On LPG use at diesel engine: pollutant emissions level and cycle variability aspects

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Abstract. The pollutant emissions and the combustion cycle variability of a K9K diesel engine fuelled with LPG by diesel gas method are analyzed. The emissions level decreases with 42% for NO\textsubscript{X}, with 63% for HC, with 35% for CO\textsubscript{2} and with 30% for soot at LPG fuelling. The COV’s for angles of 5%, 10%, 50% and 90% of mass fraction burned present bigger values comparative to classic diesel engines, but don’t exceed the limits that provide reliability and normal drive-ability of the diesel engine.

1. Introduction

The use of the alternative fuels, even in partial substitution, may represent a viable solution to reduce the diesel engine pollutant emissions and to maintain the diesel engines in service and in urban traffic, an issue discussed at the C40 Mayors Summit in 2016. LPG is one of the most promising alternative fuels that can be successfully use for diesel engine fuelling in order to reduce the pollutant emissions, especially NO\textsubscript{X} and smoke, in terms of maintaining the normal engine manoeuvrability [1].

According to Institut Français du Pétrole (IFP), for 10 European automotives equipped with diesel engines fuelled with diesel fuel and LPG, the emissions of CO, HC, NO\textsubscript{X}, PM and PAHs decreases with 30% and the PM emission was indistinguishable at LPG use comparative to diesel [2]. Bielaczyc presents the decrease of HC, CO, CO\textsubscript{2} and NO\textsubscript{X} emissions levels at LPG use to fuels different engine of automotives [3].

Prasad [4] uses LPG – diesel/vegetable oil in dual fuel mode on a 4-stroke single cylinder diesel engine, the LPG being admitted into the inlet manifold. At LPG use the HC emissions level decreases with 21%, the CO emissions level decreases with 33.6%, the NO\textsubscript{X} emissions level is reduced by 4.4% and the smoke opacity decreases with 10% [4]. ETSAP presents a report with results of tests carried on bi-fuel LPG automotives, results that show a 15% reduction in greenhouse gas emissions (per unit of distance), very low NO\textsubscript{X} emissions and almost zero particulate emissions PM comparative to classic engines [5]. Reductions of 86%...96% for PM, with 17%...80% for NO\textsubscript{X} and with 75%...95% for CO were registered for busses and delivery trucks diesel engines fuelled with LPG [5].

Lee [6] uses propane in small amounts to fuels a CI engines and observes the effect on 50% mass fraction burned (MFB 50) and the reduction of NO\textsubscript{X} and PM emissions versus conventional diesel combustion. Ayhan [7] fuels with LPG a DI single cylinder diesel engine, the injection rates being 5%, 10%, 15% and 25%. The NO\textsubscript{X} emission decreased by 44.7% at 1200 rpm with 25% LPG, but smoke
emission drastically increased by 16.7%. The optimum injection rate, of 5% LPG, leads to the NOx and smoke emissions decreased by 27.6% and 20% at 1600 rpm, respectively [7].

Rosha [8] uses LPG fumigated into the intake air and EGR strategy on a 3.7 kW DI diesel engine. Rosha [8] shows that the diesel+LPG fuelled engine produce less NOx, (with 8.5% less), CO2 and smoke emissions levels comparative to conventional diesel, but HC emission level increases at part loads. With EGR technique the HC emission is reduced by 46.9%.

Rao [9] fuels with LPG and diesel fuel a four-stroke, single-cylinder diesel engine, with agricultural destination, at the operating regime of 1500 rev/min and 20%-80% engine loads range. At both engine loads, with the rise of LPG content the variability of combustion increases, but the smoke density and NOx were reduced, the HC shown the reverse trend [9].

Mirgal [10] investigates the performance of a naturally aspirated diesel engine at (LPG)-diesel dual fuel mode of operations at 1500 rev/min. The dual fuelling mode leads to the decreases of NO emission from 550 ppm to 50 ppm, the rise of HC emission from 23 ppm to 824 ppm and rise of in-cylinder pressure variability [10].

The present paper presents pollutant emission level and aspects of combustion cycle variability for a K9K diesel engine (of Dacia Logan MCV van) fuelled with diesel fuel and LPG by diesel gas method. The novelty of the paper work is assured by the establish of the best correlation between engine load-LPG cycle quantity, diesel fuel injection timing and exhaust gas temperature in order to control the combustion process and to obtain the best ecological and energy performance of the dual fuelled diesel engine.

2. Experimental research method and setup
The diesel gas method is used to fuel the 1.5 diesel engine, K9K type, with diesel fuel and LPG. The fuelling system design is presented in figure 1. The LPG injectors are electronic actuated by a special ECU connected back to back with the main engine ECU (Engine Control Unit) and with a computer, the injectors being connected to the inlet manifold.

![Figure 1. Schema of LPG fuelling system (a); detail of inlet manifold LPG injectors (b) [1].](image-url)

In figure 1(a) the following components of the LPG fuelling system are presented: 1- LPG reservoir, 2-vaporizer, 3-LPG injectors, 4-electronic control unit for LPG injectors, 5-signal amplifier, 6-calculator, 7-control assembly, 8-power unit, 9- K9K diesel engine, 10-electronic control unit of K9K diesel engine, 11-electric dyno, 12-dyno control cabinet [1].
The investigated operating engine regime was the nominal regime, 85% load at 2000 min⁻¹ engine speed. At this regime the engine was firstly fuelled with diesel fuel and secondly with diesel fuel and LPG in dual fuelling mode, at different substitute ratios, the diesel fuel injection timing being maintained constant at the classic value. Thus, the LPG dose is established in order to maintain the best engine performance for the classic diesel injection timing. Using the computer and the control assembly panel, as shown in figure 1(a), the injection duration was changed so at the rise of LPG cycle dose the diesel fuel dose is reduced in order to maintain the engine power.

The substitute ratio, $x_c$, defines the energetic substitution of diesel fuel by LPG and is evaluated by using the fuel consumptions and the lower heating values of both fuels. For each substitute ratio the pollutant emissions level were measured by an AVL DiCom 4000 gas analyser which was prior calibrated. In order to evaluate if the normal drive ability of the diesel engine is assured at LPG fuelling a combustion variability study was developed. Thus, the results of a cycle-by-cycle variation of LPG combustion study will decide if the LPG can assure a normal engine operation and a good drive ability of the automotive equipped with an LPG diesel engine. The cycle variability study was realised for 150 combustion cycles so an accurate analysis can be developed. Pressure diagrams and MFB have being measured and registered by AVL Indimodul 621 data acquisition system and analyzed for different substitute ratios, $x_c$.

The coefficients of cycle variability (COV) for MFB of 5, 10, 50 and 90% reflect the intensity of cycle-to-cycle variation of MTB values being calculated with the following relation (1):

$$\text{(COV)}_a = \left\{ \frac{\sum_{i=1}^{n} a_i}{n} \cdot \left( \frac{\sum_{i=1}^{n} a_i}{n} \right)^2 \cdot \left( n-1 \right)^{-1} \right\}^{1/2} \cdot \left( \frac{\sum_{i=1}^{n} a_i}{n} \right)^{-1} \cdot 100\%$$

where $n$ is the number of cycles, $a$ is the parameter of which variability is study and is defined by 5%, 10%, 50% and 90% MFB values, peak pressure and indicated mean effective pressure reached in the cycle number “i”, [1], [11].

The COV of maximum pressure is suitable at cycle-by-cycle variability evaluation for regimes with injection timing closer to the value of timing for MBT (Maximum Brake Torque). The COV values reflect the combustion cycle to cycle variability during the first phase of combustion, main phase and end of combustion. The accepted limit values of COV define the limit of in-cylinder mixture leaning, the maximum accepted LPG quantity and reflects the variability of diesel-LPG combustion. The COV values for maximum pressure and IMEP are taking into consideration when the limit value of $x_c$ is established. If COV values don’t exceed 10% the normal automotive manoeuvrability is assured [1], [11].

3. Results
The text The NO$_x$ and HC emissions levels are presented in figure 2(a) and figure 2(b). The NO$_x$ decreases with 42% for $x_c$=2.5% as results of global in-cylinder temperature decrease at the use of small LPG cyclic doses.

The diminution of NO$_x$ emission level at LPG quantity increases appears due to reduction of available oxygen and gases temperature. At LPG does increase, the decrease of inlet air quantity admitted in cylinder leads to the NO$_x$ forming process reduction due to the relative reduction of oxygen.

The HC emission level is influenced by the reduction of the carbon percent in the final mixture and the higher speed of combustion of air-LPG homogeneous mixtures.

The HC level decreases with 63% due to lower carbon content in the final mixture at LPG fuelling. At the rise of LPG dose, high speed combustion of air-LPG homogeneous mixtures leads to the
reductions of HC emissions. The NO\textsubscript{x} emission level decreases with almost 36% at the maximum \( x_c \), in relation with a much higher combustion speed reached at diesel-LPG fuelling.

![Graph](image1.png)

**Figure 2.** (a) NO\textsubscript{x} emission level versus \( x_c \); (b) HC emission level versus \( x_c \).

![Graph](image2.png)

**Figure 3.** Smoke emission level: (a) opacity versus \( x_c \); (b) K smoke number versus \( x_c \).

The smoke emission decreases with 30% for \( x_c = 2.5 \) due to reduction of carbon content and acceleration of the combustion process at LPG fuelling, as shown in figure 3(b). After \( x_c = 2.5 \) the smoke number and opacity starts to increase because the inlet air quantity is reduced ones with the rise of LPG inlet quantity, but the registered values remains under the reference regime of diesel fuelling. Thus, for maximum \( x_c \) the decrease in smoke emission is around 23%, as visible in figure 3(b). A similar variation tendency is registered for opacity, as shown in figure 3(a). The CO\textsubscript{2} emission level decreases by 35% at LPG fuelling due to improvement of combustion process at LPG use, as visible in figure 4(a). Reduction of CO\textsubscript{2} emission is related with the reduction of carbon content in the mass composition of the final mixture.

![Graph](image3.png)

**Figure 4.** CO\textsubscript{2} emission level: (a) CO\textsubscript{2} level versus \( x_c \); (b) CO\textsubscript{2} level versus \( x_c \).

The ultra lean air-LPG mixtures established in-cylinder before combustion starts influence the beginning of the combustion process, which is defined by a raised variability evaluated by variability of the angle of 5% of mass fraction burned. The COV\( _{\alpha_{5\%}} \) increases from 5.6, for diesel fuelling to 10.7 at maximum LPG dose, as shown in figure 4(b). To assure the normal manoeuvrability of the diesel engine the LPG substitute ratio \( x_c \) must be limited at 28%. The accepted limit value of COV for 5% MFB defines the limit of in-cylinder mixture leaning and reflects the variability of flame development during the first phase of combustion. The increases variability during the stage of nucleus of flame developing leads to the rise of the combustion variability into the premixed combustion phase. The COV for 10% MFB increases from 6.6% to 106% for maximum LPG cycle dose, as visible in figure 5(a), because of air-LPG ultra-lean mixture combustion. For low \( x_c = 2.4 \) the
COV of 10% MFB is 5.9% which is below the value registered for diesel, 6.6%, but for \( x_c = 6.7 \) COV of 10% increases up till 137%.

![Figure 4](image1.png)

**Figure 4.** (a) CO\(_2\) emission level versus \( x_c \); (b) COV of MFB 5% versus \( x_c \).

![Figure 5](image2.png)

**Figure 5.** (a) COV of MFB 10% versus \( x_c \); (b) COV of MFB 50% versus \( x_c \).

The cyclic variations in MFB in the first and second phase of combustion are related with the cyclic variability of in-cylinder maximum pressure. The COV in peak pressure rise from 0.56% (\( x_c = 0 \)) to 1.44% at LPG fuelling (\( x_c = 28 \)) which is a result of MFB 5% and 10% variability increase. This fact is in correlation with the variability of flame development during the premixed stage of combustion. Variability of the flame development during combustion premixed phase is affected by the increase of \( x_c \) and leads to the increase of \((\text{COV})_{\text{IMEP}}\) from 1.1% (\( x_c = 0 \)) to 1.3% (at \( x_c = 28 \)), but the value don’t exceed 3%. Due to high combustion velocity of LPG, the acceleration of combustion process leads to the limited values of 50% MFB registered during the main combustion phase, as visible in figure 5(b). The air-LPG mixture combustion with higher rate and lower duration leads to the decrease of the cyclic variations. The combustion of the homogeneous LPG-air mixture near the diesel pilot is developed so fast influences the heat release rate and decreases the cyclic variations of 50% MFB. During the diffusive combustion COV values for \( \alpha_{50\%} \) are restricted to 9.5% for maximum \( x_c \). The values registered for \( x_c = 2.5 \ldots 6.7 \) are also the value of 10% registered for only diesel fuelling.

The start of combustion in ultra lean mixture conditions rise the variability at the beginning of the combustion process and influences the end of combustion. The raised variability registered during the initial phases of combustion, defined by raised values of \((\text{COV})_{\alpha_{5\%}}, \ (\text{COV})_{\alpha_{10\%}}\), leads to an increased variability at the end of combustion process when the 90% MFB is reached, as shown figure 6. At only
diesel fuelling the variability of angle $\alpha_{90\%}$ is 5.8%. At LPG fuelling the variability of 90%MFB rise at 9% for $x_c=2.5$, 7.2% for $x_c=6.7$ and 13% for $x_c=28$.

![Figure 6. COV of MFB 90% versus $x_c$.](image)

The maximum registered value is only with 3% above the admitted values for a good engine maneuverability, as shown in figure 6, but the raised value registered for $\alpha_{10\%}$ may represents a limitation criteria for the substitute ratio values at $x_c=28$, as visible in figure 5(a). Also, the general response of the engine to the combustion variability at diesel-LPG fuelling is assured by the fact that COV values for IMEP and maximum pressure are bellow 3% at maximum $x_c$.

4. Conclusions

The main conclusions of the experimental investigations of the LPG use at diesel engine by applying the diesel-gas method are:

- the NO$_x$ emissions level decreases with 42% due to reduction of available oxygen and gases temperature at LPG cycle quantity increase.
- the HC emissions level decreases with 63% due to high speed combustion of air-LPG homogeneous mixtures
- the smoke emission, evaluated by K number, decreases with 30% due to reduction of carbon content and increase of air-LPG homogeneous mixture combustion speed
- the CO$_2$ emission level decreases with 36% due to reduction of carbon content in the mass composition of the final mixture
- COV of 5% MFB rises from 5.57% to 10.73%...10.83% at $x_c=6.7$...28, in relation with the rise of maximum pressure COV value
- COV of 10% MFB increases from 6.6% to 106.8%...137% at $x_c=6.7$...28, in relation with the rise of maximum pressure COV value
- COV of 50% MFB decreases from 10% to 5.6%...9.7% at $x_c=6.7$...28 due to high combustion velocity of LPG, which accelerates the combustion process
- COV of 90% MFB rises from 5.8% to 7.4%...13% at $x_c=6.7$...28
- the LPG is a viable alternative fuel for diesel engine due to pollutant emissions levels decrease in terms of maintaining the normal engine manoeuvrability reflected by values of COV in IMEP and peak pressure which are under 3%.

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