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OPERATING ASPECTS OF AUTOMOTVE DIESEL ENGINE FUELLED WITH LPG

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The paper presents some aspects of a cyclic variability study developed for an automotive diesel engine dual fuelled with diesel fuel and LPG. The COV values for maximum pressure, indicated mean effective pressure and angles of mass fraction burned are presented. The LPG-diesel fuel dual fuelling operation leads to the increase of the cyclic variability, especially for large LPG cyclic doses. The COV values don't exceed the acceptable value, but the increasing tendency of the variability of the combustion at LPG dose rise is taken into consideration. The substitute ratio is limited to assure the engine normal operation.

Keywords: LPG, diesel engine, cycle variability, mass fraction burned.

1. Introduction

Over the following years few European cities decide to restrict the access of diesel engines automotives in the urban areas because of the pollution issues, the decision being taken after the C40 Mayors Summit. In the report on the Future Transport Fuels for the year of 2050 [1] made by the European Commission the liquid petroleum gas (LPG) is presented as an alternative fuel with great perspectives in use for automotives equipped with diesel engines, the reduction of the pollutant emissions on this vehicles at LPG use being a saving solution which will allows to maintain in use the diesel engines. Many researchers use the LPG for diesel engine fuelling and as results important decreases of pollutant emissions levels were shown. Beside the advantage of lower pollutant emissions levels at LPG use the experimental research's must be completed with studies of combustion cycle variability in order to evaluate if the LPG can assure the normal operation of the engine comparative to diesel fuel fuelling, so the normal drive-ability of the automotive to be assured.

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Tira [2] develops a study for the combustion process for a diesel engine fuelled with LPG and diesel fuel using methyl ester of rapeseed (RME) and gas to liquid diesel fuel (GTL). Tira observes that for percents of LPG increased up to 60%, which substitute the liquid fuel, the combustion cycle variability is acceptable [2]. The use of LPG-RME fuels leads to an improved combustion variability comparative to LPG-diesel fuel dual fuelling. For all investigated engine load regimes the use of LPG leads to the increase of the cyclic variability, the influence being more accentuated at low engine loads. At these regimes the addition of LPG to GTL leads to the rise of the IMEP variability coefficient, but the values for COV of IMEP remains in the acceptable interval and do not exceed 10% [2]. Liu [3] shows that the LPG dose influences the combustion in a diesel engine (PCCI engine - Premixed Charge Compression Ignition) fuelled with dimethyl ether and diesel fuel. At the rise of LPG quantity (in mixture with DME-dimethyl ether) the maximum pressure slightly decreases, but the combustion duration is shortened. Lee [4] uses propane, in percents of 30%...70%, to fuel a diesel engine in dual mode in order to decrease the emissions of nitrogen oxides, NO_x, and particulate matter, PM. From Lee [4] observation, at 70% propane the combustion process starts to be unstable and new strategies for injection must be applied in order to stabilize the combustion at higher propane ratio use. Kang [5] shows the necessity of propane ratio limitation in order to reduce the values of maximum pressure and of the IMEP cycle variability coefficient, at the operation of a diesel engine at diesel fuel and propane fuelling. Lata [6] uses LPG and hydrogen to fuel a turbocharged 4 cylinder diesel engine and shows the increase of maximum pressure and combustion duration for 30% LPG use, with 6.9 bar and with 5 CAD (Crank Angle Degree), respectively. If the LPG content is increased to 70% (and hydrogen is added too), the combustion duration is decreased with 4 CAD and the maximum pressure rises with 5.2 bar [6]. Tira [7] shows that the use of LPG as addition fuel to diesel engine leads to the delay of the combustion start, at small engine loads, and assures the reduction of combustion duration. For the maximum LPG cycle quantity, which replace 60% from mass of diesel fuel, the cycle variability is acceptable, the COV value for IMEP being under 5%, at low engine load. Selim [8] uses liquid petroleum gas and pilot injection of jojoba methyl ester to fuel a Ricardo E6 diesel engine for operation at partial engine loads. Selim compares the performance of dual fuelled engine with the classic diesel fuelling operation and after analyzing of 100 combustion cycles shows that jojoba oil –LPG engine operation is characterized by a lower cyclic variability of maximum pressure comparative to the rest of the tested fuels [8]. After experimental tests on aspirated and supercharged engines fuelled with gaseous fuels Baratta [9] affirms that the reduction of the combustion cyclic variability is related with reduction of $\Delta\theta_{10\text{-}90\%}$ combustion duration. Jamsran [10] uses LPG and DME intake manifold injection to fuel a HCCI diesel engine. The LPG use leads to the increase of the combustion duration and to the rise of the COV of IMEP versus classic fuelling. Rimkus [11], [12] uses diesel fuel and LPG (in percents of 20%-75%) to fuel a 1Z 1.9 TDI diesel engine and develops experimental and theoretical analysis for dual fuelling. The use of LPG (especially in large percents) leads to the rise of the maximum pressure and of the rate of maximum pressure rise. The MFB values are affected by large LPG doses, the first stages of heat release being achieved later on cycle, but the heat release is accelerated during the 50%-MFB and 90%-MFB, the combustion duration being shorted for some individual cycles [11], [12]. Engenc [13] shows that the LPG fuelling leads to the rise of in-cylinder maximum pressure with 2…5 bar and to a higher speed of combustion, for an LDA 450 engine.

The purpose of the paper is to presents some operating aspects of a Dacia Logan diesel engine at diesel fuel and LPG fuelling. A cycle to cycle combustion analysis studies the engine response to LPG fuelling and decides if the normal engine operation can be assured. Thus, combustion cycle variability aspects for the operating regime of 40% engine load and 3900 min^{-1} are shown. Comparative to others regimes, the NO_x and smoke emissions levels were decreased with 30% and 67%, respectively [14]. The best correlation between engine parameters (diesel pilot quantity, LPG inlet percent and exhaust temperature) to obtain high performance of the engine represents a novelty aspect of the research, the use of larger LPG quantities being possible.

2. Research Methodology

The experimental test bench of the dual fuelled diesel engine is presented in the Fig. 1.

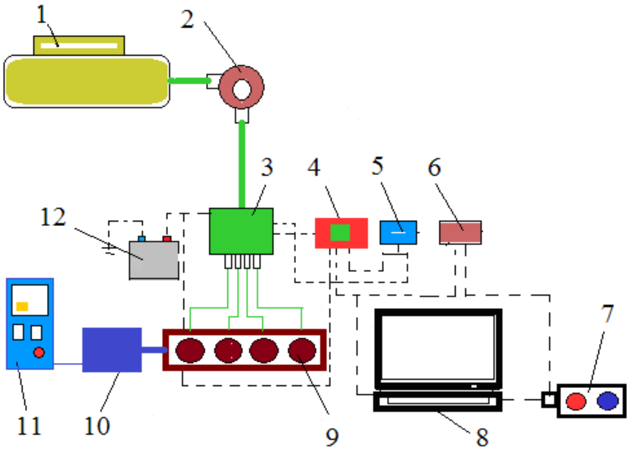

Fig. 1. The experimental test bed schema

The main components of the experimental test bed are: 1-LPG reservoir, 2-vaporizer, 3-LPG injectors, 4-ECU of LPG injectors, 5-signal amplifier, 6- ECU of K9K engine, 7-control assembly, 8- calculator, 9-K9K diesel engine, 10- eddy curent dyno, 11- dyno control cabinet, 12- electric battery.

In order to maintain the engine power at the value of the reference regime, during the experimental investigation the quantity of diesel fuel was reduced at the increase of the inlet LPG quantity. The LPG and diesel fuel cyclic masses were controlled thru tune of injector's opening time maps, acting on engine electronic control unit connected to a tuning unit with Dastek Unichip software. Thus, the quantity of the liquid petroleum gas which substitutes the classic fuel is defined by an energetic substitute ratio *xc*, the values being *xc*=0,…,51.57%.

For cyclic variability study a number of 300 consecutive combustion cycles were recorded with the resolution of 1 CAD (Crank Angle Degree). For determination of the cycle-to-cycle variation during the combustion process, the coefficients of variability (COV) for maximum pressure (MP), indicated mean effective pressure (IMEP) and angles of 5%, 10%, 50% and 90% of mass fraction burned (MFB) were calculated. The COV of MP is suitable at evaluation of the cycle variability for operating regimes with injection timing closer to the value of timing for MBT (Maximum Brake Torque) [15], [16]. The cycle-to-cycle variability of the IMEP influences the engine performance and torque and is correlated with the variation of the combustion rate and variation of the energy released during combustion process [15], [16]. If values of COV don't exceed 10% the normal operation of the automotive diesel engine is assured [15].

3. Results

The maximum pressure variation in consecutive cycles is presented in Fig. 2.

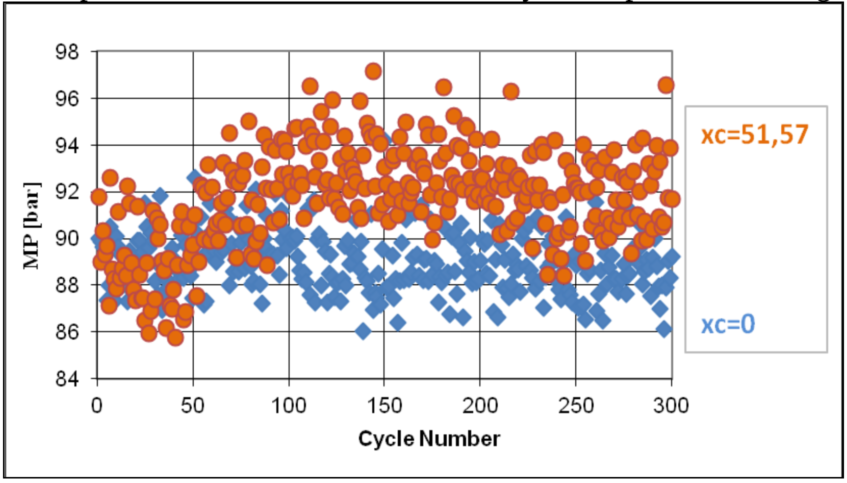

Fig. 2. Maximum pressure (MP) dispersion in consecutive cycles for diesel fuel fuelling (*x*c=0) and maximum substitute ratio (*x*c=51.57)

At LPG and diesel fuelling, the formation of high homogeneous air-LPG mixtures, which burns with high speed during the rapid phase of combustion, leads to the rise of cycle by cycle dispersion between the values of maximum pressure MP, a slightly increase of MP with 3% at maximum *xc=51.57* versus classic fuelling *xc=0* being observed. The increased irregularity which appears between the values of maximum pressure in the consecutive operating cycles is shown in the Fig. 2, for *xc=51.57* and *xc*=0.

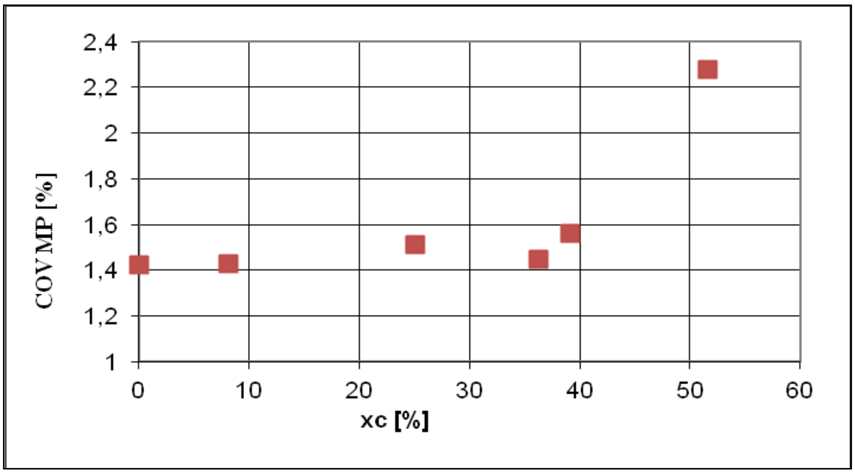

Fig. 3. COV of MP for different substitute ratios *xc*

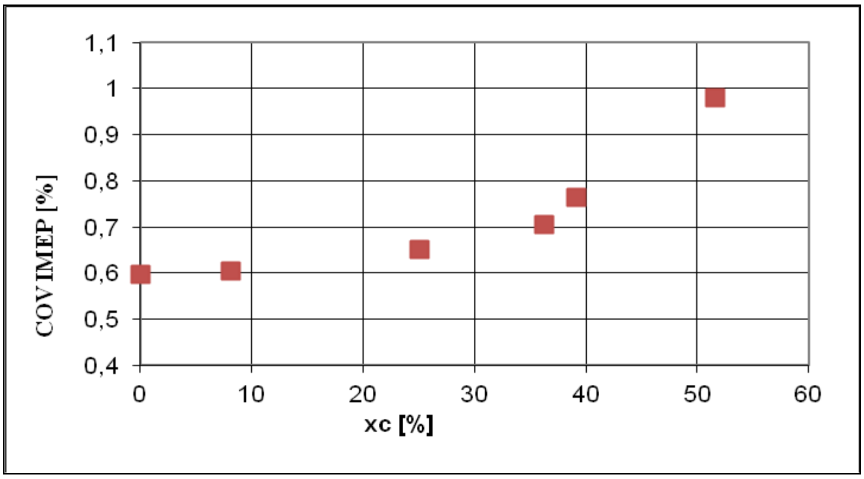

Fig. 4. COV of IMEP for different substitute ratios *xc*

The cyclic dispersion of maximum pressure starts to slightly increase for the substitute ratios of *xc*=25.11,...,51.57 as figure 2 and Fig. 3 show. The variability coefficient of maximum pressure $(\mathrm{COV})_{\mathrm{MP}}$ don’t exceed the value of 2.28 % for maximum *xc*=51.57.

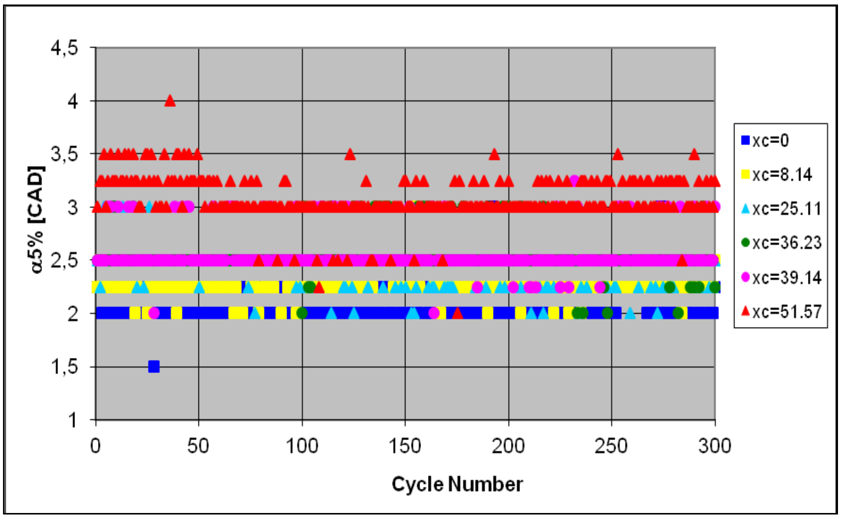

Fig. 5. Angle of 5%-MFB variation at different substitute ratios *xc*

A similar variation tendency for COV of IMEP is registered, Fig. 4. At dual fuelling, the $(COV)_{IMEP}$ rises from 0.59%, for diesel fuel fuelling, up to 0.98% for maximum *xc*=51.57. Even if the admitted value of COV is not exceeded, the increasing tendency of COV's, especially at maximum *xc*, must be taken in consideration.

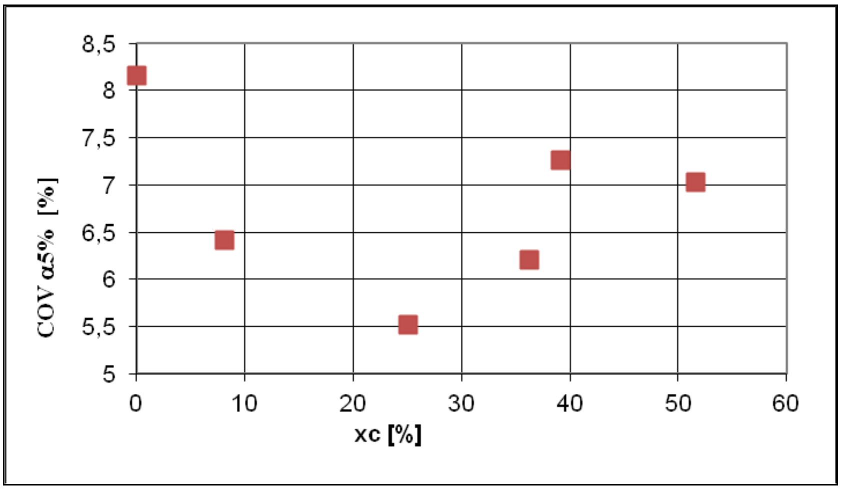

Fig. 6. COV of α5% for different substitute ratios *xc*

The increase of the substitute ratio influences the moments per cycle for angles of 5%, 10%, 50% and 90% of heat release versus TDC (Top Dead Centre). For LPG and diesel fuel fuelling the 5%-MFB occurs later on the cycle comparative to classic fuelling, as general tendency, Fig. 5.

The heat release early phase is achieved much later on the operating cycle, for all *xc*, but the cyclic dispersion between the angles values of 5%-MFB is slightly reduced by the increase of *xc*, from 8.16% (*xc*=0) to 7.02% (*xc*=51.57), figure 6. In some individual cycles, the 5%-MFB for dual fuelling is reached in the same angles intervals as classic fuelling.

For 10%-MFB a similar general variation tendency of a later $\alpha_{10\%}$ angle versus TDC at substitute ratio increase is registered, Fig. 7.

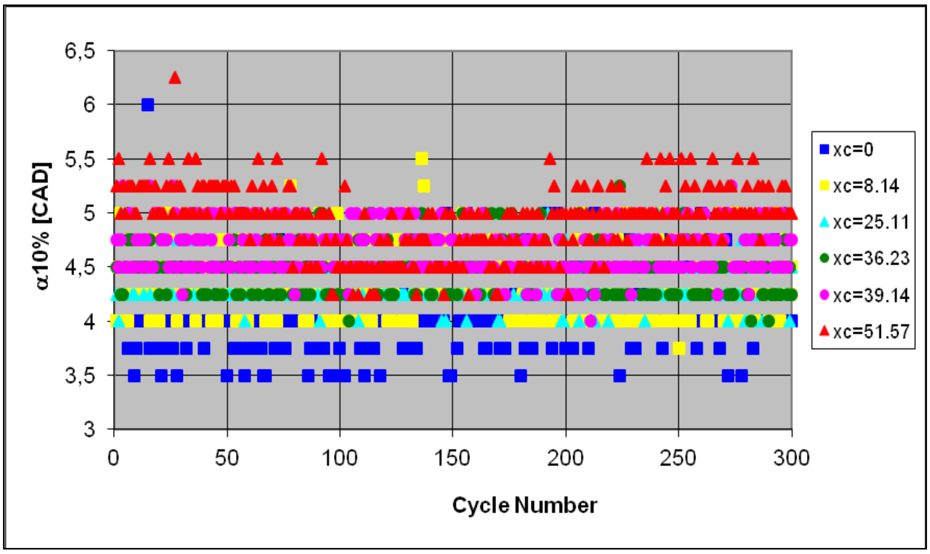

Fig. 7. Angle of 10%-MFB variation at different substitute ratios *xc*

In some individual cycles, the 10%-MFB for dual fuelling is reached in the same angles intervals as classic fuelling or even sooner per cycle comparative to diesel fuel fuelling.

The decrease of diesel fuel cycle dose, once with the rise of LPG quantity, leads to a later cycle achievement of 5%-MFB and 10%-MFB.

Also, in this case the cyclic dispersion between this values is decreased at the rise of *xc*, the $(COV)_{\alpha 10\%}$ decreases from 8.7% (*xc*=0) to 6.46% at maximum *xc*, figure 8.

For *xc*=39.14,...,51.57, the heat release is boosted due to the increase of combustion rate of homogeneous air and LPG mixture once with the *xc* rise, a sooner achievement per cycle of 50% and 90% fractions of heat release being registered. Thus, the angles of 50%-MFB and 90%-MFB start to get closer to

TDC at the rise of substitute ratio, Figs. 9 and 11, in correlation with the rise of maximum pressure, Fig. 2.

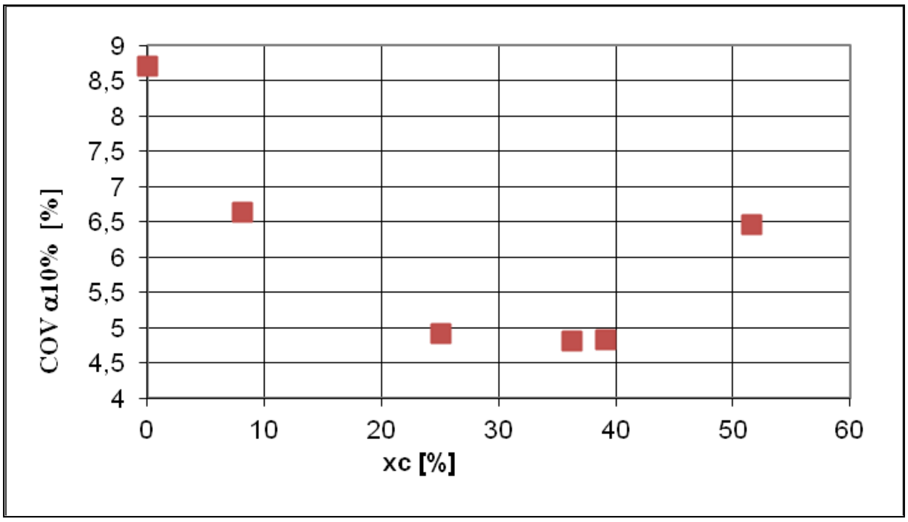

Fig. 8. COV of α10% for different substitute ratios *xc*

The increasing tendency of combustion variability which appears for *xc*=39.14,...,51.57 is also reflected in the dispersion of the α_{50} and α_{90} angles.

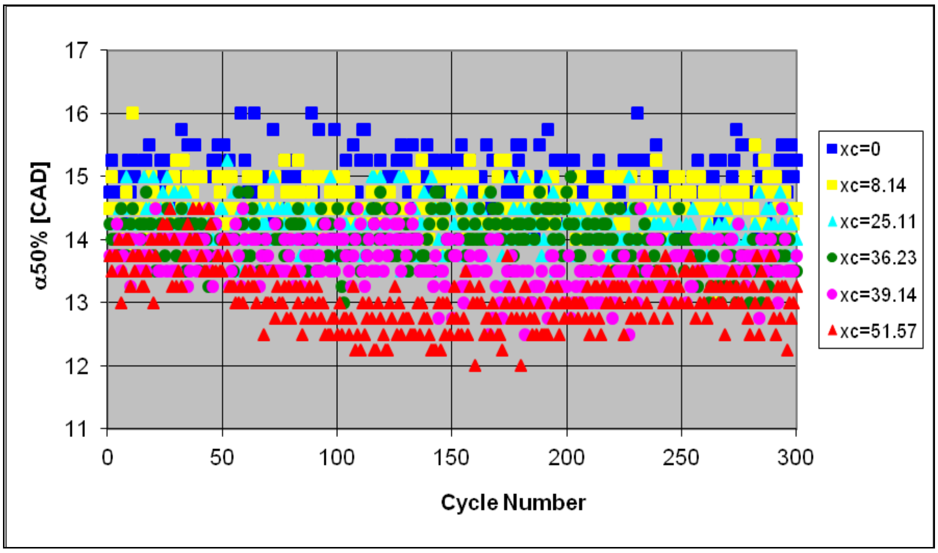

Fig. 9. Angle of 50%-MFB variation at different substitute ratios *xc*

The presence inside the engine cylinder of a very lean mixture of air and LPG before combustion starts influences the combustion process, which is defined by a raised variability of the angle of 50% and 90% of mass fraction burned, comparative to diesel fuelling.

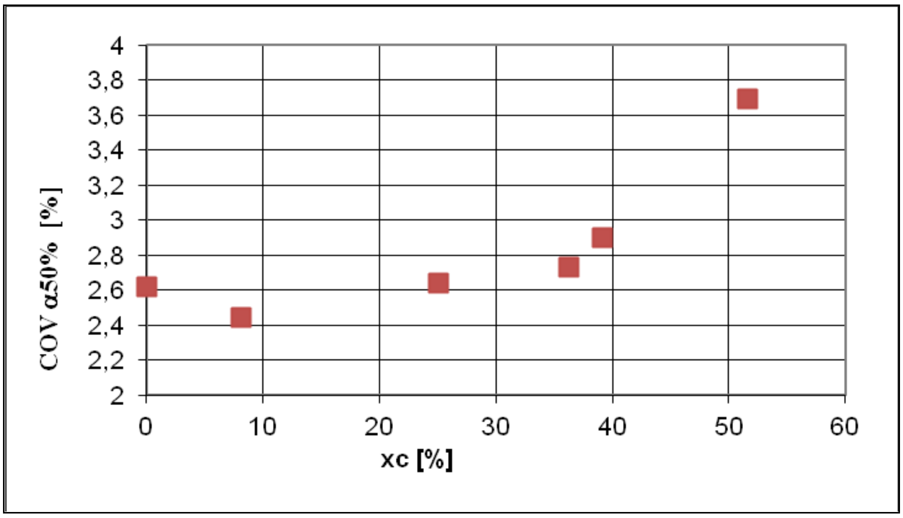

Fig. 10. COV of α50% for different substitute ratio *xc*

The values of COV$\alpha_{50\%}$ and COV$\alpha_{90\%}$ start to increase for *xc*=36.23,…,51.57, but don’t exceed 10%, Fig. 10 and Fig. 14.

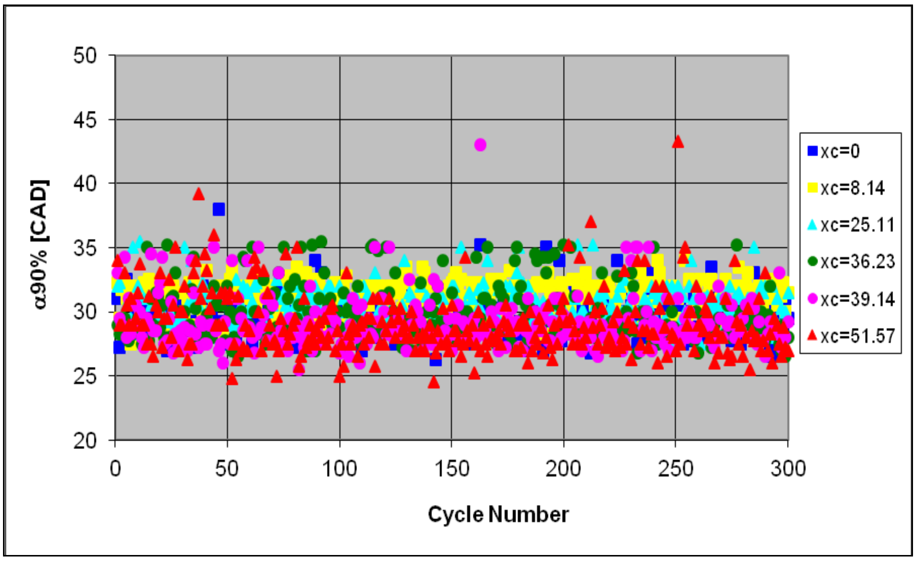

Fig. 11. Angle of 90%-MFB variation at different substitute ratios *xc*

The (COV)$\alpha_{50\%}$ rises from 2.61% (*xc*=0) to 3.69% (*xc*=51.57), Fig. 10, and (COV)$\alpha_{90\%}$ increases from 5.04% to 9.58% at maximum *xc*, as Fig. 12 shows.

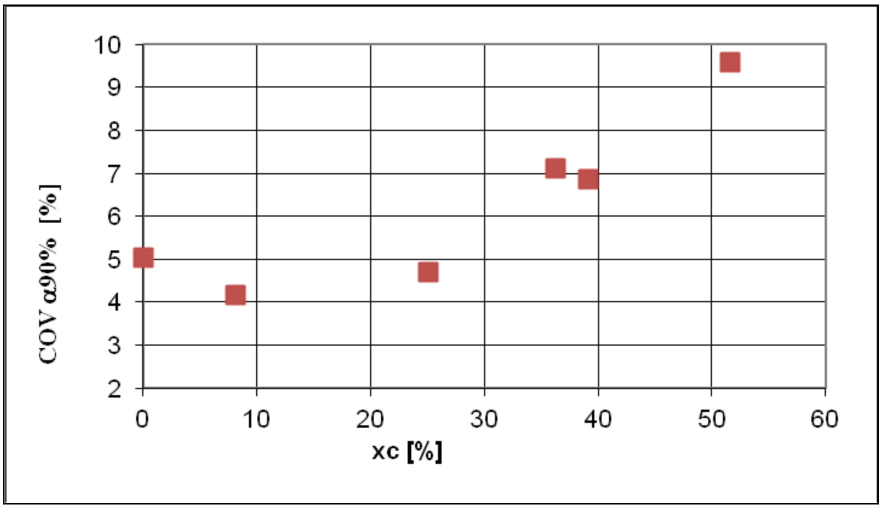

Fig. 12. COV of α90% for different substitute ratio *xc*

The general tendency of the combustion variability increase at LPG use is reflected by the values of COV for MP, IMEP, 50%-MFB and 90%-MFB which are increased by the rise of LPG dose, but without exceeding the acceptable limit value of 10%. In order to assure the normal dive-ability of the automotive diesel engine at dual fuelling the maximum substitute ratio is limited to *xc*=51.57. A similar tendency in engine operation at LPG fuelling appears also at others operating regimes that were previously investigated. At full load for 2000 and 4000 min^{-1} speeds regimes the maximum pressure and the COV values for maximum pressure, indicated mean effective pressure and mass fraction burned tend to rise with the increase of LPG inlet quantity [17]. This issue leads to the limitation of *xc* at 9.25% for 2000 min^{-1} and at 40% for 4000 min^{-1} [17]. Also, at high partial load of 85% and 2000 min^{-1} the rise of maximum pressure is observed and the COV for maximum pressure and mass fraction burned starts to rise once with the increase of LPG dose, the *xc* being limited to 28% [18], [19]. Thus, engine operating regimes defined by small engine loads and high speeds allow larger LPG quantities comparative to other operating regimes, the diesel fuel substitution being increased. If the reduction of the combustion cyclic variability is related with reduction of $\Delta\alpha_{10\text{-}90\%}$ combustion duration [9], the increase tendency of the combustion cyclic variability is also in correlation with the increase tendency of $\Delta\alpha_{10\text{-}90\%}$ combustion duration, registered for the maximum values from the individual cycles, Fig. 13.

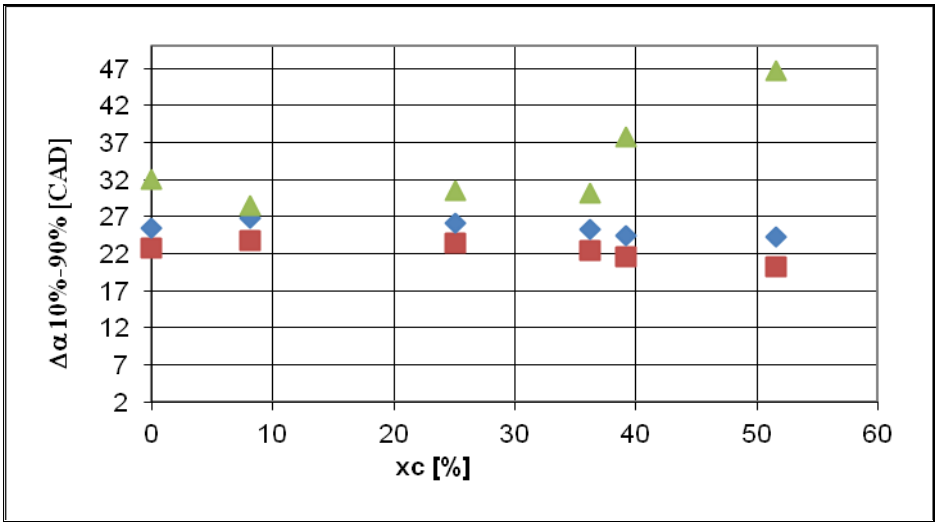

Fig. 13. Variation tendency of the combustion duration $\Delta\alpha_{10\%-90\%}$ for different substitute ratios, *xc* defined for minimum (in red), averaged (in blue) and maximum (in green) values

4. Conclusions

At the investigated operating regime, the LPG-diesel fuel fuelling leads to the rise of maximum pressure and of the COV values calculated for maximum pressure and indicated mean effective pressure, but the values remain in the normal range area. The COV of maximum pressure rises from 1.42% (standard fuelling) to 2.28% at maximum LPG dose. The COV of indicated mean effective pressure increases from 0.59% (*xc*=0) to 0.98% for dual fuelling and maximum *xc*=51.57. The 50% and 90% of heat release are achieved sooner on combustion cycle (angle of 50%-MFB and 90%-MFB are decreased) aspect which is related rising tendency of maximum pressure for *xc*=51.57. The increased variability of angles α_{50} for 50%-MFB, in the premixed combustion phase, leads to the rise of variability of the indicated mean effective pressure $(COV)_{IMEP}$ and maximum pressure $(COV)_{MP}$. The COV values for maximum pressure, IMEP and angles of 5%, 10%, 50% and 90% MFB don’t exceed the acceptable limit of 10%, showing that the normal operation of the LPG-diesel fuel diesel engine can be assured. The results presented in the paper contribute to the completion of the data’s needed for efficient use of LPG at the automotive diesel engine.

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