Effects of CNG quantity on combustion characteristics and emissions of a dual fuelled automotive diesel engine

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Abstract. The paper reveals some experimental aspects of compressed natural gas (CNG) use in dual fuel mode at an automotive diesel engine. Brake specific energetic consumption, in-cylinder pressure, emissions and variability of indicated mean effective pressure are analysed at operating regime of 2000 rpm and 40% load. Using CNG as an alternative fuel reduces brake specific energetic consumption by 50%, the CO_2 emission by 10% and sets the in-cylinder maximum pressure 13 bar higher comparative to diesel fuel fuelling. The smoke and hydrocarbons emissions and the variability of indicated mean effective pressure are affected by the injection of compressed natural gas into intake manifold: HC emission grows 24 times, the smoke number and the coefficient of variability of IMEP double their values. The use of compressed natural gas at an automotive diesel engine improves its energetic performances and combustion process, having positive effects on CO_2emission and fuel consumption.

Keywords: diesel engine, CNG, combustion, diesel-gas, dual-fuel, COV, IMEP, BSEC.

1. Introduction

The automotive industry experiences nowadays a tremendous pressure as the more aware society demands reduction of emission that have a negative effect on climate safety and on the health of population. Restrictions on CO_2, NO_x, HC and smoke emissions are more and more severe, lots of publications showing the negative effect of diesel emission on humans' health [1, 2, 3]. In this context the diesel engine loses a lot of ground because

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of its high smoke and NO_x emissions level. Even though there exist optimistic opinions about electric propulsion (50% percent for passenger cars by 2040 [4]) and there are ways to facilitate the transition from internal combustion engines to full electric propulsion (mild and full hybridization), the pollution actual issues impulse the engineers to find solutions that could be applied very fast and with real improvements on the current or next generation of diesel engines. Two main directions are taken into consideration related to internal combustion engines: development of more efficient internal combustion engine that have better aftertreatment systems and development of technologies for cleaner alternative fuel use. Due to the higher efficiency of diesel engine comparative to spark ignition engine, researcher all over the world try to reduce its emissions by fuelling it with clean alternative fuels (LPG, LNG, CNG, animal fat, biogas, butanol). The most common technology for use of alternative fuels is the dual-fuel mode when the alternative fuel is injected into the intake manifold [5]; this offers the main advantage of less engine design modification and so the procedure can be applied to the in-use engines. The compressed natural gas (CNG) is an alternative fuel used in the transport industry due to its important features: low carbon content (1 kg of CNG contains 750 g of carbon as opposite to diesel fuel that has over 870g of carbon), lower heating value (49 MJ/kg) and high octane number (130) [6]. There are many studies that reveal diesel engine operation when it is fuelled in dual fuel mode with compressed natural gas. Basavarajappa [7] states that the electronically controlled injection of compressed natural gas has the best results in combustion and gave as optimum an injection timing of 5°before TDC and injection duration 60°CA. Egúsquiza [8] presents better energetic performances and lower emission of a supercharged diesel engine fuelled with compressed natural gas. Imran shows that the NO_x emission level is 53% less for all range of substitution and at all engine loads; the CO_2 emission decreases by 25% at all engine loads due to the lower carbon content of the CNG; the HC emission increases 8 times at medium load and with 25% at high load [9]. Yousefi presents a 32% growth of in-cylinder maximum pressure and lower levels of NO_x at highest substitution ratio; the CO emission rises because of the lack of oxygen as opposite to the conventional fuelling [10]. Mahla [11] presents improvements of the brake thermal efficiency, hydrocarbons and nitrous oxides emissions levels and negative effects on the ignition delay, in-cylinder pressure, smoke and CO emissions levels when using exhaust gases recirculation at a diesel engine fuelled with CNG.

This paper comes in accordance with specialty literature studies mentioned above and has as objective the study of combustion at CNG use at an automotive diesel engine, focusing on in-cylinder pressure, brake specific energetic consumption, emissions level of carbon dioxide, nitrous oxides, smoke, hydrocarbons and cyclic variability of indicated mean effective pressure (IMEP).

2. Research methodology

Figure 1 present the design of the experimental test bed which use a K9K diesel engine (1), designed for Dacia Logan, which is equipped with a CNG fuelling system which incorporates a CNG injector (11) connected to the inlet manifold, flame arrestor (10), mass flow meter for gaseous fuels (9),pressure regulator (8) and CNG reservoir (7) pressurised at 220 bar. The steel pressure tank is tested at pressure around 300 bar. The CNG reducer releases CNG at fueling pressure (2.5 – 3 bar) after two stages of reduction (first stage is at 10 bar). The CNG injector is controlled with an open electronic control unit (ECU) (12). By this ECU the operator has access to the operating parameters (CNG quantity and injection timing) of the fuelling system by using computer (13). The conventional fuelling system is compounded of diesel fuel tank (3), liquid mass flow meter (4), low/high pressure pump system (5) and common rail and injectors (6). The inlet air quantity admitted into the cylinders is measured by volumetric flow meter (14). The engine is loaded by an eddy current dyno (2); the accelerator pedal (20) is actuated by a step-by-step controller (19) driven by electronic unit (18). In-cylinder pressure is measured by a piezoelectric transducer (21); the in-cylinder pressure can be observed on oscilloscope`s (17) screen; the in-cylinder pressure data is stored on computer (16). Emissions level from the exhaust gases are measured with a gas analyser – opacimeter system (15).

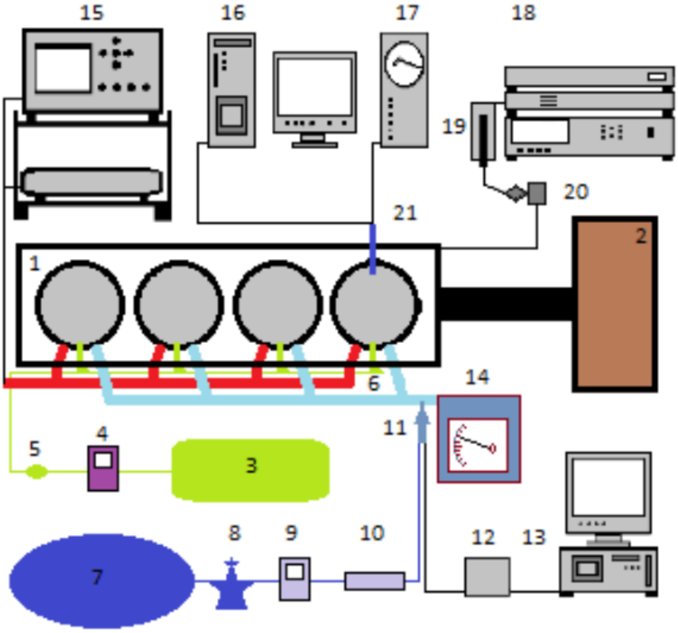

Fig. 1. The research test bed

The paper's objective is to demonstrate that the use of CNG as an alternative fuel at an automotive diesel engine at low loads, determines improvements in fuel performances and emission exhaust.

At the investigated operating regime, 40% engine load and 2000 rev/min, diesel fuel and CNG quantities, volume and temperature of air admitted into the cylinder, the emissions levels for NO_x, CO_2, hydrocarbons and smoke, temperatures of exhaust gases, and 200 in-cylinder pressure diagrams of consecutive combustion cycles had been recorded. Also, temperature in certain points on intake and exhaust manifolds and of cooling liquid have been recorded; atmospheric pressure and temperature were also monitored. All measurement equipment was previously calibrated and before the official experimental investigation the engine ran until it reached the optimal values of the operating parameters. During entire investigating procedure the GNC injection timing was kept constant for all energetic substitution ratios.

During the entire experimental investigation procedure there were several main activities developed:

- engine fuelled only with diesel fuel was set to regime of 2000 rpm and 40% load.
- the diesel fuel quantity was reduced.
- the CNG was injected until the engine power was re-established at the reference.

A set of parameters has been calculated:

-the brake specific energetic consumption (BSEC) [12] in kJ/(kWh) is:

$$BSEC = (C_{hCNG} * LHV_{CNG} + C_{hDiesel} * LHV_{Diesel}) / P_e \quad (1)$$

-the energetic substitution ratio (x_c) is:

$$x_c = (C_{hCNG} * LHV_{CNG}) / (C_{hCNG} * LHV_{CNG} + C_{hDiesel} * LHV_{Diesel}) * 100 \quad (2)$$

where $C_{hCNG/diesel}$ is CNG/diesel consumption, in kg/h, and $LHV_{CNG/diesel}$ is lower heating value for CNG/diesel in kJ/Kg.

The effective power [13] is:

$$P_e = M_e * (\pi * n) / 30 \quad (3)$$

where M_e is the effective torque measured in Nm, n is engine speed in rev/min.

Indicated mean effective pressure (IMEP) represents the indicated mechanical work divided by total displacement of engine and it represents a criterion to evaluate the capability of the engine to convert heat into mechanical work. The IMEP it is calculated using the analytic formula:

$$imep = n * \{\sum_0^{720} [p_i * (V_{(i+1)} - V_i)]\} / Vt \quad (4)$$

where n represents the number of engine's cylinders, i is the position of crankshaft in °CA, p_i/V_i represents the in-cylinder pressure/volume at certain crankshaft position measured in bar/cubic centimetres and V_t total engine's displacement in cubic centimetres.

The coefficient of variability [14]is used to determine the degree of variation for the interest parameters and it is calculated using the formula:

$$COV = \sigma_x / x_{avg} * 100 \quad (5)$$

where σ_x represents the standard deviation and x_{avg} is the average value of all elements belonging to the analysed set.

The standard deviation is calculated using the formula:

$$\sigma_x = (\sum_{i=1}^{n} (x_i - x_{avg})^2 / n)^{½} \quad \mathbf{(6)}$$

where n is the number of elements in the series, $x_i$represents a specific element of the series and x_{avg} is the average value of all elements belonging to the analyzed series.

3. Results

The most important aspect of this work was to determine the maximum quantity per cycle of CNG that can be injected. For all energetic substitution ratios, the influence of CNG dose on the in-cylinder maximum pressure are presented, figure 2. The maximum pressure p_{max} rises with16 bars at highest energetic substitution ratio.

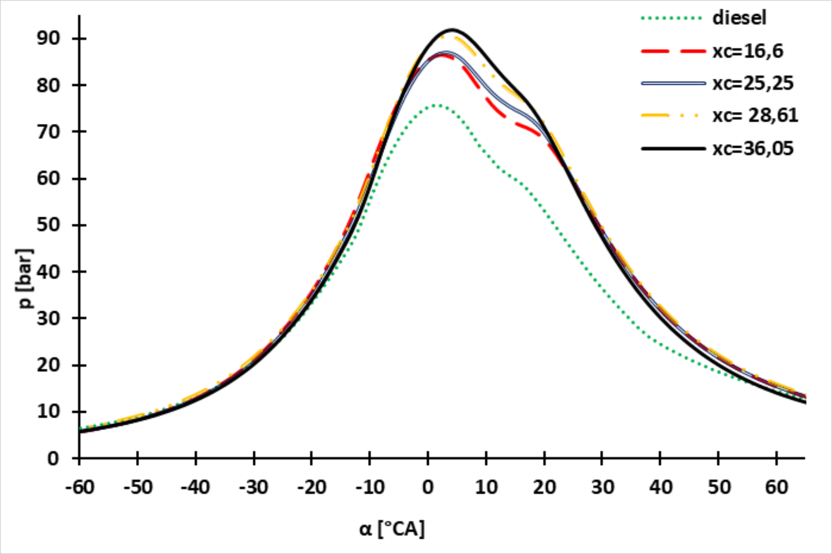

Fig. 2. In-cylinder pressure as function of crankshaft position for different energetic substitution ratios.

As seen in figure 2 and 3 the in-cylinder maximum pressure rises with over 20% at highest energetic substitution ratio. A very important aspect to be highlighted is that the highest in-cylinder pressure attained in the conventional fuelling mode –76 bar – is reached 10 °CA sooner in dual fuel mode and it also lasts for 12 times longer at highest energetic substitution ratio. In standard fuelling mode the pressure peak of 76 bar is recorded for 2 °CA as in dual fuel mode at highest x_c, equal or higher pressure is recorder for 24 °CA. This may have a great impact on NO_x emission level, figure 6, as it determines higher in-cylinder temperature for longer periods. Higher in-cylinder pressure are determined by two very important factor: the lower heating value of CNG is 17% higher than that of diesel fuel; the charge in dual fuel mode has a greater percentage of fuel in gaseous state and this means that the heat used to vaporize the fuel is lower comparative to classic fuelling.

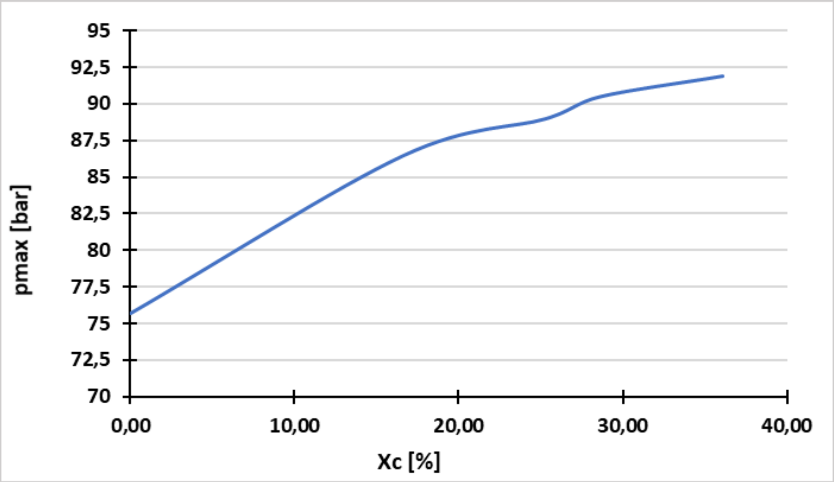

Fig. 3. In-cylinder maximum pressure as function of energetic substitution ratio

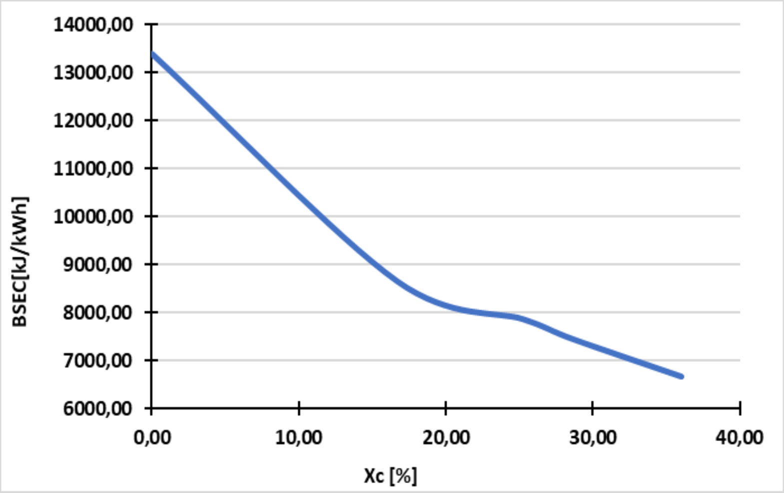

Fig. 4. Break specific energetic consumption as function of energetic substitution ratio

The lower heating value of compressed natural gas (48 MJ/kg) is higher than that of diesel fuel (41,7 MJ/kg). This added to the gaseous state of the alternative fuel determines a drop of the specific energetic consumption (BSEC). At highest energetic substitution ratio BSEC drops by 50% comparative to classic fuelling.

Compressed natural gas has 75% to 77% carbon content and diesel fuel has a content of 82% to 87 % in carbon, fact related to a lower CO_2 emission level in dual-fuel mode. At highest energetic substitution ratio, the carbon dioxide drops by 10%, as figure 5 shows.

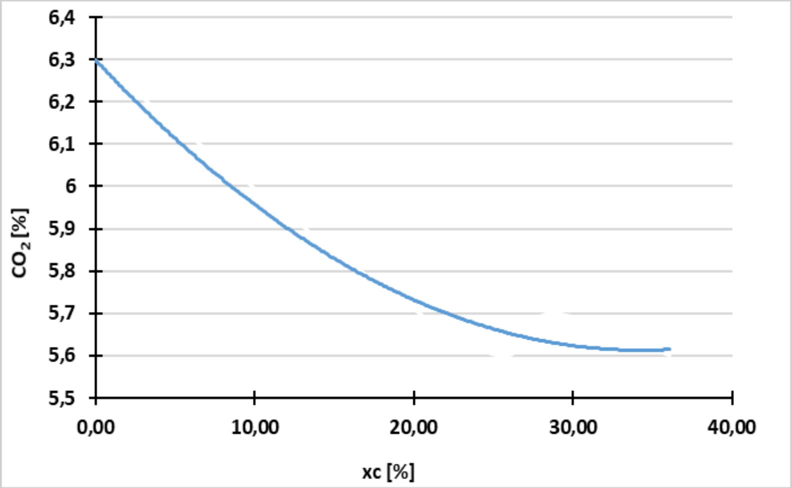

Fig. 5. Carbon dioxide emission as function of energetic substitution ratio

Also, the reduction of the BSEC, figure 4, leads to the reduction of the CO_2 emission level, figure 5.

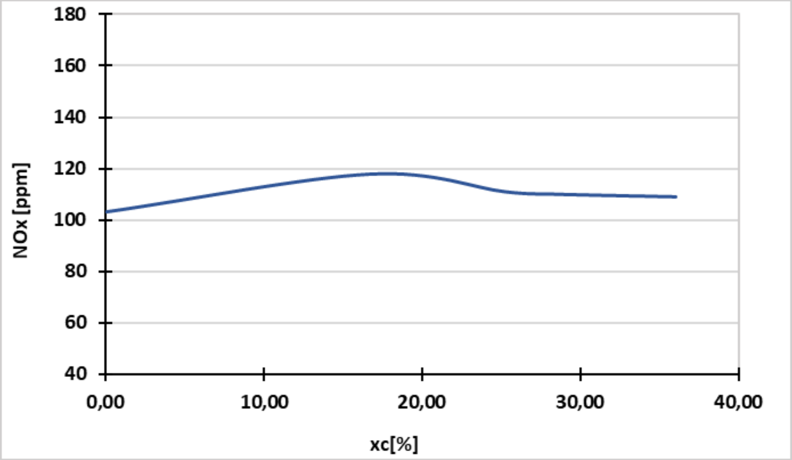

Fig. 6. Nitrous oxides emission as function of energetic substitution ratio

Nitrous oxides are formed through Zeldovich mechanism [13] favoured by in-cylinder high temperature, amount of oxygen and the time spent by nitrogen close to oxygen molecules. At medium engine loads the NO_x is very little influenced by injection of compressed natural gas into the intake manifold. Two out of the three factors mentioned earlier are influenced by CNG injection: higher temperature inside cylinder (the in-cylinder much higher pressure for longer periods and the higher percentage of gaseous premixed fuel determine a higher in-cylinder temperature) determines a growth of the NO_x emissions level. Less oxygen available per cycle (a percentage of air admitted into cylinder in conventional fuelling mode, is replaced by compressed natural gas – in dual-fuel operating mode - determining a lower quantity of oxygen) favours lower NO_x emissions. The two aspects mentioned in this paragraph have opposite effects over NO_x emission and it grows with less than 20 parts per million at highest energetic substitution ratio, the influence of temperature being more significant.

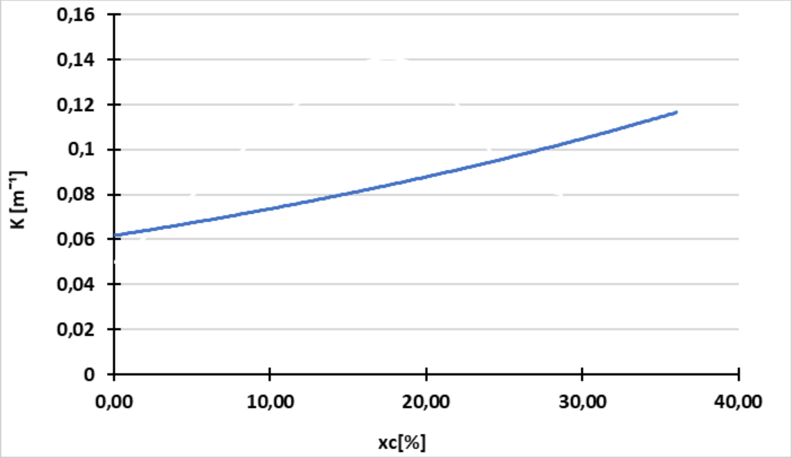

Fig. 7. Smoke number as function of energetic substitution ratio

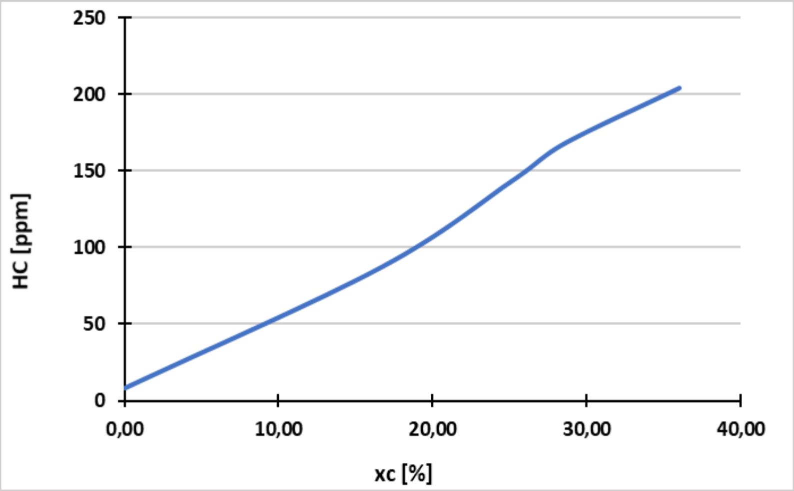

Fig. 8. Hydrocarbons emission as function of energetic substitution ratio

At medium loads, at maximum x_c the smoke number, figure 7, doubles its value at CNG use comparative to classic fuelling. At high temperatures with low intensity of in-cylinder turbulences and in absence of oxygen–determined by the percentage of air replaced by GNC – the hydrocarbons molecules lose the hydrogen atoms (dehydrogenate) and form particle matter that groups in smoke flakes.

Lack of oxygen, flame quenching at cold cylinder wall or in volume of inert gases and gaseous fuel trapped in crevices (piston top land, fire ring and cylinder wall)represent main reasons for the growth of hydrocarbons emission (figure 8). The HC emission at highest energetic substitution ratio is 24 times higher than that of engine running in conventional mode. Also, the reduction of inlet air quantity at CNG use that leads to the increase of smoke emission influences the HC emission level.

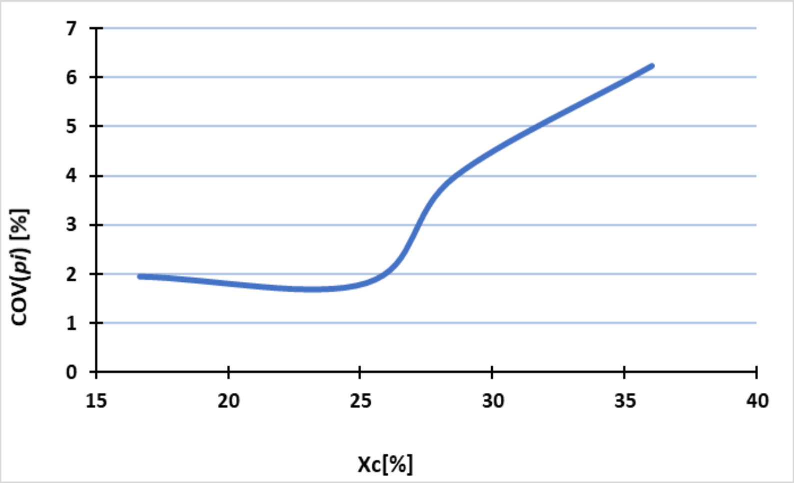

Fig. 9. COV of indicated mean effective pressure as function of energetic substitution ratio

The variation of $(COV)_{IMEP}$ reflects a reduced influence of CNG quantity on cycle to cycle variation of the combustion process, for xc=0% … 25% (figure 9). After this value of energetic substitution ratio, the stability of IMEP is affected, the $(COV)_{IMEP}$ for maximum xc being 3 times higher comparative to $(COV)_{IMEP}$ of xc=0, the irreproducibility of the combustion phase from cycle to cycle being influenced by large CNG doses. The rise of the $(COV)_{IMEP}$ at the increase of CNG cyclic dose is related with the decrease of the inlet air quantity. The maximum value of $(COV)_{IMEP}$ is under 10%, the normal running of the engine being assured at dual fuelling, [13].

The rise tendency registered for HC and smoke emissions levels and for $(COV)_{IMEP}$ may represents a criterion for limitation of the CNG used quantity at xc=36%.

4. Conclusions

The results obtained during the experimental investigation of CNG use to fuel an automotive diesel engine at the regime of 2000 rev/min and40%load allow the formulation of the following conclusions:

- the in-cylinder maximum pressure rises from 76 bar, in conventional fuelling mode, to 92 bar in dual fuel mode;
- CNG gaseous state and a higher heating value determines a 50% reduction in terms of brake specific energetic consumption at highest x_c comparative to efficiency registered for the engine fuelled in conventional mode;
- at the highest energetic substitution ratio, the carbon dioxide emission level is with 10% lower comparative to standard mode, due to a lower carbon content in compressed natural gas;
- the NO_x emission level is affected by the increased pressure and temperature reached during the combustion of the air-CNG mixture, the NO_x emission level slightly increase with 15%; factors like temperature rise and oxygen reduction have opposite effects thus the rise of NO_x emission level is limited;
- the smoke emission level doubles its value as *xc* reaches highest level, mainly due to low quantity of oxygen inside the cylinder;
- the HC emission level grows 24 times when the energetic substitution ratio is at 36%, because of the gaseous fuel trap inside crevices and reduction of inlet air;
- for xc=0…25% the combustion stability is assured, but for xc>25% the COV of IMEP rises from 2% (at only diesel fuel fuelling) to 6.3% at CNG-diesel fuel use at maximum xc, because of a more significant reduction of inlet air quantity at rise of CNG at the maximum value. However, the engine operates normally at dual fuelling since COV of IMEP doesn't exceed 10%.

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