EXPERIMENTAL RESEARCHES OF USING LPG AS A FUEL FOR A CAR DIESEL ENGINE

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The increasing number of cars over the years forces us to find alternative solutions for a cleaner environment. One of the best solutions is the use of alternative fuels and Liquefied Petroleum Gases are a very good choice. On one hand, this solution offers the possibility to reduce pollutants; on the other hand, from an economic point of view, LPG gives us the opportunity to use a cheaper fuel.

This paper presents relevant results of experimental investigations made on a 1.5 l K9K 792 diesel engine fuelled with LPG, using a Diesel-Gas method. The fuelling systems consist of two circuits: a standard diesel fuel circuit and another one for LPG gaseous injection in the intake manifold. LPG injectors are driven by an external ECU, mounted in parallel with the control unit of the engine. The influencs of LPG on the energetic and pollution performances of a diesel engine are presented in this research.

Keywords: Combustion, Pollutants, Diesel-LPG, Fuel

1. Introduction

Liquefied Petroleum Gases are light hydrocarbons resulted from crude oil or natural gases processing [1] and their contents are in general propane C_3H_8 and C_4H_{10} in different proportions. LPG properties are presented in table 1.

Table 1

LPG properties compared to diesel fuel [2].

Properties	Diesel fuel	LPG		
		Propane	n-butane	i-butane
Density [kg/m³]	800-840	503		
Vaporization heat [kJ/kg]	465	420		
Self ignition temperature [ºC]	225	481	544	
Inflammability limits [%]	0.6-5.5	2.1-9.5		
A/F ratio [kg/kg]	15	15.71	15.49	
Flame temperature [ºC]	2054	1990		
Lower heating value [MJ/m³]	$3.6 * 10^4$	$2.3 * 10^4$		
Lower heating value [MJ/kg]	42.5	46.34	45.55	45.7
Cetane number CC	40-55	-2		
Boiling point [ºC]	71-193	-42.1	-11.7	-0.5

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In table 1, we can notice important differences between LPG proprieties and diesel fuel proprieties: LPG density is ~1.6 times lower than the density of diesel fuel; flame temperature is lower than the flame temperature of diesel fuel; the favorable aspect for NO_x emission; the lower heating value for 1 kg of fuel is higher than for the diesel fuel, instead, it is less for 1 m^3, so this needs to increase the cycle fuel dose; self ignition temperature is ~2.3 times higher than the one of diesel fuel and the cetane number is very small, resulting in very poor auto ignition properties. Because of its poor self ignition properties, LPG fuelling can be realized only by the following methods:

a. Diesel-LPG method

The LPG is burned in the combustion chamber, the gas being prior injected in the intake manifold, on the intake stroke and ignited by the pilot diesel fuel sprays. The diesel engine is equipped with another fuelling system for LPG injection. The injected LPG quantity in the intake plenum is adjusted with the load and limited by the occurrence of the knock (compression ratio being higher, and the mixture homogeneous), and by the smoke emission, which is in high concentrations in exhaust gases at higher substitute ratios. Due to researches made by Hess and Simek on 150 buses in Vienna [3] the maximum substitute ratio of diesel fuel with LPG is 33%, energetically expressed. Moreover, because of homogeneity of the air-LPG mixture, the flame produced in the envelope of the jet will propagate very fast, resulting a high rate of pressure rise and therefore a high sound level [1]. This aspect is another limitation, because the durability of the engine can be affected [1]. Smoke emission is less than diesel fuel smoke emission, and the same is for NOx emission [1]. CO_2 and unburned hydrocarbons is kept at the same level as in the case of the corresponding standard engine [1].

b. I-LPG method

This method consists of a diesel engine transformation in a spark ignition engine which is LPG fuelled. The fuelling system is replaced by a LPG fuelling system, built for a spark ignited engine. The cylinder head must be modified for spark plugs mounting, and the piston head must be cut off to decrease the compression ratio. The new LPG fuelling system has injectors for each cylinder, the mass of the fuel being very well adjusted with the load of the engine, corresponding to a map saved in the ECU. This kind of conversion was made on a Nissan FD1L experimental diesel engine [4]. Vaporized LPG is injected in the intake in the front of a throttle valve. Investigations have been done using different combustion chambers: bowl combustion chamber, spherical and Nebula combustion chamber [4]. Helical intake port was kept, for swirl effect creation, with a swirl ratio of 2:1. In order to avoid power loss, the engine was supercharged. At full load, there were problems either with the stoichiometric mixture, when knock occurred and the NO_x level was high, or with the lean mixtures, with air excess ratio λ>1.8, because ignition issues occurred [4], especially when the load decreased [4]. The optimum air excess ratio coefficient has been determined to be between 1.4 and 1.6, where brake thermal efficiency, pollutant emissions and cyclic dispersion had the best values [4]. Either standard combustion chamber or Nebula chamber assured a fast combustion, with good values for cyclic dispersion and keeping the brake thermal efficiency at high levels [4]. However, from the point of view of nitrous oxides, Nebula combustion chamber offers a better behavior [4].

c. Direct LPG injection method

This method consists in replacing the diesel fuel with liquid LPG. Because LPG has a very low cetane number, an additive must be added [5]. The additives used are DTBP (2-tertiary-butil-peroxide), 2EHN (2-ethilehexile-nitrate) [5]. Because of very poor lubrication properties, another additive must be used to increase these properties [5]. To maintain LPG liquid at the injection pump entrance, low pressure circuit must be pressurized to a pressure above 20 bars. For DTBP concentrations above 7%, the brake thermal efficiency is approximately the same as in the case of using diesel fuel [5]. Concentrations below 5% led to unstable combustion, lack of ignition and, thus, higher pollutant emissions [5]. The same effects occurred with 2EHN [5].Up to 50% engine load, smoke doesn't exist in exhaust gases; then, smoke appears, its concentration being 10% lower than in the case of diesel fuel [5]. Another aspect is higher LPG compressibility, and this needs to increase injection timing advance [5].

d. Double injection method

Liquid LPG is directly injected in the combustion chamber and ignited by the pilot diesel fuel sprays, which had previously been injected. The advantage of the Diesel-LPG method is that air intake is not worsened [1]. Because of LPG weak lubrication properties, a teflon coated cylinder injection pump must be used [6]. The fuelling system consists of two circuits: one for the diesel fuel and another one for the LPG fuel. First the diesel fuel injection occurs and then the LPG injection takes place. Auto ignition phenomena are optimally realized by the diesel fuel pilot, then LPG is injected in the flame, allowing a very good combustion control [1]. By using this method we can avoid flame extinguishing in lean homogeneous mixtures, an aspect which occurs when using Diesel-LPG. LPG must not be injected in the auto ignition period, because this could increase its value [1], and LPG flow rate must be increased because of a smaller lower heating value on volume unit (MJ/m³) (1.6 times lower than diesel fuel) [6].

2. The research state of the art

In previous work [7], the authors studied the pollutant emission level of a diesel engine dually fuelled, using primer fuel propane. Carbon monoxide emission was higher than standard diesel engine, especially for 50% load. NO_x emission was, on the other hand, smaller for all the regimens. To increase the engine performances, a small percentage of recycled exhaust gasses will give very good results. An aspect can be the increase of intake process temperature, with a better brake thermal efficiency, and another aspect could be a lower smoke emission [8]. Unburned hydrocarbons quantity becomes low with increasing EGR percentage, because combustion becomes fast in the presence of radicals [9].

Ayhan et al. [10] studied the effects of the LPG injection in the intake stroke for engine performances and emissions. The engine was modified to determine the LPG optimum substitute ratio in the case of a dual operation, their aim being to decrease pollutant emissions and maintain energetic performances the same as with the standard engine, fuelled only with diesel fuel. For the fuelling system they used an electronic controlled injection system. The substitute ratios which were used were: 5, 10, 15, and 25 %. The minimum brake specific fuel consumption and maximum brake thermal efficiency were obtained for 15% substitute ratio, between 1400 and 1800 rpm, and optimum solution for either emissions or performances was obtained for 5% substitute ratio.

Qi et al. [11] experimented direct injection of a liquid diesel-LPG mixture, using a compressed nitrogen tank to maintain LPG liquid. They used different proportions: 0, 10, 20, 30, and 40 %. The conclusion was that diesel-LPG mixtures bring many advantages to control pollutant emissions.

Another very important aspect regarding the diesel engine is combustion noise. Ever since it was first discovered, engineers did studies to control this noise. In 1931, Ricardo was the first to discover a connection between the noise and the pressure rise rate [12]. Although there are a lot of sound sources, the most important source is combustion. The combustion noise is determined by the fast rate of pressure rise and formation of a shock wave which propagates in the entire engine mass and produces vibrations. The combustion noise can be modified by using substances like: diesel fuel-water emulsion [13], [14], water vapors injected in the intake stroke in the case of an engine dually fuelled [15], argon injected in the intake manifold [16], exhaust gas recirculation [17], dual fuelling with LPG, methane or other gases [18], [19], [20].

3. Experimental investigations

Experimental investigations were carried out on a K9K 792 1.5 dCi diesel engine, equipped with an LPG fuelling system, at 85% engine load and 2000 rpm. Laboratory equipment are: Schenck E90 eddy current engine dynamometer, load actuator, AVL acquisition system, AVL piezoelectric pressure transducer, AVL DiCom 4000 gas analyzer and opacimeter, Optimass fuel mass flow meters, Khrone volumetric air flow meter, thermocouples and thermoresistences for temperature measuring, gas leak detector. The engine parameters are presented in Table 2 and the test bed diagram is given in Fig. 1 below.

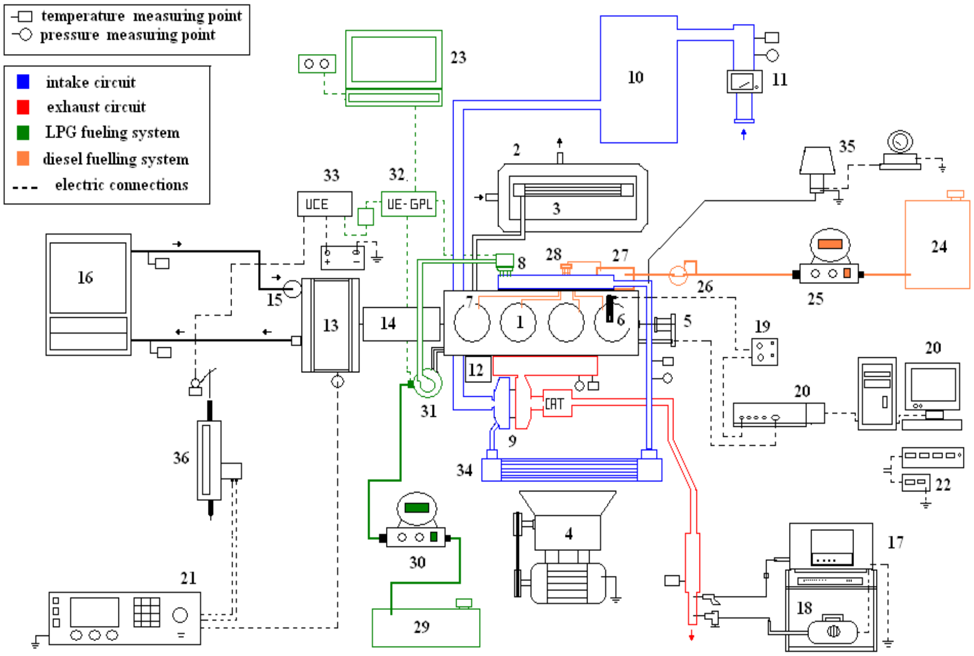

Fig. 1. Test bed diagram.

1 – 1.5 dci diesel engine; 2 – engine cooling system; 3 – engine water cooler; 4 – intercooler fan; 5 – engine angular encoder; 6 –AVL piezoelectric pressure transducer; 7 – diesel fuel injector; 8 – LPG injector; 9 – Turbocharger; 10 – intake air drum; 11 – intake air flow meter; 12 – exhaust gas recirculation; 13 –Schenck E90 dyno; 14 – dyno-engine coupling; 15 –Schenck E 90 dyno cooling water pump; 16 –dyno cooling system; 17 –AVL Dicom 4000 gas analyzer; 18 –AVL Dicom 4000 Opacimeter; 19 –AVL charge amplifier; 20 – PC + AVL data acquisition system; 21 –Schenck E 90 dyno controller; 22 – temperatures displays: a) – exhaust gas; b) – intake air; c) – engine oil; d) – engine cooling liquid; e) – engine oil pressure; 23 – diesel fuel and LPG injection control Laptop; 24 – diesel fuel tank; 25 – diesel fuel mass flow meter; 26 – fuel filters; 27 – high pressure pump for common Rail; 28 –Common Rail; 29 – LPG tank; 30 – LPG mass flow meter; 31 – LPG vaporizer; 32 –LPG ECU; 33 –diesel engine ECU; 34 –intercooler; 35- supercharge pressure measuring system; 36- throttle actuator.

Table 2

Engine parameters

Bore	76 mm
Stroke	80.5 mm
Connecting rod length	134 mm
Maximum power/speed	52 kW @ 3900 rpm
Maximum torque/speed	156 Nm @ 2000 rpm

The main objective of this paper is to determine the substitute ratio influence of diesel fuel with LPG over engine energetic performances, combustion noise and pollutant emissions. The substitute ratio x_C is evaluated by [1]:

$$COV_{pmax} = \frac{\sqrt{(\sum_{i=1}^{n}(p_{maxi} - \overline{p}_{max})^2)/(n-1)}}{\overline{p}_{max}} \cdot 100 \qquad (1)\ [1]$$

where: m_{LPG} - LPG cyclic dose; $m_{dieselfuel}$ - diesel fuel cyclic dose.

Working procedure: For each substitute ratio investigated, the diesel fuel dose is reduced, and LPG dose is increased to keep the standard engine power. To limit maximum pressure, injection timing was modified.

4. Results and discussions

First of all, investigations have been carried out on a standard diesel engine, to determine the reference and then the diesel fuel was partially substituted with the LPG fuel. The engine power has been conserved. In Figs. 2-14 below, we present the LPG influences over the energetic and pollutant performances, in case of dual fuelling. Fig. 2 presents the substitute ratio influence over the in-cylinder maximum pressure. The maximum pressure is higher for all the substitute ratios, because of a simultaneous higher heat release rather than in the case of using diesel fuel. In order to get a proper combustion positioning near the top dead center and to limit the maximum pressure, injection timing advance was modified with 1.1 to 6.7 degrees CRA.

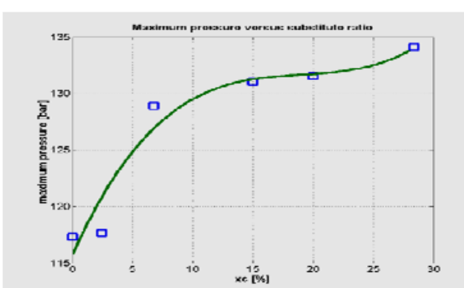

Fig.2.Maximum cylinder pressure versus the substitute ratio

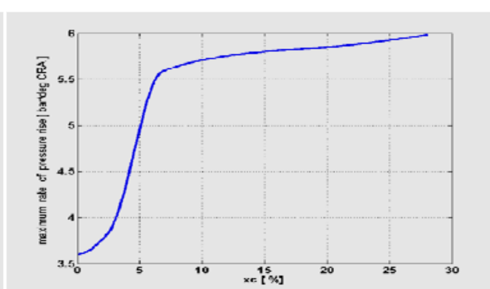

Fig. 3. The maximum rate of pressure rise versus the substitute ratio

The combustion noise, represented by the rate of pressure rise dp/dα is in the same lines. Fig. 3 represents the maximum rate of pressure rise variation versus the substitute ratio x_c. If we take a look at the figure above, we can see that the maximum rate of pressure rise becomes higher when the substitute ratio increases (~1.5 times higher for x_C=28.39 %). This aspect can be explained by a higher flame speed in the air-LPG homogeneous mixture, the flame appeared in the envelope of the diesel fuel jet. Also, the rate of pressure rise becomes higher rather than in the case of using diesel fuel, because of a higher rate of heat release in the first stages of combustion. The rate of heat release versus alpha (deg CRA) for three of the substitute ratios used are presented in Fig. 4.

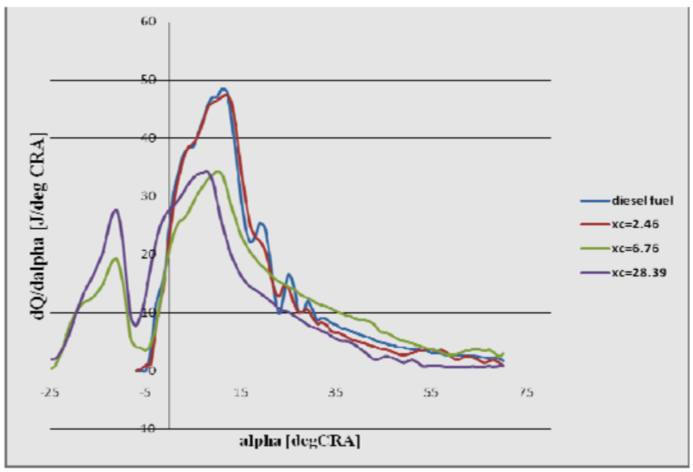

Fig. 4. The rate of heat release

The cumulative heat which is released is presented in the Fig. 5.

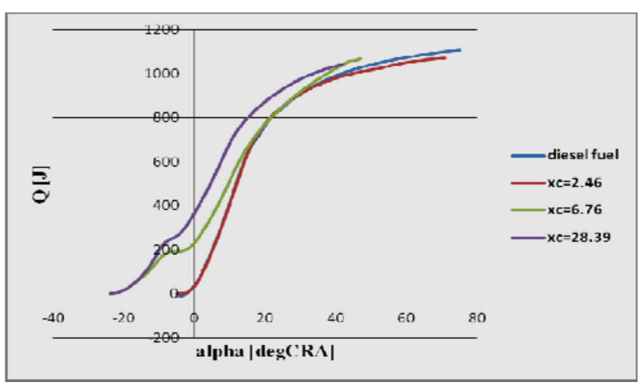

Fig.5. The cumulative heat released

Nitrous oxides emission had lower values than in the case of diesel fuel for all the investigated substitute ratios x_c. This is possible because, in the case of using LPG, the excess air ratio becomes lower and the cylinder global temperature decreases. Nitrous oxides emission is presented in Fig. 6.

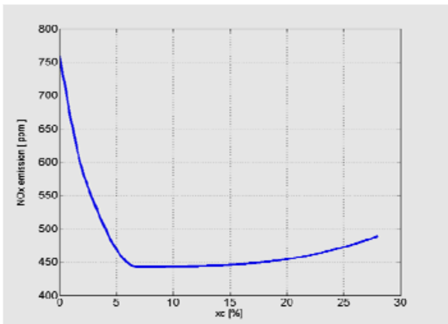

Fig. 6. NOx emission.

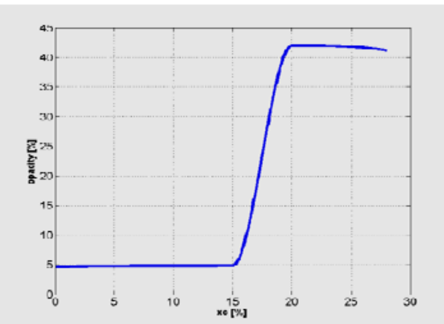

Fig. 7. The smoke emission versus the substitute ratio

Smoke emission, when the engine is LPG fuelled, is kept at the same level as in the case of diesel fuelling, for substitute ratios smaller than 15%.

Beyond this value of substitute ratio, the smoke emission increases because the mixture becomes rich, LPG being injected in the intake manifold and partially replacing the intake air. The smoke emission, represented by opacity is presented in Fig. 7.

The carbon dioxide emission increases a bit, and the unburned hydrocarbons increase for substitute ratios lower than 3.5 and decrease for x_c>3.5.

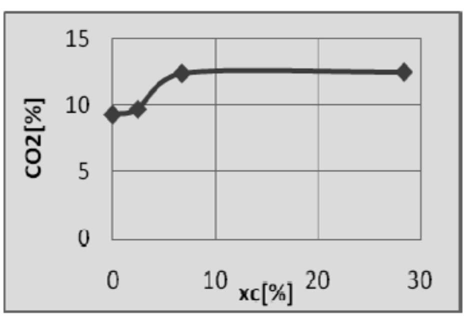

Fig. 8. The carbon dioxide emission

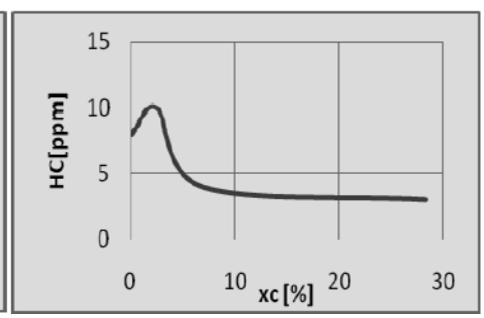

Fig. 9. The unburned hidrocarbons emission

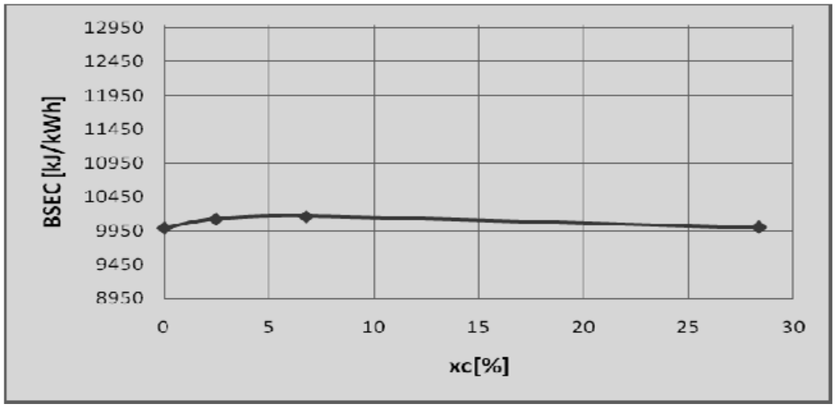

Fig. 10. The brake specific energetic consumption.

As far as fuel consumption is concerned, it is approximately kept constant and this is a good aspect, because LPG is cheaper than diesel fuel and thus the engine will operate with a smaller cost. In Fig. 10, we present the energetic brake specific fuel consumption versus the substitute ratio.

Another important parameter which describes engine running very well is the cyclic variability. LPG fuelling led to better results for cyclic variability than pure diesel fuelling. The following figures comparatively present the maximum pressures and the indicated mean effective pressures for 150 cycles, in the case of standard engine and LPG fuelled engine.

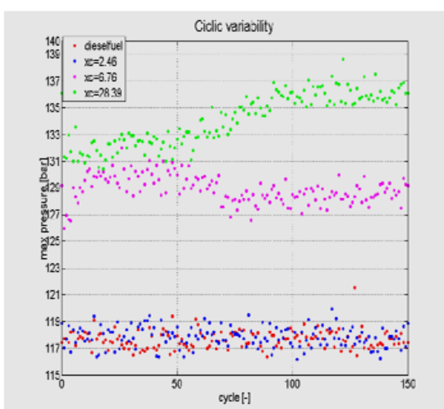

Fig. 11. The maximum pressure for 150 investigated cycles.

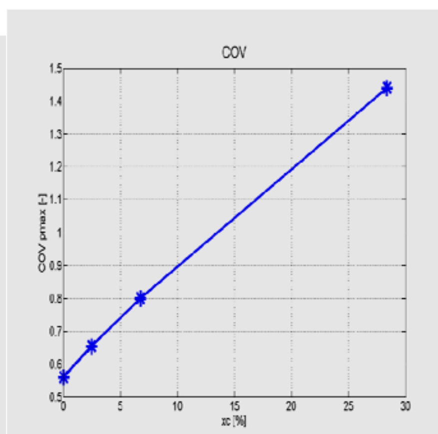

Fig. 12. COV_{pmax} variation versus substitute ratio.

It can be seen that the best behavior was obtained with x_c=2.46, where the maximum pressure had the smaller variation. Cyclic variability is evaluated by cyclic variability coefficient COV_{pmax}, which is given by the following relation:

$$COV_{pmax} = \frac{\sqrt{(\sum_{i=1}^{n}(p_{maxi} - \bar{p}_{max})^2)/(n-1)}}{\bar{p}_{max}} \cdot 100 \qquad (2)\ [21].$$

Fig. 12 presents the variation of COV_{pmax} versus x_c

As far as the indicate mean effective pressure is concerned, the results are presented in Figs.13 and 14 below.

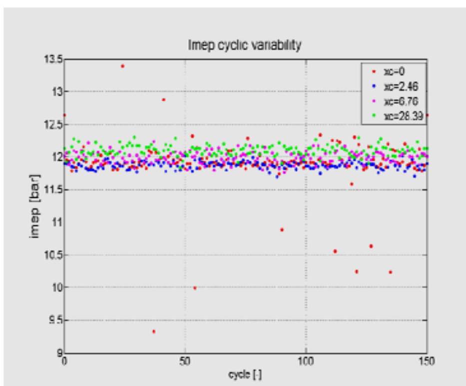

Fig.13. The Imep for 150 cycles

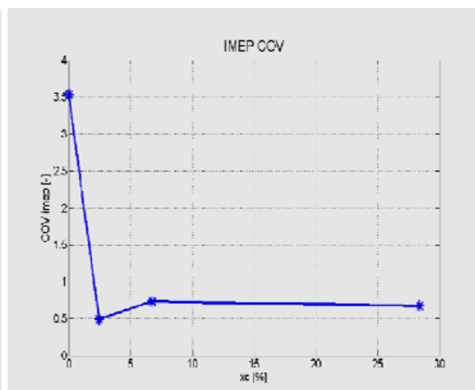

Fig. 14. m_{LPG}

The results are better in the case of LPG fuelling for all the substitute ratios investigated.

5. Conclusions

1. As far as mechanical stress is concerned, LPG fuelling doesn't affect the engine very much; maximum pressure resulted for the maximum substitute ratio investigated being higher only with 13% than in the case of pure diesel fuel.
2. The combustion noise increases especially for substitute ratios greater than 5, reaching a value with 40% higher for x_c=28.39.
3. Nitrous oxides emission decreases for all the investigated substitute ratios.
4. Unburned hydrocarbons emission decreases for substitute ratios higher than 4.
5. The brake specific fuel consumption and the carbon dioxide emission increases a bit when LPG is used.

6. The smoke emission is kept at the same level as in the case of using pure diesel fuel for substitute ratios up to 15% and it increases its value for greater substitute ratios, because of air intake worsening. In order to reduce this emission, when higher substitute ratios are used, it is necessary to increase the intake air quantity.

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