PERFORMANCE COMPARISON BETWEEN HYDROGEN AND DIESEL FUEL FUELLED COMPRESSION IGNITION ENGINE

Ionel MIRICA[1], Alexandru CERNAT[2] , Constantin PANA[3], Niculae NEGURESCU[4], Cristian NUTU[5]

Due to its combustion properties, the hydrogen has a great potential for the improving energetically and emissions performance of compression ignition engine. In this respect, the paper presents comparative results of the experimental researches carried on a truck compression ignition engine fuelled with diesel fuel or with hydrogen and diesel fuel at 40% engine partial load. The hydrogen is injected in engine intake manifold and the diesel fuel is injected into combustion chamber assuring the ignition of the hydrogen. The obtained experimental results show that the engine fuelled with hydrogen in addition at fuel diesel has better energetically and pollution performance than the standard engine. Are shown the influences of hydrogen addition engine operate.

Keywords: hydrogen, combustion, emissions, diesel fuel, engine fuelling

1. Introduction

The most significant effect of the pollution due to the internal combustion engines is represented by the pollutants emissions, which are caused by the imperfection of the fuel combustion. The hydrocarbons HC, the carbon monoxide CO, the nitrogen oxides NO_x, the particles PM and the smoke are main pollutants of the diesel engine. The CO_2 is considered greenhouse gas emission. It has been even estimated the contribution of the automotive transportation to the environment degradation. Special laws are promoted nowadays in order to restrict the level of the pollutants emissions by applying an efficient control of the processes inside the engine cylinder. The problem of applying certain measures to limit the pollutants emissions is generally difficult because of the great number of influencing factors and because of the opposite influence of some factors on

[1] Ph-D student, Dept. of Thermotechnics, Engines, Thermical and Frigorific Equipment, University POLITEHNICA of Bucharest, Romania, e-mail: ionel_mirica@yahoo.com
[2] Lecturer, Dept. of Thermotechnics, Engines, Thermical and Frigorific Equipment, University POLITEHNICA of Bucharest, Romania, e-mail: cernatalex@yahoo.com
[3] Professor, Dept. of Thermotechnics, Engines, Thermical and Frigorific Equipment, University POLITEHNICA of Bucharest, Romania, e-mail: constantinpana@yahoo.com
[4] Professor, Dept. of Thermotechnics, Engines, Thermical and Frigorific Equipment, University POLITEHNICA of Bucharest, Romania, e-mail: niculae_negurescu@yahoo.com
[5] Ph-D student, Dept. of Thermotechnics, Engines, Thermical and Frigorific Equipment, University POLITEHNICA of Bucharest, Romania, e-mail: cristi_cmt@yahoo.com

different categories of emissions. Various strategies were applied to reduce environmental pollution [1, 2], most researcher's recommending the use of the alternative fuels [3-7]. The benefit of diesel engine is obvious especially in cases of using alternative fuels such as hydrogen which does not content sulphur and carbon and produces substantially diminished emissions. The great interest in the decrease of the pollutants emissions, which are responsible for greenhouse effect, justifies the efforts of the specialists for the use with high efficiency of the hydrogen in diesel engines.

Hydrogen is considered a privileged alternative fuel due to its properties, table 1, which makes it the cleanest fuel and due to its unlimited producing resources [8, 9, 10]. Due to its proprieties it seems very possible to reach homogenous air-fuels mixtures during the pre-formed phase of the carburant mixtures combustion. Therefore it is possible to decrease the soot and CO_2 emissions by using hydrogen in diesel engine at the same energetic level achieved when only diesel fuel is used.

Due to higher autoignition of the hydrogen, it can not be use as single fuel at the diesel engine, being necessary an ignition source [11, 12]. The best simple method of hydrogen use at the diesel engine is diesel-gas method; the hydrogen is injected in the intake manifold, as addition at diesel fuel and it is ignited from the flame initiated through diesel fuel autoignition. Another diesel-gas method advantage is the higher air-hydrogen mixture homogeneity, being assured all conditions for a reliable engine run- good mixture formation, a reliable ignition of hydrogen and an efficient combustion.

The experimental researches carried out on compression ignition engines fuelled with hydrogen have highlighted certain specific aspects of the combustion comparative to diesel fuel: at small percents of substitute ratio of diesel fuel by hydrogen the maximum pressure slightly increases (2%) due to more rapid combustion of air- fuel mixture and of the decrease of auto ignition delay of diesel fuel [13]. If the percent of substitute ratio of diesel fuel by hydrogen is greater, at small engine loads the maximum pressure and maximum pressure rise rate decrease because of the reduce of diesel fuel dose and of increase of auto ignition delay [14]; the rapid increase of the peak pressure and of the maximum pressure rise rate due to the higher combustion rate of hydrogen compared to other fuels at higher engine loads [15]. Through hydrogen addition optimization, the both measures can be used to avoid knock combustion; 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) [16]; in-cylinder pre-ignition followed by rapid pressure increase during the compression stroke that leads to a loss of the engine efficiency [16]. The thermal efficiency increases at the increases of hydrogen addition in cycle fuel dose, at the same engine speed and load, due to the improvement of combustion process (hydrogen has a great diffusivity, the hydrogen-air mixture is homogeneous and hydrogen has better combustion proprieties which assures the decreases of the duration of combustion process).

Table 1

Properties of hydrogen and diesel fuel [10]

Property		Diesel fuel	Hydrogen
Molecular weight, [kg/kmol]		226	2.016
Stoichiometric A/F ratio, [kg air/kg fuel]		14.7	34.32
Density at 0°C and 760 mmHg, [kg/m^3]		820-860	0.0899
Ignition limits in air, at 20 ^{o}C and 760 mm Hg	% vol.		4.1-75.6
	λi….λs	0,34…1,68	0.136…10.12
Laminar flame speed in air (λ=1), at 20 ^{o}C and 760 mm Hg [m/s]			2.37
Cetane Number		45-55	
Minimum ignition energy in air [mJ]		0.2-0.3	0.15
Heat of vaporization [kJ/kg]		250-314	458.1
Boiling temperature, ^{0}C, la 101300 Pa		180-359	-253
Autoignition temperature, [K]		473...493	845
Lower Heating Value (gas at 0°C and 760mmHg)	stoichiometric fuel-air mixture [kJ/m^3]	3344	3279
	[kJ/kg]	41800	119 600

Thus, Haroun A.K. Shahad and Nabeel Abdul-Hadi made an experiment on a diesel engine with hydrogen manifold injection and show that thermal efficiency accented increases (~ 40%) at the 60-80% engine loads, but at higher loads it reduces dramatically because of the incomplete combustion of richer mixture [12]. The heat release rate for hydrogen is much higher comparative to diesel fuel due to its instantaneous combustion.

At use of the hydrogen in addition with diesel fuel, CO, HC and smoke emissions level decreases due to improvement of the combustion, but CO_2 emission slight increases [17]. The NO_x emissions increase with hydrogen addition percent at higher engine loads only when the gas temperature is over the temperature for NO_x formation [18].

2. Experimental research

The experimental research has been followed on the D2156 MTN8 engine at the operating regimen of 40% load -53 ±2% kW - engine speed of 1400 ±2% rpm and normal thermal regimen (80 ^{0}C cooling agent temperature). The engine was mounted on a test bench equipped with an eddy-current dynamometer and appropriately instrumented with: data acquisition system, thermometers, thermocouples, thermo resistances and manometers monitoring the engine functional parameters, air flow meter, hydrogen flow meter, gas-oil consumption device and gas analyzer. Fig. 1 shows the scheme of the experimental bench.

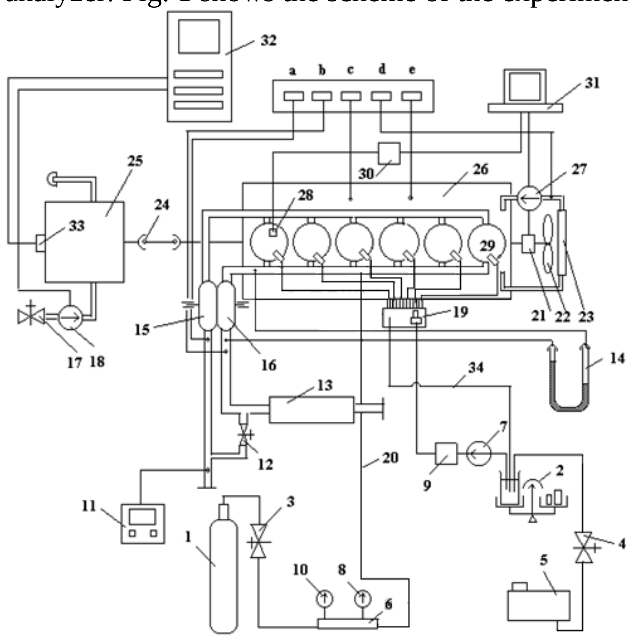

Fig. 1. The scheme of the experimental bench
1. Hydrogen bottle 2.Weight balance; 3. Hydrogen valve; 4. Diesel fuel valve; 5. Diesel fuel tank; 6. Pressure regulator; 7. Diesel fuel supplying pump; 8. Manometer high pressure; 9. Diesel fuel filter; 10. Low pressure manometer; 11. AVL DiCom 4000 gas analyzer; 12. Gas recirculation valve; 13. Meriam air flowmeter; 14. Differential manometer for turbocharging pressure measuring; 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 circulation pump for the engine cooling; 28. Kistler piezoelectric pressure transducer; 29. Injector; 30. Kistler charge amplifier; 31. PC with Keithley 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 and discussions

The engine was fuelled firstly only fuel diesel, then with diesel fuel and hydrogen at different rate between 9.12 L/min and 39.6L/min corresponding some percents of substitute energetic ratios of diesel fuel by hydrogen of 1.14%, 2.62%, 3.73% and 4.81%.

Fig. 2 presents the variation of in-cylinder pressure at the engine fuelled only with diesel fuel and with diesel fuel-hydrogen (21 L/min hydrogen rate) at a percent of substitute ratio of diesel fuel by hydrogen of 2.62% for which the brake specific energetic consumption (BSEC) has minimum value.

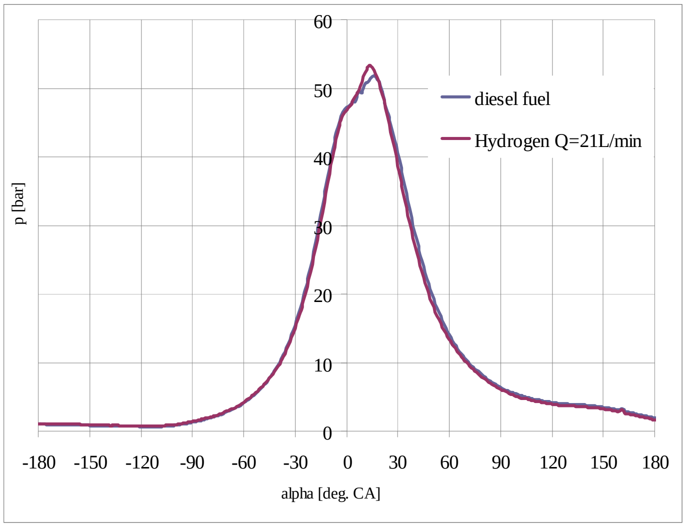

Fig. 2. Pressure diagrams at the engine regime of 40% load and 1400 min^{-1} speed

The percents of diesel fuel substitute ratios with hydrogen being small, the maximum pressure increases and the maximum pressure rise rate slightly increases, Fig.3, 4, due to the increase of the amount of fuel which burns in the pre mixed combustion faze and of the auto ignition delay decreases comparison to diesel fuel engine.

The minimum brake specific energetic consumption is smaller than one of diesel fuel engine with ~8 %, fig 5, due to combustion improvement. For exemple, for 21 L/min hydrogen rate ($BSEC_{min}$) the combustion duration is smaller with 11% to standard diesel engine and heat release peak rate is higher with 10.45%, fig. 6; for same operating regimen the available heat on cycle is smaller. Same effects on the combustion found and for 1...3% hydrogen additions for which BSEC has near values of minimum value.

In Fig. 6 is presented the heat release rate characteristic for the percent of substitute ratio of diesel fuel with hydrogen of 2.62 % at which BSEC has a minimum value. At hydrogen use, the heat release rate increases with the rise of diesel fuel substitute ratio percent due to a better combustion.

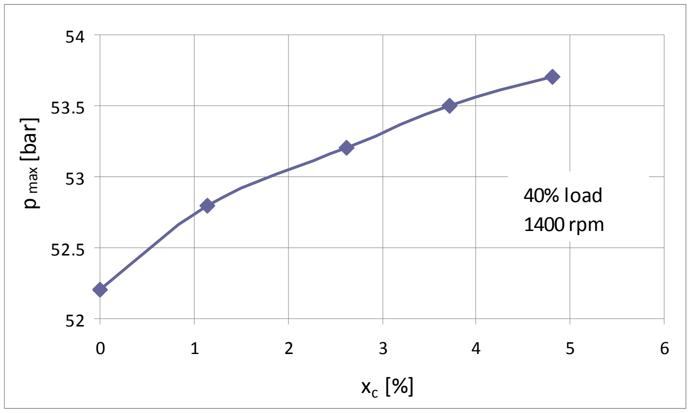

Fig. 3. Maximum pressure vs. different substitute ratios $\mathbf{x_c}$, at the engine regime of 40% load and 1400 min^{-1}speed

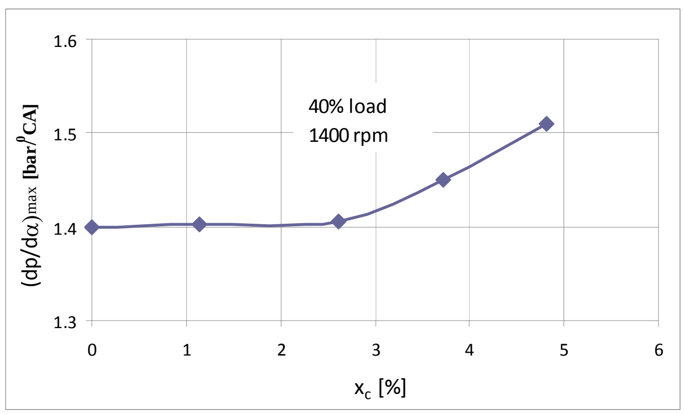

Fig. 4. Maximum pressure rise rate vs. different substitute ratios x_c, at the engine regime of 40% load and 1400 min^{-1} speed

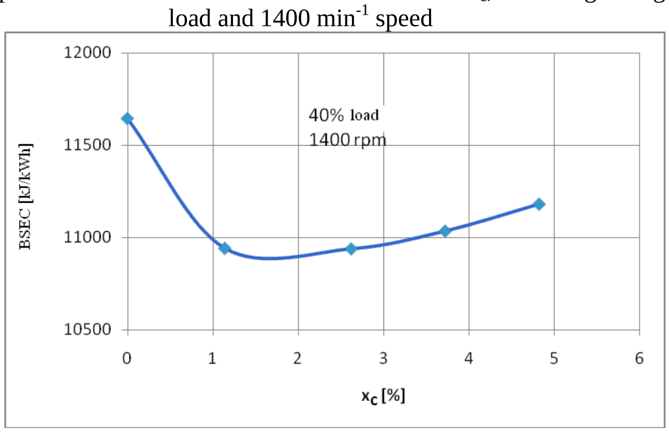

Fig. 5. Break Specific Energetic Consumption vs. different substitute ratios $\mathbf{x_c}$, at the engine regime of 40% load and 1400 min^{-1} speed

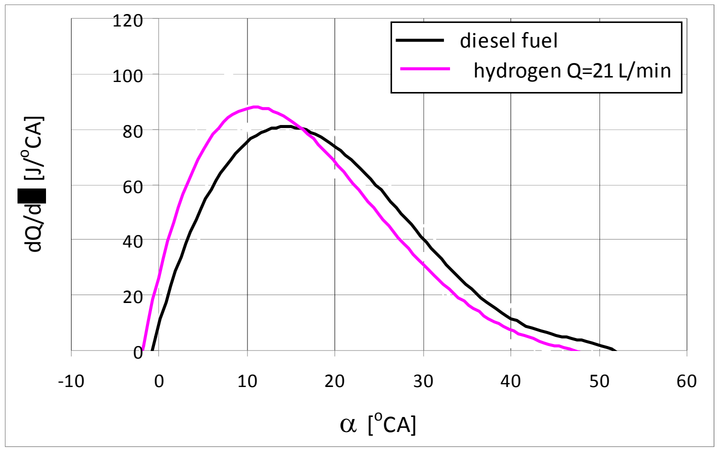

Fig. 6. Heat release rate characteristics at the engine regime of 40% load and 1400 min^{-1} speed

The maximum heat release rate it is with 8% higher at the engine running with hydrogen in addition comparative to the diesel fuel engine due to the higher combustion velocity of hydrogen and of the premixed combustion faze weight increases. The investigated engine is equipped with Meurer combustion chamber.

At this combustion proceed is known the fact that the preformed mixtures are in small quantity and the trend of the heat release rate has an aspect specific. At the hydrogen adding, the auto ignition delay decreases and the heat release rate increases at the combustion beginning when firstly burn the preformed mixtures; in continuation the combustion is developed after M proceed.

Fig. 7 shows the variation of NO_x emissions level. With hydrogen-diesel oil dual fuelling operation mode NO_x emissions level decreases with 12% comparative to diesel engine at 40% load for a 2.62% percent of substitute ratio of diesel fuel by hydrogen. Similar results were obtained and by other researchers. Thus, Lambe and Watson [3] and Tomita et al [19] have reported considerable reductions in NOx emissions level at the engine operate with hydrogen addition.

The high effect of the temperature on the NO_x emissions formation is known. At the engine small loads the diesel-fuel cycle dose is reduced. At the hydrogen adding, at the same engine load, the cycle dose of diesel fuel and the combustion duration decrease. For the investigated engine operating regimen (small engine load and hydrogen additions) the combustion duration for which the heat release rate is greater than at the engine operate with diesel fuel is shorter.

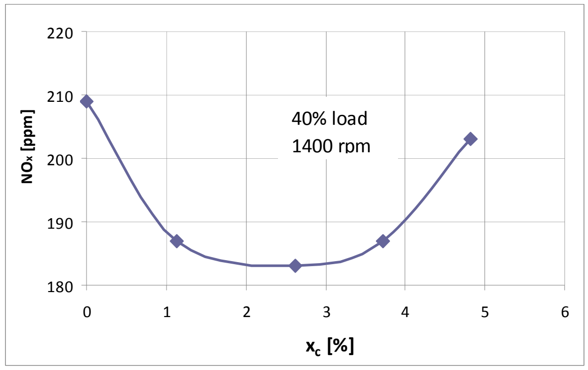

Fig. 7. NO_x emission level vs. different substitute ratios $\mathbf{x_c}$, at the engine regime of 40% load and 1400 min^{-1} speed

The authors explication regarding the NO_x emissions level decrease at the engine operate with small hydrogen quantities in addition is the fact that though the hydrogen burns fast and the temperature increases is avoided NO_x emissions formation due to a shorter duration of the combustion and high temperatures are registered only for short time ~1.8 ms. Same explication is given by Georgios Pechlivanoglou :"the combustion is so rapid that the high temperatures exist only for approx. 2ms" [20]. Whatson [3] and Thalibi et al. [17] explains NO_x decrease at the hydrogen adding through the increase of the mole fraction of water vapours in the combustion products produced at the hydrogen combustion which absorb energy released from combustion and thus the peak combustion temperatures decrease [17].

At the hydrogen addition increase the temperature effect regard the NO_x formation is high because the heat release is greater and high temperatures time duration increases. Thus is explained the NO_x emissions level increase at percents of substitute ratio of diesel fuel by hydrogen greater of 3%.

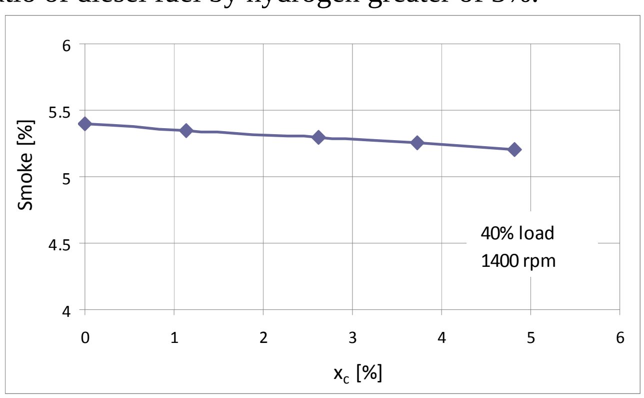

Fig. 8. Smoke emission level vs. different substitute ratios $\mathbf{x_c}$, at the engine regime of 40% load and 1400 min^{-1} speed

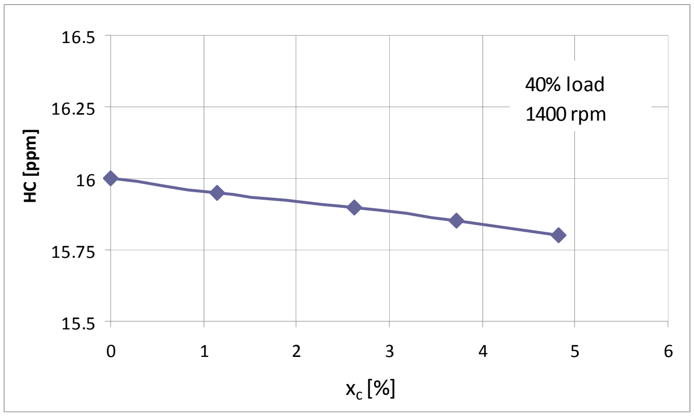

Fig. 9. HC emission level vs. different substitute ratios $\mathbf{x_c}$, at the engine regime of 40% load and 1400 min^{-1} speed

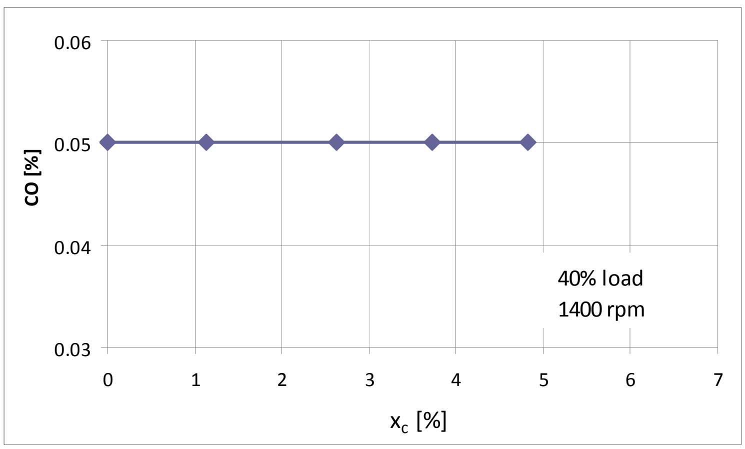

Fig. 10. CO emission level vs. different substitute ratios $\mathbf{x_c}$, at the engine regime of 40% engine load and 1400 min^{-1} speed

The variation of smoke, HC and CO emissions level is shown in fig. 8, 9, 10. The smoke and HC emissions level slowly decreases comparative to diesel fuelled engine due to combustion improvement and the lower content of carbon in the fuel-air mixture. The reduction of HC emission level is and due to the higher burning velocity of hydrogen, which amplifies the diesel fuel burning at small engine loads. The reduction of smoke emission level is and due to the fact the hydrogen forms a homogeneous mixture during combustion rather than the heterogeneous mixture specific diesel engine. Hydrogen assists diesel fuel during the combustion process to obtain a greater reduction of the smoke value [14].

The variation of CO with different substitute ratios is shown in fig. 10, emission level being constant.

4. Conclusions

Experimental investigations were conducted on a truck diesel engine with hydrogen in the dual fuel mode (hydrogen was injected in the intake manifold), under constant load and speed engine operation (40% load and 1400 rpm). The engine was fuelled with diesel fuel and hydrogen at different rate between 9.12 L/min and 39.6L/min representing some percents of substitute energetic ratios of diesel fuel by hydrogen of 1.14%, 2.62%, 3.73% and 4.81%.

The following conclusions of the experimental research could be formulated:

- hydrogen in dual fuel operation showed a decrease of the minimum brake specific energetic consumption by about 8 % compared to standard diesel engine
- at the hydrogen-diesel oil dual fuelling operation mode NO_x emissions level decreases with 12% comparative to diesel engine for a 2.62% percent of substitute ratio of diesel fuel by hydrogen
- the HC and smoke emissions level slowly decreases at the hydrogen addition increase compared to standard diesel engine
- hydrogen in addition at diesel fuel is a promising alternative fuel for compression ignition engines
- the use of the hydrogen in addition at diesel fuel by diesel-gas fuelling method doesn't required major engine design modifications.

Acknowledgements

The authors would like to thank to AVL List GmbH Graz, Austria, for providing the possibility to use the Simulation Software AVL BOOST. The work has been funded by the Sectoral Operational Programme Human Resources Development 2007-2013 of the Ministry of European Funds through the Financial Agreement POSDRU/159/1.5/S/134398.

R E F E R E N C E S

[1] *G. Karim* , Hydrogen as a spark ignition engine fuel, International Journal Hydrogen Energy, 2003, 56:256e63.
[2] *M. Masood, M. Ishrat, A. Reddy*, Computational combustion and emission analysis of hydrogen diesel blends with experimental verification, International Journal Hydrogen Energy, 2007, 32:2539e47.
[3] *S. Lambe, H. Watson*, Optimizing the design of a hydrogen engine with pilot diesel fuel ignition, International Journal Vehicles Design, 1993, 14:370e89.

[4] *G. Lilik, H. Zhang, J. Herreros*, Hydrogen assisted diesel combustion, International Journal Hydrogen Energy, 2010, 35:4382e98.
[5] *N. Saravanan, G. Nagarajan*, Combustion analysis on a DI diesel engine with hydrogen in dual fuel mode, Fuel, 2008, 87:3591e9
[6] *F. Christodoulou, A. Megaritis*, Experimental investigation of the effects of separate hydrogen and nitrogen addition on the emissions and combustion of a diesel engine, International Journal Hydrogen Energy, 2013, 38:10126e40.
[7] *K. Varde, L. Varde*, Reduction of soot in diesel combustion with hydrogen and different H/C gaseous fuels, In: 5th world congress of hydrogen energy, Toronto, Canada, 1984.
[8] *H. Rottengruber, M. Berckmüller, S. Elsässer, N. Brehm, C. Schwarz, A* High-efficient Combustion Concept for Direct Injection Hydrogen Internal Combustion Engine, 15th World Hydrogen Energy Conference, Paper nr. 28 J-01, Yokohama, Japan, 2004.
[9] *V. Subramanian, J. Mallikarjuna, A. Ramesh*, 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
[10] *M.G. Popa, N. Neguregscu, C. Pană*, Motoare Diesel. Procese (Diesel Engines. Processes), **Vol. I, II**, Editura MATRIX ROM, Bucuresti, 2003.
[11] W. B. Santoso, R. A. Bakar, A. Nur, Combustion characteristics of diesel-hydrogen dual fuel engine at low load, International Conference on Sustainable Energy Engineering and Application [ICSEEA 2012], Energy Procedia 32 (2013) 3 – 10
[12] *A. K. Shahad Haroun, A.H. Nabeel*, Experimental Investigation of the Effect of Hydrogen Manifold Injection on the Performance of Compression Ignition Engines, World Academy of Science, Engineering and Technology 76, 2011.
[13] *Peter Prechtl; Frank Dorer; Franz Mayinger, C. Vogel; V. Schnurbein*, Energy Conversion in a Hydrogen Fuelled Diesel Engine: Optimization of the Mixture Formation and Combustion, Heat Transfer Enhancement of Heat Exchangers, Kluwer Academic Publishers, Printed in the Netherlands, 1999, pp. 423-432.
[14] N. Saravanana, G. Nagarajana, C. Dhanasekaranb, K.M. Kalaiselvan, Experimental investigation of hydrogen port fuel injection in DI diesel engine, International Journal of Hydrogen Energy 32 (2007) 4071– 4080
[15] *N. Saravanan, G. Nagarajan, C. Dhanasekaran, K. M. Kalaiselvan*, Experimental Investigation of Hydrogen Fuel Injection in DI Dual Fuel Diesel Engine, Paper SAE 2007-01-1465, 2007.
[16] *N. Negurescu, C. Pana, M. G. Popa, A Cernat* , Performance Comparison Between Hydrogen and Gasoline Fuelled SI Engine, Thermal Science, Vol. 15, No. 4, 2011, pp.1155-1164
[17] *M. Talibi, P. Hellier, R. Balachandran,N. Nicos Ladommatos*, Effect of hydrogen-diesel fuel co-combustion on exhaust emissions with verification using an in-cylinder gas sampling technique, International journal of hydrogen energy, 39 (2014) 15088 el. 5102.
[18] *W.B. Santoso, A. Nur, S. Ariyono, R.A. Bakar*, COMBUSTION CHARACTERISTICS OF A DIESEL-HYDROGEN DUAL FUEL ENGINE, Editors: M.M. Rahman, M.Y. Taib, A.R. Ismail, A.R. Yusoff, and M.A.M. Romlay©Universiti Malaysia Pahang, National Conference in Mechanical Engineering Research and Postgraduate Studies (2nd NCMER 2010), Faculty of Mechanical Engineering, UMP Pekan, Kuantan, Pahang, Malaysia;, ISBN: 978-967-0120-04-1, 3-4 December 2010, pp. 23-32.

[19] *Tomita E, Kawahara N, Piao Z, Fujita S, Hamamoto* Y. Hydrogen combustion and exhaust emissions ignited with diesel oil in a dual fuel engine. SAE Pap 2001:2001e01e3503
[20] *Georgios Pechlivanoglou*, Hydrogen Enhanced Combustion History, Applications and Hydrogen Supply by Plasma Reforming, University of Oldenburg PPRE 2005-2007