheme of the experimental test bench is shown in the fig. 1.

The in-cylinder pressure was measured with a piezoelectric pressure transducer, Kistler 6056A mounted in the cylinder head. The crankshaft angle was measured by a crank angle encoder mounted on the crankshaft. The pressure signal and angle signal were sent to data acquisition system, Indicom AVL. The pollutant emissions were measured by AVL DiCom 4000 gas analyzer. The gas analyzer was prior calibrated. The diesel fuel consumption was measured with a gravimetric balance and hydrogen consumption was measured by a digital hydrogen flowmeter, in the range of 0–40 $L \cdot min^{-1}$, and the air consumption by Meriam air flowmeter. Firstly, the engine was fuelled only with fuel diesel to set up the reference regime. Secondly, the engine was fuelled with diesel fuel and hydrogen, the hydrogen was aspirated into the cylinder along with inlet air at flow rates between 9.12 $L \cdot min^{-1}$ and 39.6 $L \cdot min^{-1}$. The quantity of the hydrogen in inlet air that substitutes the diesel fuel is established by an energetic substitute ratio value which takes into consideration the energetically value of the both fuels, x_c [%]:

$$x_c = \frac{Ch_H \cdot Hi_H}{Ch_{DF} \cdot Hi_{DF} + Ch_H \cdot Hi_H} \cdot 100 \quad (1)$$

where: HiDF, HiH represents the lower heating value of diesel fuel and hydrogen in kJ·kg-1 and ChDF, ChH are diesel fuel and hydrogen consumptions in kg·h-1. For only diesel fuelling the xc value is zero and at diesel fuel and hydrogen fuelling the hydrogen flow rates of 9.12 - 39.6 L·min-1 corresponds to percent of substitute energetic ratios of diesel fuel by hydrogen of 1.14%, 2.62%, 3.73% and 4.81% for the 40% engine load, respectively 0.80%, 1.62%, 2.42% and 3.2% for the 70% engine load.

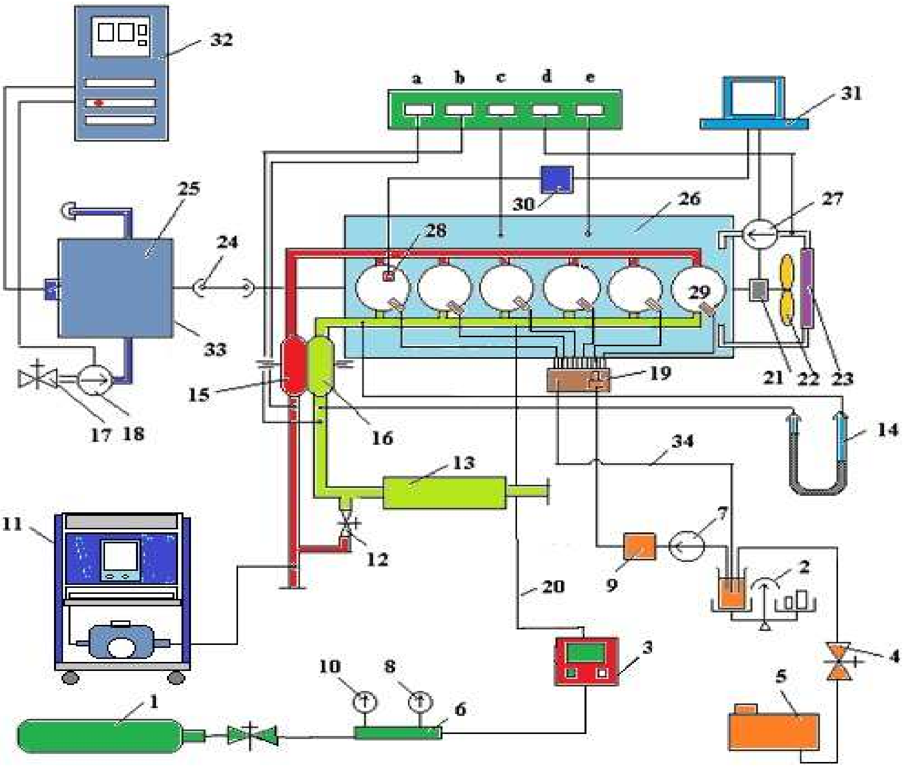

Figure 1. The scheme of the experimental test bench

The test bench schema has the following components: 1. hydrogen bottle 2. weight balance; 3. Alicat Scientific hydrogen flowmeter; 4. diesel fuel valve; 5. diesel fuel tank; 6. hydrogen pressure regulator; 7. diesel fuel supplying pump; 8. low pressure manometer; 9. diesel fuel filter; 10. high pressure manometer; 11. AVL DiCom 4000 gas analyzer; 12. exhaust gas recirculation valve; 13. Meriam air flowmeter; 14. differential manometer for turbocharging pressure measurement; 15-16. turbo-compressor group; 17. dynamometer water cooling valve; 18. water circulation pump for dynamometer cooling; 19. diesel fuel injection pump; 20. hydrogen pipe; 21. incremental speed transducer; 22. ventilator 23. cooling liquid radiator; 24. couple; 25. Hoffman eddy-current dynamometer; 26. D2156 MTN8 diesel engine; 27. water pump of engine cooling system; 28. Kistler piezoelectric pressure transducer; 29. diesel injector; 30. Kistler charge amplifier; 31. PC with AVL acquisition board; 32. dynamometer controller; 33. dynamometer power cell; 34. diesel fuel pipe; a) inlet air temperature indicator; b) exhaust gas temperature indicator; c) oil temperature indicator; d) oil pressure indicator; e) water cooling temperature indicator.

3. Results

Because the values of diesel fuel substitute ratios with hydrogen are small, the maximum pressure slightly increases, 2.8% for 40% engine load, respectively 3.8% for 70% engine load, fig. 2, due to slightly increase of the amount of fuel which burns in the premixed combustion phase and due to autoignition delay decrease comparative to diesel fuel engine.

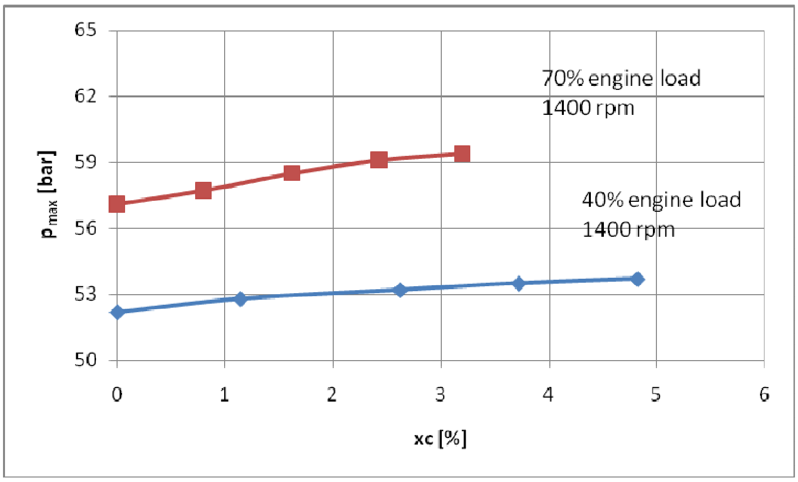

Figure 2. Maximum pressure vs. different substitute ratios x_c, at the engine regime of 40% and 70% load and 1400 min^{-1} speed

The same explication is suitable for the maximum pressure rise rate variation, fig. 3. Figure 4 shows the variation of brake specific energetic consumption (BSEC) with substitute ratios x_C. The BSEC decreases at the increase of hydrogen addition in inlet air. At diesel fuelling, x_C=0, the BSEC for 40% and 70% load is 11645 $kJ \cdot kW^{-1} \cdot h^{-1}$, respectively 11207 $kJ \cdot kW^{-1} \cdot h^{-1}$. The lowest BSEC value of 10943 $kJ \cdot kW^{-1} \cdot h^{-1}$ (hydrogen rate of 20.82 $L \cdot min^{-1}$, 40% engine load) and 10435 $kJ \cdot kW^{-1} \cdot h^{-1}$ (hydrogen rate of 29.8 $L \cdot min^{-1}$, 70% engine load) are registered at hydrogen fuelling due to better homogeneous fuel-air mixture and combustion improvement.

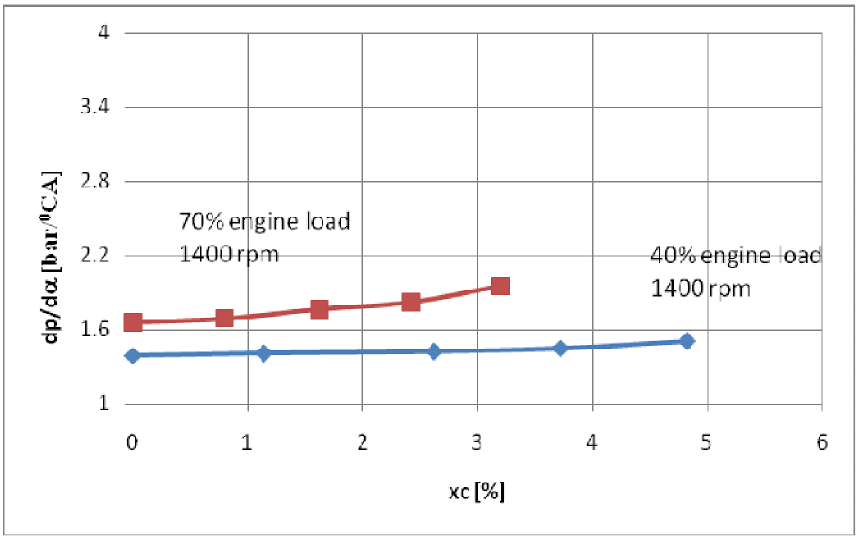

Figure 3. Maximum pressure rise rate vs. different substitute ratios x_c, at the engine regime of 40% and 70% load and 1400 min^{-1} speed

At higher hydrogen flow rate the BSEC increases because the oxygen concentration in the intake charge decreases and autoignition delay increases [15]. The BSEC was decreased by 6% (diesel fuel economy is 1.44 $kg \cdot h^{-1}$ for the same engine power of 53 kW) at 40% engine load and by 6.9% (diesel fuel economy is 1.92 $kg \cdot h^{-1}$ for same engine power of 83.5 kW) at 70% engine load, fig.4. In fig. 5 it is presented the variation of brake thermal efficiency, BTE, versus substitute ratios x_c. The hydrogen flow rate of 20.82 $L \cdot min^{-1}$ at 40% engine load, respectively of 29.8 $L \cdot min^{-1}$ at 70% engine load assures the highest brake thermal efficiency (32.9% and 34.5%, respectively) comparative to diesel fuelling (30.9% and 32.1%, respectively). The brake thermal efficiency increases with the rise of x_c substitute ratio due to better homogeneous fuel-air mixture and due to the combustion improvement at hydrogen use.

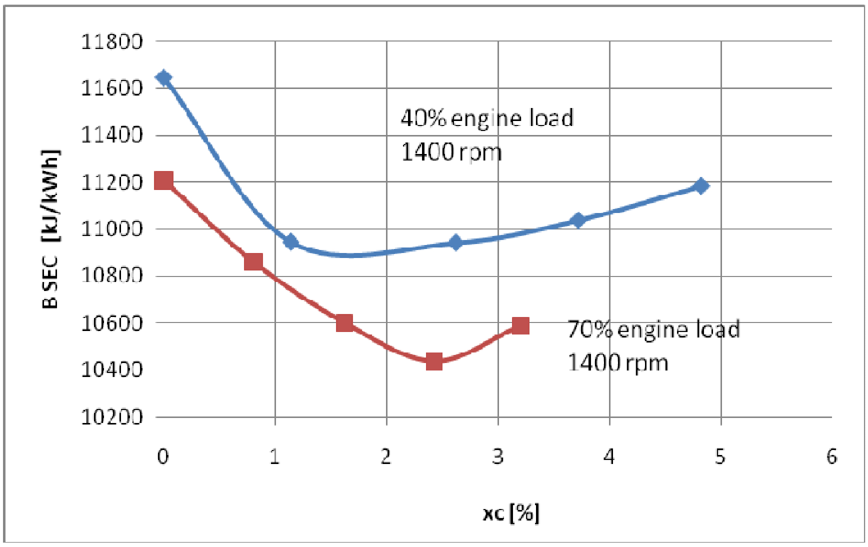

Figure 4. Break Specific Energetic Consumption vs. different substitute ratios x_c at the engine regime of 40% and 70% load and 1400 min^{-1} speed

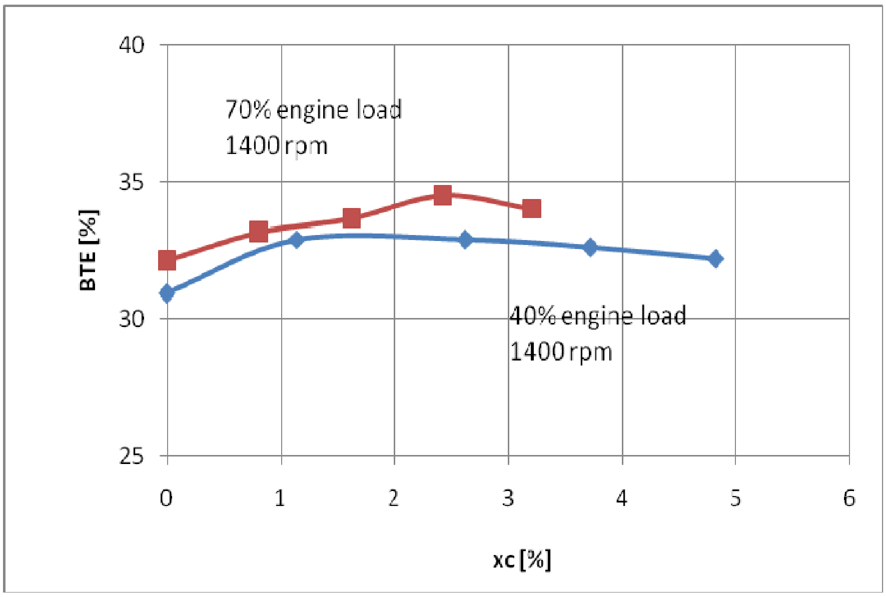

Figure 5. Brake thermal efficiency vs. different substitute ratios x_c at the engine regime of 40% and 70% load and 1400 min^{-1} speed

In fig. 6 are presented the heat release rate characteristics for diesel fuelling and for hydrogen fuelling at the substitute ratio x_c of 2.62% for 40 % engine load, evaluated in [J·°CA^{-1}]. At hydrogen use, the heat release rate increases with the rise of the diesel fuel substitute ratio due to a better combustion. Due to the greater combustion velocity of hydrogen comparative to diesel fuel and of the premixed combustion faze effect increases the maximum rate heat release is with 8% higher at the engine running with hydrogen in addition in air comparative to the classic diesel engine.

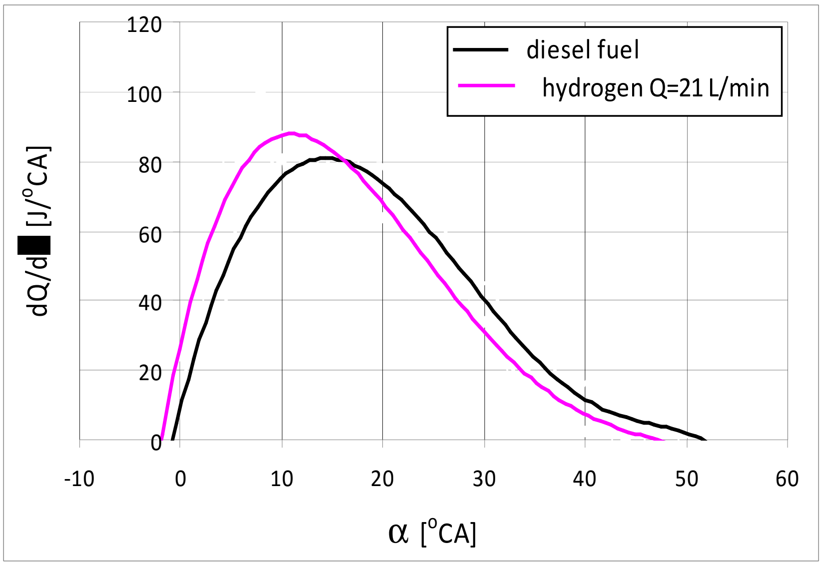

Figure 6. Rate of heat release characteristics at the engine regime of 40% load and 1400 min^{-1} speed

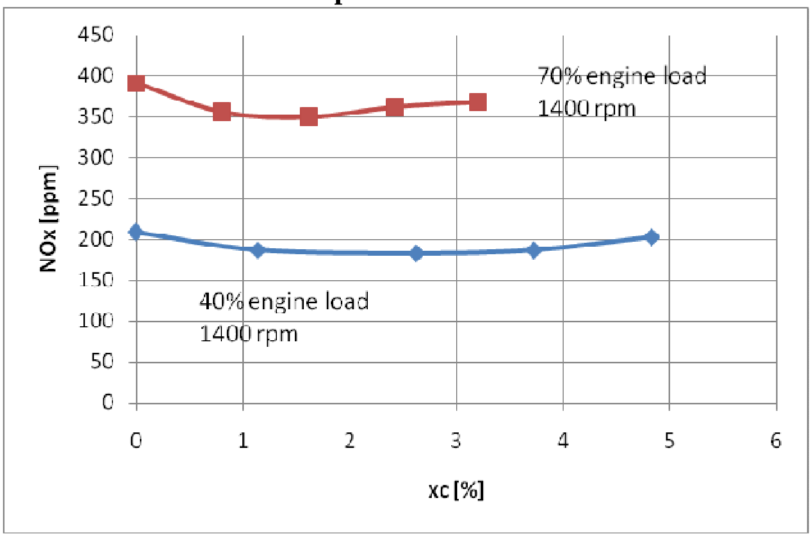

Figure 7. NO_x emissions level vs. different substitute ratios x_c, at the engine regime of 40% and 70% load and 1400 min^{-1} speed

Figure 7 shows the variation of NOx emissions level with diesel fuel substitute ratios with hydrogen. In hydrogen-diesel dual fueling operation mode the NOx emissions level decreases with 12% (at 20.82 L·min-1 hydrogen flow rate, 40% engine load) and with 10.48%, respectively (at 29.8 L·min-1 hydrogen flow rate, 70% engine load) comparative to classic diesel engine. The authors' explication, regarding the NOx emissions level decreases at the engine operating with small hydrogen quantities in addition in air, is the fact that hydrogen burns fast and the temperature increases, leading to the avoiding of NOx formation due to a shorter duration of the combustion and high temperatures are registered only for a short period of time ~1.8 ms – 2 ms, ("the combustion is so rapid that the high temperatures exist only for approximate 2 [ms]" after Pechlivanoglou, [27]). Whatson [13] and Thalibi et al. [15] explains NOx decrease at the hydrogen adding in inlet air through the increase of the mole fraction of water vapors in the combustion products produced at the hydrogen combustion. The increased mole fraction of water vapors from the combustion products absorbs the energy released from the combustion and thus the peak of combustion temperatures decrease [13]. For increased hydrogen quantities the temperature effect connected with the NOx formation is high because the heat release is greater and the time duration in which the high temperatures exists is increased. Thus, is explained the NOx emissions level increases at greater percents of substitute ratio of diesel fuel by hydrogen, fig. 7.

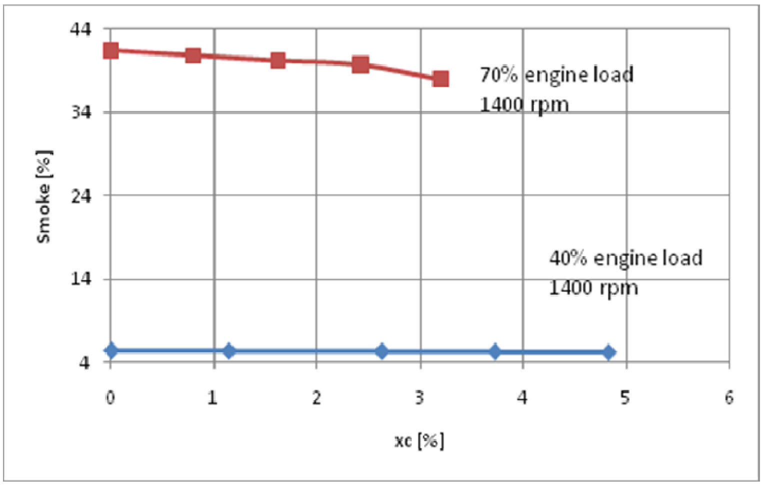

Figure 8. Smoke emission level vs. different substitute ratios x_c, at the engine regime of 40% and 70% load and 1400 min^{-1} speed

The variation of smoke emission level with the substitute ratios xc is shown in fig. 8.The smoke emission level slowly decreases comparative to the diesel fuelled engine due to combustion improvement and lower carbon content in the air-fuel mixture. The variation of carbon dioxide emission level with different substitute ratios is shown in fig. 9.

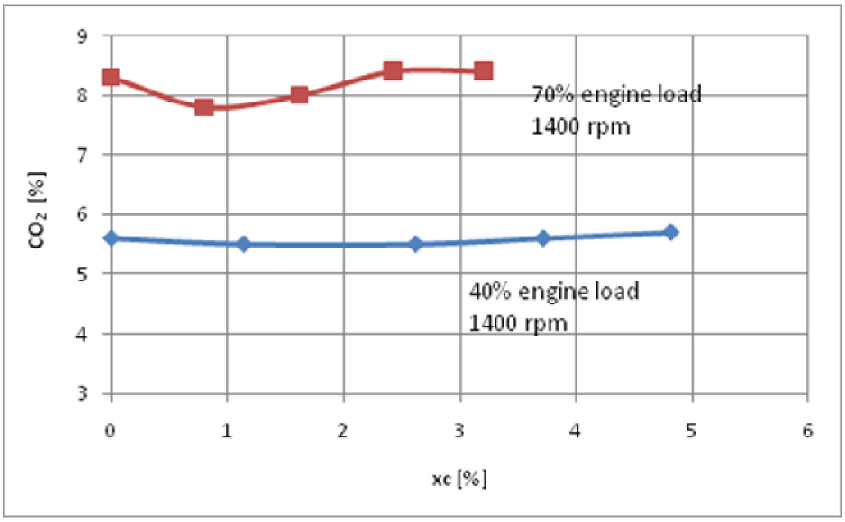

Figure 9. CO_2 emission level vs. different substitute ratios x_c, at the engine regime of 40% and 70% load and 1400 min^{-1} speed

Figure 10 presents the variation of HC emissions level with the diesel fuel substitute ratios with hydrogen, similar results being obtained by other researchers [4], [7], [8], [23], [25]. At hydrogen fuelling, due to the fact that hydrogen does not contain carbon, has a higher combustion velocity and the fuel combustion is improved, the HC emissions level decreases.

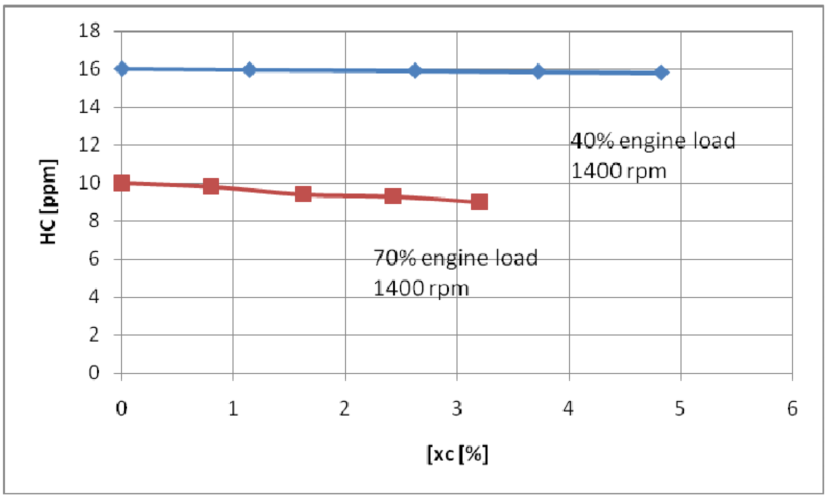

Figure 10. HC emission level vs. different substitute ratios x_c, at the engine regime of 40% and 70% load and 1400 min^{-1} speed

4. Conclusions

The use of hydrogen at the diesel engine is a good opportunity to improve the combustion process due to its better combustion properties in comparison with the diesel fuel. The experimental investigations carried on an automotive diesel engine fuelled with hydrogen as addition in air, show that the increase of the amount of hydrogen that replaces the diesel fuel, leads to:

- a slightly increases of maximum pressure with 2.8 % (at 40% engine load) and 3.8%, respectively (at 70% engine load), due to slightly increase of the amount of fuel which burns in the premixed combustion phase and due to autoignition delay decrease comparative to classic diesel engine.
- the maximum pressure rise rate increases with 25% and 10%, respectively at 70% and 40 % load.
- the decreases of BSEC with 6% at 40% engine load and with 6.9% at 70% engine load due to a higher degree of homogeneity of air-fuel mixtures and combustion improvement.
- the rise of the brake thermal efficiency from 30.9% to 32.9% (40% load) and from 32.1 % to 34.5 % (70% load).
- the decrease of NO_x emissions level with 13% at 70% engine load and with 18% at 40% engine load, when small hydrogen quantities in addition to inlet air are used.
- the decrease of the smoke emission level with ~11% especially at high load, due to combustion improvement and a lower carbon content in the air-fuel mixture.
- the decrease of the CO_2 emission level with 8% at 70% engine load and with 5.2% at 40% engine load.
- the reduction of the HC emission level by 8% at 70% engine load and with 5.2% for 40% engine load, due to higher combustion velocity of hydrogen, combustion improvement and absence of carbon.

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Nomenclature

BSEC - brake specific energetic consumption, $[kJ\cdot kW^{-1}h^{-1}]$
BSFC – brake specific fuel consumption, $[g\cdot kW^{-1}h^{-1}]$
BTE – brake thermal efficiency, [%]
°C – Celsius degree
°CA – crankshaft angle, [deg.]
Ch_{DF} – diesel fuel consumption, $[kg\cdot h^{-1}]$
Ch_{H} - hydrogen consumption, $[kg\cdot h^{-1}]$
CO – carbon monoxide, [%]
CO_2 - carbon dioxide, [%]
$dp/d\alpha$ – maximum pressure rise rate, [bar/°CA]
HC – unburned hydrocarbons, [ppm]
Hi_{DF} – lower heating value of diesel fuel, $[kJ\cdot kg^{-1}]$
Hi_{H} – lower heating value of hydrogen, $[kJ\cdot kg^{-1}]$
NO_x - nitrogen oxide, [ppm]
PM - particulate matter, [ppm]
p_{max} – in-cylinder maximum gas pressure, [bar]
rpm – revolutions per minute
SO_2 - sulphur dioxide, [%]
Q – hydrogen flow, $[L\cdot min^{-1}]$
x_c – substitute ratio, [%]

Greek symbols

α- crankshaft angle, [°CA]
$dQ/d\alpha$ – heat release rate, [J/°CA]
λ- air fuel ratio, [-]

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