Experimental investigations of an automotive diesel engine fuelled with natural gas in dual fuel mode

S Rotaru¹, C Pana¹, N Negurescu¹, Al Cernat¹, D Fluiorescu¹, Cr N Nutu²

¹Thermotechnics, Engines, Thermical and Frigorific Equipment Department, University Politehnica of Bucharest, Bucharest, Romania
²Automotive Engineering Department, University Politehnica of Bucharest, Bucharest, Romania

E-mail: silviu_r.rotaru@yahoo.com

Abstract. The compressed natural gas (CNG) is a viable alternative fuel for diesel engine use due to its good combustion properties and low carbon content. The general objective of the research is CNG use at the automotive diesel engine for improving of the energetic performance and decrease of the emissions level. By achieving these specific objectives, the paper brings an important contribution to solving pollution problems in large urban areas for diesel engines, the solution can be easily implemented on diesel engines in running, even on the old design which can be converted to fit the current rules of pollution. All investigations were conducted at engine operating regime of 55% load and 2000 rev/min. Following the analysis of all recorded data the proper quantity of CNG will be determined in order to have lower emissions level and better energetic performances. The specific energetic consumption is expected to decrease with more than 40%; at the highest substitution ratio the maximum in-cylinder pressure reaches values superior with more than 10% and the maximum pressure rise rate with over 20%; CO₂ emission reaches 10% lower level. The CNG use at automotive diesel engine leads to the improvement of combustion process and engine energetic performance.

1. Introduction

International awareness regarding pollution, pollution factors and action to be taken in order to improve environment wellbeing become nowadays some of the most important subjects for everyone regardless of age; the September 2019 IPSOS survey brings climate change worries on 8th place representing 16% of 19,511 interviewed people, [1]. Furthermore, this issue is the first among young generation (less than 30 years old), [2]. Same studies show that as important as climate change is the healthcare issue, especially pollution caused health problems; numerous studies are performed to assess the impact of internal combustion engine`s exhaust gases, [3],[4],[5] on health of people that live or work in industrialized or urban areas. As a result of this awareness, Governments from all over the word impose more sever rules for transport propulsion, [6],[7] and create opportunities for people to adopt more cleaner ways of transportation. To attain very accurate data of vehicle emissions, authorities put in place testing procedures and developed testing instrument, [8]. Real Driving Emission (RDE) has become the main European standard to evaluate vehicles emissions. PEMS (Portable Emissions Measurement System) is an instrument build especially developed for RDE tests.

The continuously changing reality puts a tremendous pressure on automotive industry, forcing it to develop more efficient and even brand-new means of propulsion; on the other hand, researchers struggle to find alternative, less pollutant and with greater calorific power fuels. In this context, there...
is a great interest in natural gas use as alternative fuel. Main reasons for choosing compressed natural gas as alternative fuel are: low carbon content (75% C as opposite to diesel fuel 86% C), high octane number (above 115), high lower heating value (above 50 MJ/kg). Also, the ease of obtaining CNG contributes to the level of importance which is given to this alternative fuel. Aklouche, [9] presents a thorough analysis performances and exhaust emission of a diesel engine fuelled with CNG and with biogas; Aklouche, [9] highlights combustion improvement and lower emissions levels at CNG use. Shah, [10] presents improvements recorded in diesel engine’s performance when it is fueled with CNG. Similar results were obtained by Egúsquiza, [11] during the experiments carried on a supercharged diesel engine fuelled with natural gas. Mahla, [12] shows the effect of exhaust gases recirculation system (EGR) use on performance and pollution level at a diesel engine fuelled by natural gas. Mahla, [12] shows that the use of EGR at a diesel engine fuelled with CNG leads to improve of the brake thermal efficiency, NOx and HC emissions levels, but affects the ignition delay, in-cylinder pressure, smoke and CO emissions levels. Jamrozik, [13] studies the operation of a stationary diesel engines fuelled in dual fuel (DF) mode. Jamrozik, [13] shows that the use of CNG leads to the rise of the in-cylinder pressure and pressure rise rate due to acceleration of the combustion. 30%-40% CNG assures a stable running of the diesel engine in dual fuel mode and reduction of the HC emission level. The CO emission level is reduced at CNG use, but when the percent of CNG rise from 0% to 90% the NOx increase, [13]. Karim, [14] presents performance of different diesel engines fueled with different gaseous fuels (like CNG, LPG, hydrogen etc) and shows and analyze the benefits of CNG use versus classic fuel.

The general objective of this research is CNG use at the automotive diesel engine in order to improve the energetic performance and to reduce the emissions level. Thus, the paper brings an important contribution to the issue of pollution produced by diesel engines in large urban areas, the fuelling solution can be easily implemented on diesel engines there are still in running, even on the old design which can be converted to fit the actual rules of pollution.

2. Research methodology

As seen in figure 1 the test bed comprises of: 1 diesel engine, 2 eddy current dyno, 3 diesel fuel tank, 4 diesel fuel suction, 5 mass flowmeter for diesel, 6 high pressure fuel pump, 7 common rail and diesel fuel injectors, 8 CNG tank, 9 manual shutoff valve, 10 two-stages pressure reducer, 11 mass flow meter for CNG, 12 flame arrestor, 13 CNG injector, 14 control unit for CNG, 15 computer (connected to the electronic control unit of the CNG injector), 16 computer (to store data related in-cylinder pressure), 17 oscilloscope, 18 gas analyzer, 19 opacimeter, 20 step by step electric actuator, 21 brake electronic unit controller, 22 accelerator pedal. The 1.5 liters Renault diesel engine was fueled with compressed natural gas and diesel fuel by diesel-gas method.

The specificity of this research setup is the compressed natural gas fueling system; the CNG is stored into a special tank at 200 bars (the tank is tested at pressures above 300 bars); for safety reasons the tank is equipped with a manual shutoff valve; a stainless steel pipe tested at over 250 bars connects the tank to the fuel pressure reducer (a two-stages reducer) that drops the pressure at fueling pressure of 3 bar. The reducer also has an emergency electronic controlled shutoff valve. The compressed natural gas is injected into the intake manifold through set of four injectors controlled by an opened control unit; by this unit the start and the period of injection can be adjusted.

All tests are performed at 55% load and 2000 rev/min operating regime. In order to have a standard set of data, the diesel engine was fueled only with diesel fuel. To assess the impact of CNG usage as an alternative fuel for the diesel engine, sets of data were recorded at different energetic substitution ratios of diesel fuel by CNG. To have very accurate data there have been recorded two hundred consecutive combustion cycles.
The steps that constitute the research procedure are: firstly, the engine was fuelled only with diesel fuel; secondly, the diesel fuel quantity was reduced until the engine’s power was affected; thirdly, was injected the compressed natural gas into the inlet manifold in order establishment the standard engine’s power. Throughout all investigations, data of the following parameters were recorded: in-cylinder pressure, CNG, diesel fuel and air consumption, intake air temperature, atmospheric temperature and pressure, CNG fuelling pressure, engine speed and load, NOx, CO, CO₂, smoke and HC emissions level, exhaust gases temperature, coolant temperature, boost pressure. There is a set of calculated parameters, like: effective power ($P_e$) measured in kW calculated with formula

$$P_e = M_e \frac{\pi n}{30}$$

(1)

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

The energetic substitution ratio ($x_e$) is:

$$x_e = \frac{C_{\text{CNG}} \cdot \text{LHV}_{\text{CNG}}}{C_{\text{CNG}} \cdot \text{LHV}_{\text{CNG}} + C_{\text{Diesel}} \cdot \text{LHV}_{\text{Diesel}}} \times 100$$

(2)

where $C_{\text{CNG/diesel}}$ is CNG/diesel consumption, in kg/h, and $\text{LHV}_{\text{CNG/diesel}}$ is lower heating value for CNG/diesel in kJ/Kg.

The brake specific energetic consumption (BSEC) in kJ/(kWh) is:

$$\text{BSEC} = \frac{C_{\text{CNG}} \cdot \text{LHV}_{\text{CNG}} + C_{\text{Diesel}} \cdot \text{LHV}_{\text{Diesel}}}{P_e}$$

(3)
3. Results

The experimental results are presented in diagrams represented for brake specific energetic consumption (BSEC), in-cylinder pressure (p) and pressure rise rate (dp/d\(\alpha\)), hydrocarbons (HC), nitrogen oxides (NO\(_x\)), carbon dioxide (CO\(_2\)) and smoke emissions (K value).

![BSEC as function of energetic substitution ratio.](image1)

**Figure 2.** BSEC as function of energetic substitution ratio.

The energetic specific consumption drops as the energetic substitution ratio gets higher. As \(x_c\) reaches 35\%, the energetic consumption diminishes with more than 50\% from 11600 kJ/kWh to 5600 kJ/kWh. This drop in energetic consumption is due to the low heating value of CNG that is 15\% higher than that of diesel fuel according to [15]; another factor that determines the lowering of the energetic consumption is the gaseous state of the alternative fuel, thus the heat lost for vaporization of the alternative fuel being eliminated.

![In-cylinder pressure as function of energetic substitution ratio.](image2)

**Figure 3.** In-cylinder pressure as function of energetic substitution ratio.
Studying the p-\(\alpha\) diagram, showed in the figure 3, one can conclude that maximum in-cylinder pressure achieved when engine is fueled only with diesel fuel is 11\% less than to the maximum in-cylinder pressure achieved when the energetic substitution ratio is the highest (fact sustained by figure 4); the fresh charge (air/GNG/diesel) admitted into the cylinder has a higher percentage of vapor phase fuel than in standard fueling mode; there is less heat used by the fuel to pass from liquid to vapor phase so for the same energetic consumption a higher in-cylinder pressure will be reached. The engine fueled in dual-fuel mode reaches with almost 10 \(^{\circ}\)CA in advanced 93 bars; this is the maximum in-cylinder pressure obtained in standard mode operation. In-cylinder pressure drops below this level at 13 \(^{\circ}\)CA later at the highest substitution ratio.

![Figure 4. Maximum pressure as function of energetic substitution ratio.](image)

The maximum in-cylinder pressure is attained very close to 364 \(^{\circ}\)CA, independently of the substitution ratio, this reflecting a higher pressure rise rate.

![Figure 5. Maximum pressure rise rate as function of energetic substitution ratio.](image)
In-cylinder maximum rise rate reaches 4.1 bar/°CA at the highest energetic substitution ratio as opposed to only diesel fueling, where a value of 3.3 bar/°CA is registered. When adding natural compressed gas, the percentage of combustible premixed charge formed during the autoignition delay will grow. This will determine higher pressure rise rate during the rapid phase of combustion and higher maximum in-cylinder pressure comparative to diesel mode, which occurs per cycle around or a little bit before 364°CA, figure 3, figure 4 and figure 5.

![Figure 6. CO₂ emissions as function of energetic substitution ratio.](image)

According to [16], for the same energetic performance of the engine, the carbon emission in the exhaust gases at combustion of diesel fuel is with 37% higher comparative to the case of CNG use. According to [17] diesel fuel has a carbon content of 0.86 (kg_{carbon}/kg_{fuel}) and methane (the main CNG component) has a carbon content of 0.75 kg carbon for each kilogram of fuel. This aspect is in correlation with the fact that the CO₂ emission level drops with 7.2% at the highest substitution ratio, figure 6. This result confirms conclusions found in some studied specialty literature, [9], [13], [14].

![Figure 7. NOx emissions as function of energetic substitution ratio.](image)
Zeldovich mechanism [19] represents the process throughout the nitrous oxides are formed. Three main factors are essential for NO\textsubscript{x} forming: the in-cylinder temperature, the amount of oxygen present into the cylinder and the time spent by the nitrogen close to oxygen molecules. Figure 7 shows that at the studied regime, fueling the engine with compressed natural gas has little impact on NO\textsubscript{x} emission. Even the exhaust gases temperature drops by 36°C and the air-fuel equivalent ratio \( \lambda \) indicates a richer mixture established in-cylinder at the highest substitution ratio. The NO\textsubscript{x} emission level grows with 34 ppm versus classic fueling (which means less than 2% increase). This slightly increase in NO\textsubscript{x} emission level may be correlated with the fact that during the dual fueling the maximum pressure rise (more than 90 bar) for all \( x_c \), figure 3 and figure 4.

![Figure 8. HC emissions as function of energetic substitution ratio.](image)

Also, the combustion duration increase, at the rise of \( x_c \), leads to long periods of time (up to 20°CA) in which higher temperature exist. This aspect may influence the Zeldovich mechanism. Similar results were obtained also by other authors, [13].

When the engine is fueled in dual fuel mode, exhaust gases contains more than 150 ppm of HC at the highest energetic substitution ratio \( x_c \). Similar data were presented in the specialty literature: in [11] is stated that at 69% energetic substitution ratio the HC emission grows with 20200 ppm at low loads, but aspect improves as the engine reaches high loads. Jamrozik, [13] presents a 200% growth in HC emissions level and affirm as primary reason for HC emission rise, the CNG quantity trapped into crevices (piston top-land, piston ring cylinder wall). Heywood, [18] explains the HC emission increase by CNG trapped into crevices and flame quenching in volume. The decrease of the inlet air quantity per cycle at the increase of the CNG intake quantity also affects the HC emission level.

Smoke emission, evaluated by the K value, reaches the lowest value at the energetic substitution ratio of 17%. At this point the smoke number K drops with 16%. When \( x_c \) reaches 25% the smoke emissions is similar to the value registered for the engine fueled only on diesel fuel. At \( x_c=34.45\% \) the smoke emission is with 160% higher comparative to the classic fueling.

The aspect can be related with the fact that at the increase of the CNG quantity injected into the inlet manifold, the air quantity per cycle is decreased, the smoke emission being increased. This issue is in correlation with the increasing tendency of HC emission level.
4. Conclusions

The analysis of the experimental data, at the regime of 2000 rev/min and 55% engine load, registered for dual fuel mode leads to the following main conclusions:

- The BSEC drops by 50% at the highest energetic substitution ratio, from 11600 kJ/kWh to 5600 kJ/kWh. This may be due to a 15% higher heating value of CNG comparative to diesel and the gaseous state of CNG, which will significantly decrease the heat lost during vaporization of the total amount of fuel.

- The maximum pressure attained in standard fueling mode (93 bar) appears in dual fuel mode operation earlier per cycle with 10 °CA; the pressure drops under this pressure 13 °CA later than in conventional fuelling mode. In-cylinder pressure is with 11% higher at the highest energetic substitution ratio, $x_c=34.45%$.

- The pressure rise rate grows with over 24 % at highest energetic substitution ratio mostly due to the greater quantity of premixed fuel which burns during the rapid phase of combustion.

- The CO$_2$ emission drops from 7.5% in diesel mode to 6.9% in dual fuel mode at highest $x_c$, due to the lower carbon content of the compressed natural gas.

- The NO$_x$ emission is little influenced by CNG use, a slightly increase of 2% being registered at maximum energetic substitution rate. This aspect may be correlated with the longer period (22°CA longer) observed for high in-cylinder pressure (above 93 bars) at the highest energetic substitution ratio.

- The HC emission increase at the rise of energetic substitution ration, comparative to classic fueling because at the rise of $x_c$ the inlet air quantity decrease and the quantity of CNG trapped into crevices increase.

- The smoke emission decrease with 16% for average values of $x_c$, but after $x_c=25.4%$ the smoke emission level start to exceeds the value registered for $x_c=0$, at maximum $x_c=34.45%$ the increase being around 160%, because the air quantity per cycle is decreased at the rise of $x_c$.

- The increasing tendency registered for HC and smoke level may represent criteria of limitation of the energetic substitute ratios at the presented values.
5. References

[1] https://www.ipsos.com/sites/default/files/ct/news/documents/2019-11/what-worries-the-world-september-2019.pdf
[2] https://www.amnesty.org/en/latest/news/2019/12/climate-change-ranks-highest-as-vital-issue-of-our-time/
[3] Silverman D T, Samanic C M, Lubin J H, Blair A E, Stewart P A, Vermeulen R, Coble J B, Rothman N, Patricia L, Schleiff P L, Travis W D, Ziegler R G, Wacholder S and Attridge M D 2012 The Diesel Exhaust in Miners Study: A Nested Case – Control Study of Lung Cancer and Diesel Exhaust J Nati Cancer Inst 104 pp 855-868
[4] Seagrave J C, McDonald J D, Bedrick E, Edgerton E S, Gigliotti A P, Jansen J J, Ke L, Naheer L P, Seilkop S K, Zheng M and Mauderly J L 2006 Lung Toxicity of Ambient Particulate Matter from Southeastern U.S. Sites with Different Contributing Sources: Relationships between Composition and Effects Environmental Health Perspectives 114 pp 1387-1393
[5] Schultz E S, Litonjua A A, Melén E 2017 Effects of Long-Term Exposure to Traffic-Related Air Pollution on Lung Function in Children, Curr Allergy Asthma Rep 17 pp 1-17
[6] http://www.mt.ro/web14/documente/acte-normative/2014/6_05/text_proiect.pdf - RNTR1
[7] DVSA Driver & Vehicle Standards Agency 2017 In Service Exhaust Emission Standards for Road Vehicles (Bristol: Executive agency of the Department for Transport- Berkeley House) ISBN 978-1-84864-176-1
[8] https://www.tuvsud.com/en/industries/mobility-and-automotive/automotive-and-oem/automotive-testing-solutions/emissions-and-fuel-efficiency-testing.
[9] Aklouche F Z 2018 Etude caractéristique et développement de la combustion des moteurs Diesel en mode Dual-Fuel : optimisation de l’injection du combustible pilote (France : Thermiqve - Ecole nationale supérieure Mines-Télécom Atlantique)
[10] Shah A, Deshmukh K, Dave N, Darekar S, Chandratre N 2018 Performance Characteristics and Emissions Evaluation of Diesel and Dual Fuel (Diesel and CNG) Engine IJRSET 17 pp 5183-5194
[11] Egúsquiza L C, Braga S L, Braga C V M 2009 Performance and Gaseous Emissions Characteristics of a Natural Gas/Diesel Dual Fuel Turbocharged and Aftercooled Engine J. of the Braz. Soc. of Mech. Sci. & Eng. 31 pp 142-150
[12] Mahla S K, Das L M, Babu M K B 2010 Effect of EGR on Performance and Emission Characteristics of Natural Gas Fuelled Diesel Engine Jordan Journal of Mechanical and Industrial Engineering 4 pp 524 - 528
[13] Jamrozik A, Tukat W and Rogalinski K G 2019 An Experimental Study on the Performance and Emission of the diesel/CNG Dual-Fuel Combustion Mode in a Stationary CI Engine Energies 12 pp1-15
[14] Karim G A 2015 Dual Fuel Diesel Engines (Boca Raton: Taylor & Francis Group - CRC Press) ISSN-13: 978-1-4987-0309-3
[15] https://www.engineeringtoolbox.com/fuels-higher-calorific-values-d_169.html
[16] https://www.eia.gov/tools/faqs/faq.php?id=73&t=11
[17] https://www.engineeringtoolbox.com/co2-emission-fuels-d_1085.html
[18] Heywood J B 1988 Internal combustion engine fundamentals (New York: McGraw-Hill, Inc) ISBN 0-07-028637-X
[19] Selim M Y E 2001 Pressure–time characteristics in diesel engine fueled with natural gas Renewable Energy 22 pp 473–489

Acknowledgements:
This work has been funded by the European Social Fund from the Sectoral Operational Programme Human Capital 2014-2020, through the Financial Agreement with the title "Scholarships for entrepreneurial education among doctoral students and postdoctoral researchers (Be Antreprenor!)", Contract no. 51680/09.07.2019 - SMIS code: 124539.
The authors address special thanks to AVL GmbH Graz Austria for providing the necessary equipment. Gratitude is also presented to Mr. Ovidiu Pavelescu for providing the CNG fuelling system. This work was supported by a grant of the Romanian Ministry of Research and Innovation, CCCDI – UEFISCDI, project number PN-III-P1-1.2-PCCDI-2017-0404 / 31PCCDI/2018, within PNCDI III.