Heliyon 10 (2024) e35010

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Research article

CNG impact on combustion quality of a diesel engine fueled in diesel-gas mode

Silviu Rotaru [a,*], Constantin Pana [a], Niculae Negurescu [a], Alexandru Cernat [b], Cristian Nutu [a], Dinu Fuiorescu [a], Gheorghe Lazaroiu [b]

[a] *National University of Science and Technology Politehnica Bucharest, Department of Thermotechnics, Engines, Thermal and Frigorific Equipment, Romania*

[b] *National University of Science and Technology Politehnica Bucharest, Department of Energy Generation and Use, Romania*

ARTICLE INFO

Keywords:
Diesel engine
DF mode
CNG
Compressed natural gas
Heat release rate
Indicated mean pressure
Emissions

ABSTRACT

The main objective of the paper is to reveal a few aspects related to combustion quality of a diesel engine fueled in diesel-gas mode with diesel fuel and compressed natural gas. The total amount of heat released per cycle will be higher when the engine is fueled in dual-fuel mode due to higher LHV and because of the gaseous state of CNG. For low and medium loads the total quality of heat released per cycle will increase with 10 % and for higher loads it will reach levels with 25 % higher. The heat release rate of the preformed mixture will double its value for low and medium loads and will reach thresholds up to 3.5 times higher (interval −15; −5°CA); admitting CNG into cylinder will help the preformed mixture to reach stoichiometric values and thus improving the fast combustion phase. Fueling the engine in dual fuel mode with diesel fuel and CNG will have a negative effect on the maximum heat release rate; there will be a 10 % drop in maximum HRR for low loads when the energetic substitution coefficient reaches 36 % and 14 % at high loads when the xc is 26 %. The gaseous state and a higher LHV of CNG will have a good impact on indicated mean effective pressure for all studied regimes when the engine is fueled in DG mode: for low and medium loads 30 % and for high loads 20 % increase will be recorded. Gaseous state of CNG will lead to a higher percentage of preformed mixture and thus the fast combustion phase will extend for longer periods for all studied regimes when the engine is fueled in DG mode (20 % longer for low and medium loads and 30 % for high loads). The diffusive combustion phase will become shorter due to a lower quantity of the main dose when CNG is injected into the intake manifold (10–15 % shorter for low loads and 7 % at high loads).

1. Introduction

1.1. International context

The demise of diesel engines started as a phenomenon related to worldwide reality: international research presented the negative

* Corresponding author.
E-mail addresses: silviu_r.rotaru@yahoo.com (S. Rotaru), constantinpana1@gmail.com (C. Pana), niculae_negurescu@yahoo.com (N. Negurescu), cernatalex@yahoo.com (A. Cernat), nikolaoscristian87@gmail.com (C. Nutu), difuiore@yahoo.com (D. Fuiorescu), glazaroiu@yahoo.com (G. Lazaroiu).

https://doi.org/10.1016/j.heliyon.2024.e35010
Received 16 February 2024; Received in revised form 14 July 2024; Accepted 22 July 2024
Available online 23 July 2024

Abbreviations

AVL – **A**nstalt für **V**erbrennungskraftmaschinen **L**ist automotive research institute which fabricates the test bench equipment's
BSFC – brake specific fuel consumption
°C – Celsius degree
°CA – crank angle degree
$C_{hCNG/diesel}$ – hourly consumption of CNG/diesel
CH_4 - methane
CNG – compressed natural gas
CO_2 – carbon dioxide
DF – dual fuel
DG – diesel–gas
$(dp/d\alpha)_{max}$ maximum pressure rise rate
dQ/dα heat release rate
HC – unburned hydrocarbons
H_i – lower heating value
HRR – heat release rate
ICE – internal combustion engine
imep – indicated mean effective pressure
L – real air quantity currently used for combustion
L_t – theoretical necessary air needed to burn the entire fuel used per cycle
LHV – lower heating value
MFB – mass fraction burned
NO_x – nitrous oxides
p in-cylinder pressure
P_e – engine effective power
p_{max} – in-cylinder peak pressure
PM - particle
ppm parts per million
Q – heat release characteristic
Q_{avl} – available heat per cycle
V_{cil_i} – cylinder volume coresponding to the crankshaft position angle
V_s – cylinder diplacement
x_c – diesel fuel substitute ratio with CNG, % energetic
α crankshaft angular position
ʎ - air excess ratio
ρ_{air} air density

impact that diesel emissions had on the health of people who live or work in urban areas [1–3]. To answer to this situation European governments, promote more strict laws to cut down both vehicle and stationary engines emissions; more sever testing procedures and performant testing equipment are developed to have more accurate data (eq: Real Driving Emission test realized with PEMS - portable emission measurement system). In this global reality, scientists are analyzing the possibility to improve combustion and the post-treatment system and to find alternative fuels less pollutant than diesel and gasoline, [4,5]. CNG (compressed natural gas) represents a viable solution for fueling diesel engines in dual fuel mode not only because it is easily reachable but also for its low price, the possibility that one can fuel the vehicle in households and for its physical and chemical proprieties that make it a clean alternative solution as compared to the conventional fuels (gasoline and diesel fuel).

The worldwide increasing attention to reduce diesel engine emissions and the need to discover alternative and more clean fuels bring compressed natural gas to scientists' attention. As compared to a conventional diesel engine, in DF (dual fuel) fueling mode the data show an important drop in CO_2 (consequence of lower carbon content of CNG) emission, smoke and nitrogen oxides. On the other hand, hydrocarbons and CO emissions growth is recorded for certain engine operating regimes. Also, when the diesel engine is fueled in DF mode with CNG and diesel fuel, higher in-cylinder pressure, pressure rise rate, mean indicated pressure, power and torque are recorded; brake specific energetic consumption is also recorded to be significantly lower when the diesel engine is fueled in DF mode due to lower heating value (48.6 MJ/kg as opposite to 41.7 MJ/kg of diesel fuel) and gaseous state of CNG. Diesel engines fueled in DF mode with diesel and compressed natural gas are intensively studied [6–11]; Aklouche [12] presents a synthesis of the benefits that diesel engine fueled in DF mode has when it uses as alternative fuel CNG or biogas; Egúsquiza [13], shows operating differences of a supercharged diesel engine when it is fueled both in standard and DF fueling modes. Mahla [14] shows that the negative impact of CNG on HC (hydrocarbons emission) can be reduced when using an EGR (exhaust gas recirculation) system properly calibrated for DF

Table 1
Compressed natural gas composition [17].

Chemical element	Proportion (vol%)
Methane	87.0–96.0
Ethane	1.8–5.1
Propane	0.2–2.5
Isobutane	0.01–0.3
N-Butane	0.01–0.3
Isopentane	0.01–0.14
N-Pentane	0.01–0.14
Hexane	0.01–0.06
Nitrogen	1.3–5.6
Carbon dioxide	0.1–1.1
Oxygen	0.01–01
Hydrogen	0.02

Table 2
Physical and chemical properties of CNG and diesel fuel [18].

Proprieties	CNG	Diesel fuel
Lower heating value [MJ/kg]	48.6	42.5
Lower heating value of stoichiometric mixture air-fuel [MJ/kg]	2.67	2.79
Cetane number	–	52.1
Octane number	130	–
Autoignition temperature [°C]	650	180–220
Theoretical air for complete fuel combustion	17.2	14.3
Carbon content [%]	75	87
Molar mass [kg/kmol]	17.8	170–198
Density [kg/m3]	0.65	820–860
Boiling temperature [°C]	−161.5	190–280
Specific heat [kJ/(kg*K)] cp/cv	2.3/1.8	2.05/1.75
Ignition limit [%(v)gas in air] LI−/−LS	5−/−15	0.6−/−7.0

fueling mode. The behavior of a stationary engine fueled in DF mode is analyzed by Jamrozi [15]; M Mbarawa [16] show the influences that CNG has on autoignition delay and exhaust gases temperature when the engine is fueled in DF mode.

1.2. Comparison between CNG and diesel fuel proprieties and brief display of CNG's influences on engine's performances and emissions when it is fueled in DF mode

As it can be observed in Table 1, the main element of CNG is methane; this is the reason why physical, chemical proprieties and influences on combustion of compressed natural gas are similar to those of CH_4.

Table 2 depicts the differences between GNC and diesel fuel; presetting the test bed based on this datasheet is essential for good experimental investigation data acquisition.

Lower heating value and the gaseous state of CNG will have a positive impact on brake specific energetic consumption, Table 2.

The high-octane number of compressed natural gas will give it strong knock resistant features and will make the alternative fuel suited for combustion in high compression engines, Table 2.

Because of the high auto ignition temperature of CNG, Table 2, the fuel needs to be ignited by secondary energy source: spark ignition system, diesel pilot injected into combustion chamber or a very hot surface (glow plug). In diesel-gas (DG) fueling mode, the CNG is injected into intake manifold to be blended with the air and then admitted into cylinder as a homogenous charge. Inside the cylinder the injected pilot of diesel fuel will self-ignite; starting from diesel fuel's flame nuclei the combustion will propagate into the homogeneous preformed mixture.

When fueled in DF mode with diesel and CNG, the diesel engine emits lower CO_2, PM (particle matter), and nitrogen oxides. Lower carbon content of CNG, Table 2, will explain the lower CO_2 and PM emission. According to Ref. [19] the most favorable temperature conditions for Zeldovich mechanism are between 1930 and 2080 °C; as the CNG's highest burning flame temperature according to Ref. [20] is 1960 °C the temperature conditions to produce nitrogen oxides are less favorable; also, NO_x emission will have lower levels because of the CNG injection there will be less air available.

At the opposite end, emission of HC and CO increase in certain engine speed or load, when the engine is fueled in DF mode with CNG and diesel fuel. The main reasons for high HC emission are flame quenching due to low in cylinder temperatures, lean mixtures and trapping of fuel in combustion chamber crevices (piston top land, fire ring and cylinder wall); some other reason could also be the air-CNG mixture passing directly from intake manifold to exhaust manifold during valve overlapping. CO emission may be effect of in-cylinder low temperature, swirl and tumble currents and lean mixture that allow incomplete combustion to happen.

1.3. CNG influence on diesel engine fueled in DF mode (international literature review)

There is a large variety of articles globally that analyze the influence of compressed natural gas on diesel engine operating regime, when it is fueled in DF mode. This chapter groups the analyses on the parameter of concern: in-cylinder pressure, autoignition delay, heat release rate, brake specific consumption, power and torque, exhaust gas emission. The chapter also presents some adjustments or challenges described in technical literature.

a) In-cylinder pressure

According to a part of the studied papers, when the engine is fueled in DF mode, the in-cylinder pressure is higher than the one recorded when the engine is running in standard mode (e.g. Refs. [6,12]). The main factors that influence this parameter is lower heating value and the gaseous state of CNG. Injecting CNG into manifold will increase the proportion of premixed charge and as consequence the rapid combustion faze will have a higher proportion; less heat will be lost at cylinder wall and higher in-cylinder pressure will be recorded. There is also a part of literature that states that the in-cylinder pressure will decrease with the rise of CNG quantity admitted into the cylinder (e.g. Refs. [7,10,21]). Incorrectly applied injection advances or mass of the diesel fuel pilot too little for engine to operate when it is fueled in DF mode, may create conditions for incomplete combustion.

b) Autoignition delay

The duration of autoignition delay will be up to 7°CA longer when the engine is fueled in DF mode. Main reasons for this phenomenon to happen are lower in-cylinder oxygen quantity and, as read in some articles, lower in cylinder temperature at the end of compression stroke as the specific heat of CNG is much higher than that of air. Some authors would mention a chemical inhibiting reaction of diesel fuel when it meets CNG; this will presumably result in a cetane number decrease (e.g. Ref. [21]).

c) Heat release rate

There are two main contrary directions presented by the analyzed literature.

- The heat release rate will increase due to longer autoignition delay; a much larger quantity of diesel fuel will vaporize, and more flame nuclei will appear, setting favorable conditions for combustion to propagate into the homogenous charge (e.g. Refs. [6,12]).
- If the CNG mass, diesel fuel pilot timing or quantity are not very precise controlled for a specific operating point, partial combustion may appear, and the heat release rate will decrease (e.g. Ref. [10]).

d) Brake specific consumption

According to the documentation consulted for this article, BSFC (brake specific fuel consumption) is higher for low loads when engine is fueled in dual fuel mode; low in-cylinder temperatures and low swirl and tumble currents will create conditions for incomplete combustion (e.g. Refs. [12,22,23]). The flame will quench at the cold cylinder wall or in homogeneous lean mixture. The passing of air-CNG mixture from intake manifold to exhaust manifold during valve overlap will also increase the BSFC.

Above 40 % loads, the DF fueling mode is more efficient. Lower heating value of CNG, greater than that of diesel fuel, is the main reason of higher efficiency of diesel engine when it is fueled in DF mode; also, higher temperatures and higher ratio of preformed mixture will improve the rapid combustion faze. Due to a rapid combustion, the gas will exchange less heat with the cylinder wall and this factor will increase the in-cylinder pressure and the specific mechanical work (or lower BSFC for same amount of specific mechanical work). Some research shows a drop of 50 % of the total cost when using the engine fueled in DF mode when compared to standard operating mode.

e) Nitrogen oxides emission

The studies show a drop in NO_x and there are two main reasons for this phenomenon: lower air quantity (as there is a percentage of air substituted by CNG) and a lower in-cylinder temperature reached when the engine is fueled in DF mode. Some of cited papers will show an increase of nitrogen oxides rise due to knock occurrence (e.g. Refs. [9,12,24,25]).

f) Unburned hydrocarbons emission

HC record growing emissions as high as 800 % when the engine is fueled in DF mode as compared to diesel standard operating mode in lower loads; this phenomenon is due to fuel trapped in crevices, due to flame quenching in lean preformed mixture and due to HC passing from intake manifold in exhaust manifold at valves overlap. At higher loads the HC emission is still higher in DF fueling mode but with less than 250 %; the improvement of combustion is the main factor that determines a drop in HC emission with engine load (e.g. Refs. [7,9,10]).

g) Carbon dioxide emission

Table 3
Engine K9K K792 main characteristics [30].

Features	Unit	Value
Bore	mm	76
Stroke	mm	80.5
Compressing ratio	–	18.3:1
Effective torque	Nm	150
Effective power	kW	50
Supercharging pressure	bar	1.8
Diesel fuel injection pressure	bar	1600

The lower carbon content of compress natural gas is the first factor that influences the CO_2 emission of diesel engine when it is fueled in DF mode; the lower heating value of CNG will determine an even lower level of carbon dioxide emission (e.g. Refs. [7,11,12, 22]).

h) Carbon monoxide

CO emission can be a method of quality evaluation of combustion; CO emissions can reach higher levels with up to 20 % when the engine is fueled in DF mode. The drop in the quantity of air is the main factor that determines a higher CO emission. For lower loads where the in-cylinder temperature drops the flame quenching determines higher carbon monoxide (e.g. Refs. [23,26]).

i) Smoke emission

In many of the studied papers, the smoke emission drops when engine is fueled in DF mode especially due to less complex fuel molecules and due to the fac that CNG has 7 % less carbon. In some of the cases the smoke emission would drop with 80 %. At low loads there is the possibility that the combustion will stop suddenly due to low temperatures or due to lean preformed mixtures. In this situation the molecules will dehydrogenate and create smoke flakes (e.g. Refs. [10,16]).

1.4. DF fueling mode optimization and system challenges

Some cited authors present means to optimize the DF fueling mode only by adjusting diesel fuel pilot mass or timing, or by creating operating regime specific substitution ratio.

A growth in diesel fuel pilot quantity can lead to a higher in cylinder pressure, a lower autoignition delay, a drop in CO emission but will have a negative effect on NO_x emission (52 %) and HC emission (over 150 %) (e.g. Refs. [8,21]).

The reduction of diesel fuel pilot injection advance has the effect of a shorter autoignition delay and a drop in NO_x emission but will influence negatively the total burning time (the combustion will end late into expansion) and the CO and HC emission(e.g. Ref. [8]).

Lower cooling liquid temperatures can have a negative impact over combustion (partial combustion can occur) and will determine the CO, HC emission and brake specific consumption to reach higher levels (e.g. Ref. [9]).

Some of the authors calculate substitution diagrams of diesel fuel with CNG that take into consideration the engine speed and load, determining this diagram precisely would have operating costs lower with 50 % in DF mode as opposite to diesel conventional operating mode (e.g. Ref. [23]).

1.5. Challenges of diesel engine operating when it is fueled in DF mode with CNG and diesel fuel

The most frequent challenges met when a diesel engine is fueled in dual fuel mode with CNG and diesel fuel are.

- Coking of the diesel injector orifices is a problem that occurs when the injector injects only 10 % of the required amount of diesel per cycle. This causes the injector tip temperature to rise, which in turn causes the volatile fractions to vaporize and the heavy fractions to coke. The solution is to add a copper jacket around the injector tip to protect it thermally.
- Compliance with pollution standards requires the development of a very precise electronic diesel and CNG injection control system that can set optimal ratios for the two fuels (depending on engine speed and load) so that pollution standards and as well as power and torque requirements are met, (e.g. Ref. [23]).
- CNG direct injection, although it solves the problem of pollutant emissions, still requires research to improve the diesel/gas injector.
- The rate of cylinder pressure rise in diesel-gas mode is higher than in mono-fuel mode, which results in a more pronounced combustion noise, and inaccurate control of the advance or pilot quantity of diesel fuel can lead to knock (e.g. Refs. [27–29]).
- The storage of CNG at 240 bar requires a high-pressure cylinder mass (which can represent as much as 25 % of a car's net payload) and a big percentage of net volume to be occupied; the small space and low net payload of cars makes them less eligible for retrofitting with this type of system compared to LPG.

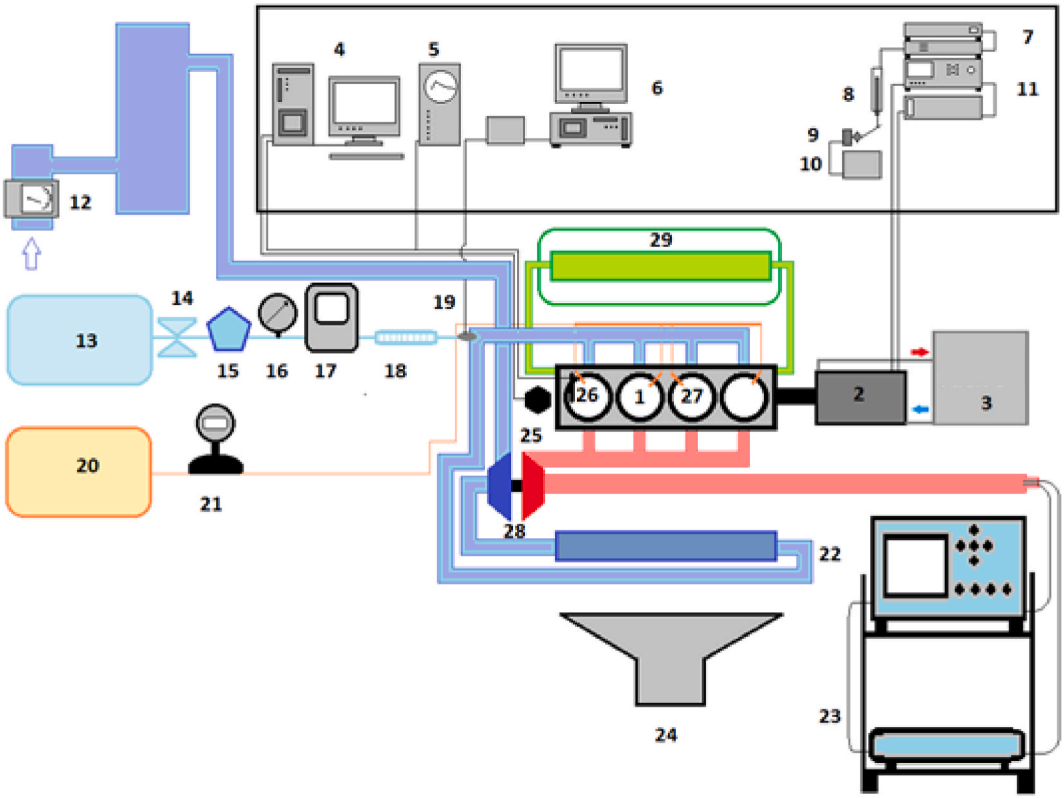

Fig. 1. The CNG-diesel engine test bench, comprises the following main equipment.

2. Experimental investigation setup

The main objective of this chapter is to provide objective data on CNG influence on combustion performance of a K9K diesel engine, Table 3, fueled in DF mode using compressed natural gas as alternative fuel. The engine is operated first in standard mode to collect benchmark data. Data recorded when the engine is fueled in DF mode will be compared to the benchmark and conclusion related the influence of CNG will be drawn. The engine will be operated at 2000 rpm (highest torque specific engine speed) and at 40 %, 55 % and 70 % loads. The smoke emission will represent the parameter used to limit the specific energetic substitution ratio of diesel fuel with CNG.

The engine used for the experimental investigation is a Renault K9K K792 model; it's features are presented in Table 3.

Specific for DF fueling mode, four electronic controlled injectors for gaseous fuels were connected to the intake manifold by the help of 4 nozzles welded onto the intake manifold after compressor.

The CNG fueling system contains the following components:

The high-pressure tank (tested for 260 bar) has 10 mm thick steel wall and stores CNG at 230 bar; it must pass very strict testing [31, 32] and it is guaranteed for 20 years.

The manual shut off valve (tested for 350 bar) is connected to the high-pressure tank and cuts the CNG flow to the pressure reducer, [33]. The high-pressure flow pipe that is testes for 250 bar connects the manual shut-off valve to the pressure reducer; it has an 8 mm diameter and a 1.5 mm thick wall, [33].

- The pressure reducer (model: Landi-Renzo NG 2-2) has a two-stage pressure reducing capacity; pressure is dropped to 3 bar (the intermediary lever is 10 bar); the pressure reducer also has an electronic shut off valve used for emergency cases when the system operates faulty [33].
- The manometer used to measure the fueling pressure. It can measure pressure up to 6 bar.
- The injecting module (4 injectors) is connected to the intake manifold with hose specific for CNG usage.
- The injector electronic control module Unichip Q00897 is a plug and play system type. It can apply corrections taking into consideration engine speed, load, temperature and several other parameters, [34].

Fig. 1 shows the general setup of the experimental test bed.

1-supercharged 4-cylinder K9K diesel engine; 2-electric eddy current brake; 3- water cooling unit or the eddy current brake; 4-AVL data acquisition unit; 5-oscilloscope; 6-compressed natural gas injection system control unit; 7-control unit and power unit for accelerator pedal actuator servo motor; 8-servomotor for accelerator pedal operation; 9-accelerator pedal; 10-electronic engine control unit; 11-control unit and power unit for for eddy current brake; 12-air volume flow meter; 13-pressure tank for the storage of compressed natural gas; 14-manual CNG shut-off valve; 15-CNG pressure regulator/reducer; 16-pressure gauge for measuring CNG supply pressure; 17- mass flow meter for measuring the quantity of CNG consumed; 18-flame extinguisher; 19-block of compressed natural gas injectors; 20-diesel tank; 21-mass flow meter for measuring the quantity of consumed diesel fuel; 22- exhaust gas analyzer; 23-opacimeter; 24-cooling fan; 25-crankshaft position sensor; 26-in-cylinder pressure transducer; 27-diesel fuel injector; 28- turbocharger.

During the experimental investigation the following data has been recorded: air volume, diesel fuel and CNG mass consumption; air, engine, exhaust gases, oil and eddy current brake temperature; engine torque; in-cylinder pressure; boost pressure; exhaust gases composition.

All these parameters were used to calculate the following.

- **Coefficient of air excess**

It represents the ratio of the quantity of air available in the cylinder to the quantity of air theoretically required to burn the fuel admitted per cycle, [35].

$$\lambda = \frac{L}{L_t} \tag{1}$$

where L is the quantity of air consumed and L_t is the theoretical quantity of air required to burn the same quantity of fuel completely. When using both fuels the theoretical air required is calculated with the following formula:

$$L_t = c_{h_{CNG}} * L_{t_{CNG}} + c_{h_{diesel}} * L_{t_{diesel}} \tag{2}$$

The theoretical air consumption for one kg of CNG is 17.2 kg and for one kg of diesel fuel it is 14.4 kg.

To determine the quantity of air allowed into the cylinder in 1 h we use the formula:

$$L = \rho_{air} * V_{air_{cons}} \tag{3}$$

where $\boldsymbol{\rho}_{air}$ is the air density at the temperature at the time of intake into the intake manifold and V_{air_cons} the hourly air consumption in cubic meters.

- **Indicated mean pressure,** [36].

Represents the indicated mechanical work in relation to the cylinder displacement. The indicated mean pressure is an essential criterion for comparing engines with similar performances. Analytically it is calculated with the formula:

$$imep = \sum_{i=1}^{720} \left[p_{cil_i} * \left(V_{cil_i+1} - V_{cil_i} \right) \right] \Big/ Vs \tag{4}$$

where p_{cil_i} is the pressure recorded in the cylinder and V_{cil_i} is the cylinder volume corresponding to the crankshaft position and Vs is the cylinder displacement, [37].

- **Specific energetic substitution coefficient of diesel with CNG,** [37].

Represents the percentage of the total amount of diesel normally consumed per hour substituted with an amount of compressed natural gas $x_{c.}$ The formula is used to determine the energy substitution coefficient:

$$x_c = \frac{Ch_{CNG} * H_{iCNG}}{Ch_{CNG} * H_{iCNG} + Ch_{diesel} * H_{idiesel}} * 100 \tag{5}$$

where Ch_{CNG} Ch_{diesel} is the hourly consumption of compressed natural gas or diesel, H_{iGNC} $H_{iDiesel}$ lower heating value, [37].

- **Heat release rate,** [38].

It is given by the relationship:

$$dQ / d\alpha = \frac{\left(k * \frac{p_{i+1} + p_i}{2} * \frac{V_{cil_i+1} - V_{cil_i}}{\Delta\alpha} + \frac{V_{cil_i+1} + V_{cil_i}}{2} * \frac{p_{i+1} - p_i}{\Delta\alpha} \right)}{(k-1) * Q_{avl}} \tag{6}$$

where Q_{avl} is the available heat per cycle, dQ/dα is the heat release rate, k is the adiabatic exponent; $p_{i,}$ p_{i+1} are the pressures read from the diagram at the set resolution (1.3 °RAC); V_{cil_i} and V_{cil_i+1} are the instantaneous cylinder volumes.

- **Heat release**

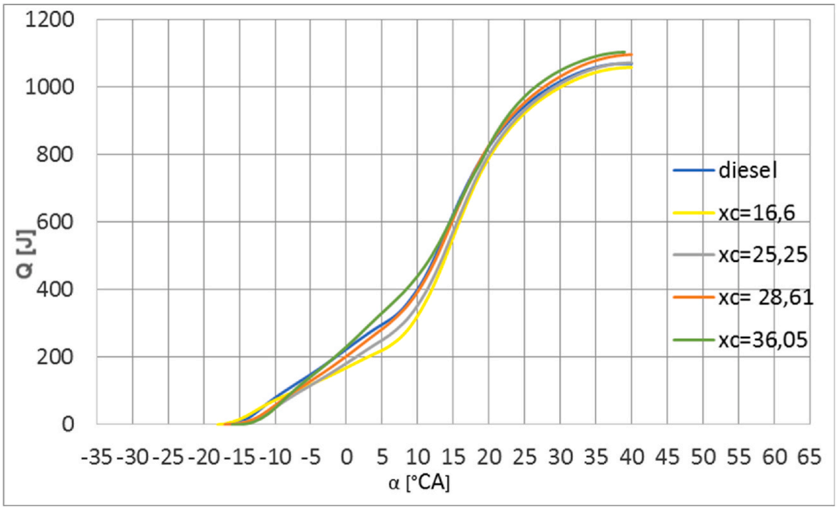

Fig. 2. Variation of heat release with crankshaft angular position at 40 % engine load.

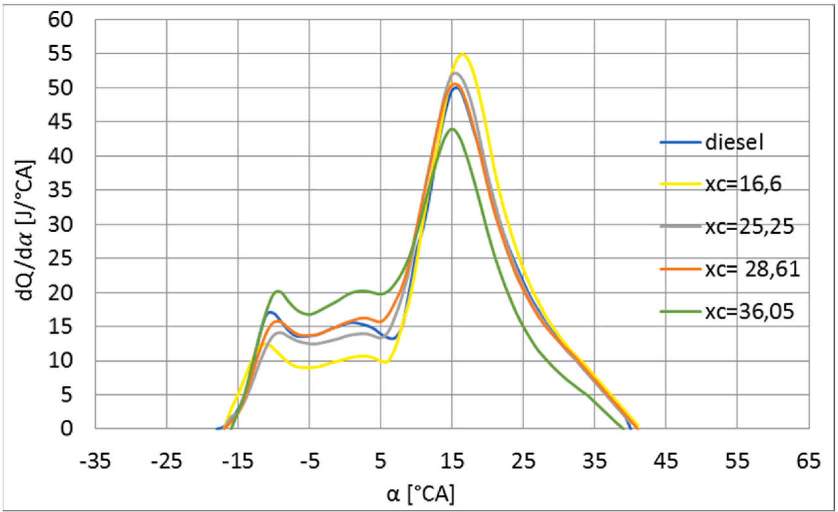

Fig. 3. Variation of heat release rate with crankshaft angular position at 40 % engine load.

To determine the amount of heat released by the combustion process, the 2following relation will be used:

$$Q = \int \frac{dQ}{dt} d\alpha \tag{7}$$

Analytically, the formula [38], will be used:

$$Q_{\alpha i+1} = \left(\frac{dQ}{d\alpha}\right)_{\alpha i+1} * d\alpha + Q_{\alpha i} \tag{8}$$

3. Results and discussions

3.1. Results at 40 % engine load

Injection of compressed natural gas causes an increase in heat release per cycle, for all the studied values of energetic substitution coefficients, Fig. 2; the lower heating value of compressed natural gas, higher than that of diesel fuel, causes an increase in heat release per cycle. Lower flame temperature of natural gas but also areas of lean homogeneous charges (especially for specific energetic substitution of diesel with CNG coefficients lower than 25 %) can lead to a delay in heat release per cycle. At highest specific energetic substitution coefficien, the homogeneous charge is close to a stoichiometric mixture and the heat is released earlier on the cycle.

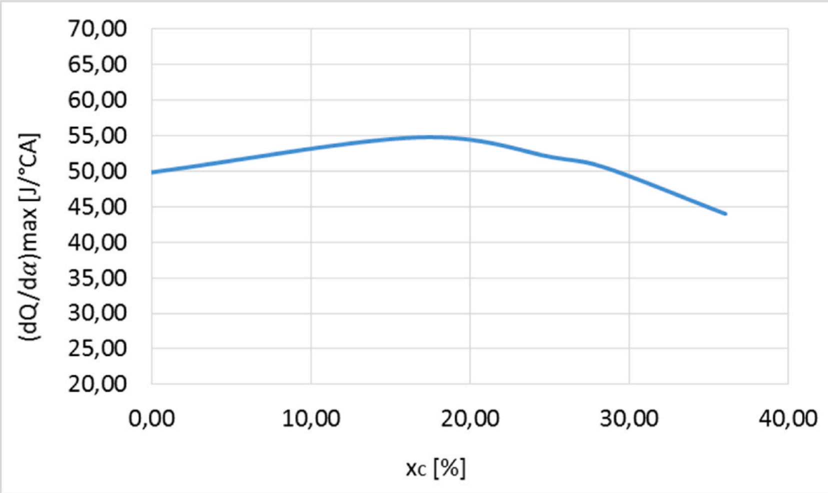

Fig. 4. Variation of maximum heat release rate with specific energetic substitution of diesel with CNG at 40 % engine load.

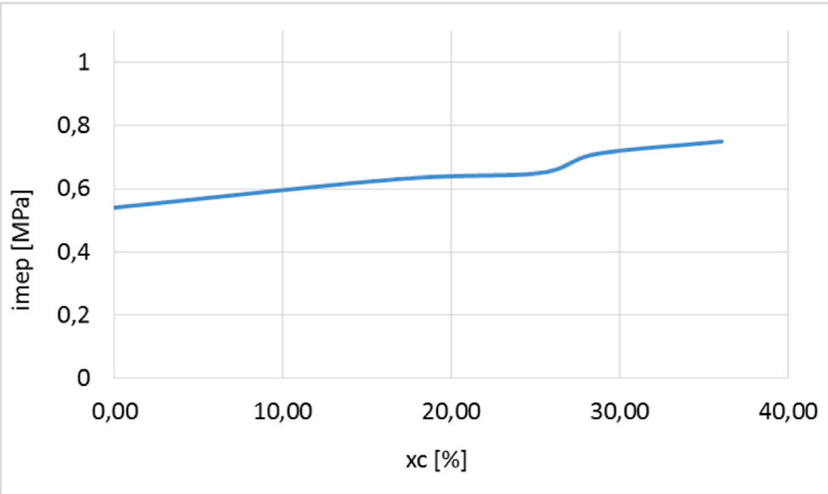

Fig. 5. Variation of indicated mean pressure with specific energetic substitution of diesel with CNG at 40 % engine load.

For the lowest x_c, a lower number of flame nuclei that appeared (due to the lower preinjection quantity) will have a negative impact on the HRR on the interval −15°CA – 5°CA. The partial vaporization of the main dose will improve the premixed mixture quality; the flame propagates into the preformed mixture, and, for the lowest substitution coefficient, the highest heat release rate is achieved; this can explain the growth on nitrogen emission recorded in Ref. [39] for x_c equal to 16,6. Increasing the amount of CNG causes the maximum heat release rate to decrease. The decrease in the heat release rate after the specific energetic substitution coefficient exceeds 20 % may be mainly due to the lack of air (displaced by CNG) to sustain the combustion or because of the diffusive combustion phase that becomes predominant. The maximum HRR is recorded close to 15°CA for both DG and standard fueling modes, Fig. 3.

An increase in the maximum heat release rate up to a specific energetic substitution coefficient of 16,6 %. Over this threshold the heat release rate decreases; the main reason may be the lack of air which is replaced by CNG or because of a more predominant diffusive combustion phase of the main dose of diesel fuel occurs, Fig. 4.

The CNG injection has a positive effect on the indicated mean pressure. Increasing the fast combustion phase percentage, reduces the contact time of the in-cylinder fluid with the cylinder surfaces and thus more heat is converted into mechanical work per cycle, Fig. 5.

Admitting CNG into engine's cylinders will increase the percentage of the preformed mixture and will have the effect of decreasing the amount of diesel fuel that will burn in the diffuse combustion phase and thus reducing this period, which will result in an exhaust gas temperature drop up to 50K, Fig. 6.

Air excess ration and air consumption will keep a descending trend for all the studied specific energetic substitution coefficients at low engine loads. Injecting GNC into intake manifold will displace a part of the air quantity admitted into the cylinder; also a higher L_t

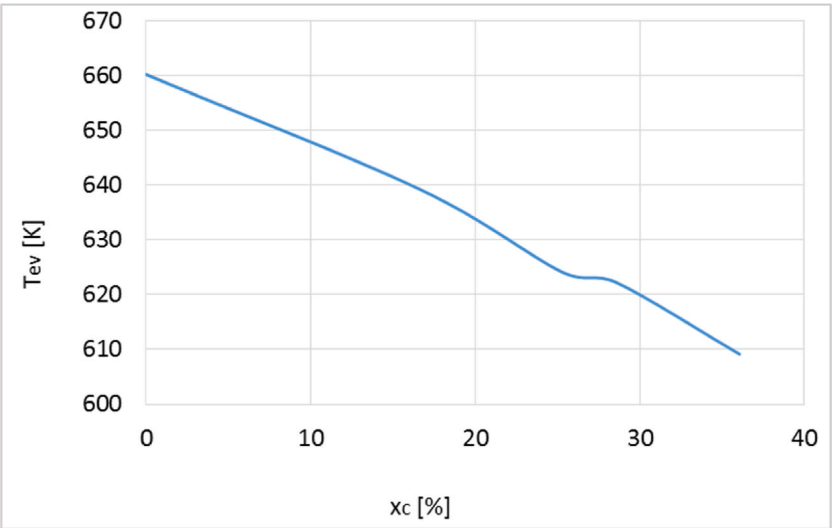

Fig. 6. Variation of exhaust gases temperature with specific energetic substitution of diesel with CNG at 40 % engine load.

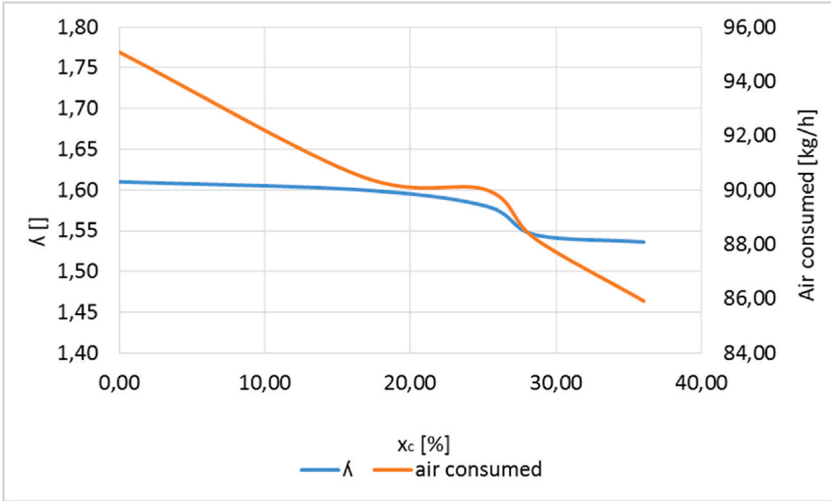

Fig. 7. Variation of coefficient of air excess and air consumption with specific energetic substitution of diesel with CNG at 40 % engine load.

needed for CNG will lower the value of air excess coefficient, Fig. 7.

Considering the time of autoignition, the end of the fast combustion phase and the end of the diffusive combustion phase, we can say that compressed natural gas admission leads to a 5 % increase in the average duration of the preformed mixture combustion phase at low loads; the rapid combustion phase in the case of diesel fueling extends over 22°CA while at the maximum value of the specific energetic substitution coefficient it extends over 24°CA, Fig. 8. The CNG injection reduces the average duration of the slow combustion phase mainly by reducing the quantity of the main dose of diesel fuel, Fig. 8.

3.2. Results at 55 % engine load

The heat release quantity per cycle is higher when engine is fueled in DG mode; the higher LHV of compressed natural gas favors a higher quantity of heat released per cycle. Fewer flame nuclei (due to reduced pilot quantity) and the lean homogeneous mixture that determine flame quenching may be the main reasons that the same amount of heat is recorded later during the cycle (in the interval −5°CA – 20°CA) when the engine is fueled in DG mode for low specific energetic substitution coefficients. At highest x_c the same quantity of heat is recorded faster on the cycle than when engine is running in standard mode; higher quality of the preformed mixture due to a larger quantity of GNC leads to a better combustion, Fig. 9.

During auto ignition delay, the most part of the diesel fuel preinjection will vaporize. This will result in an increase of HRR of 15J/°CA in the interval −10°CA – 10°CA, Fig. 10. Injecting CNG into the intake manifold will determine lower heat release rates on this

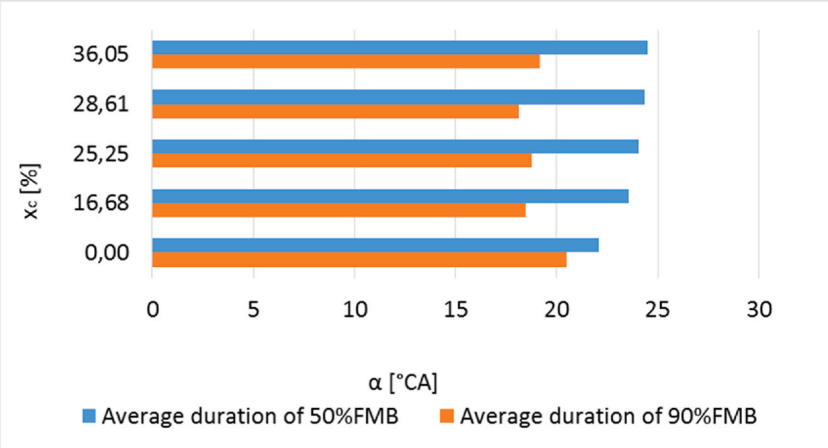

Fig. 8. Variation of average fast/diffusive combustion duration with specific energetic substitution of diesel with CNG at 40 % engine load.

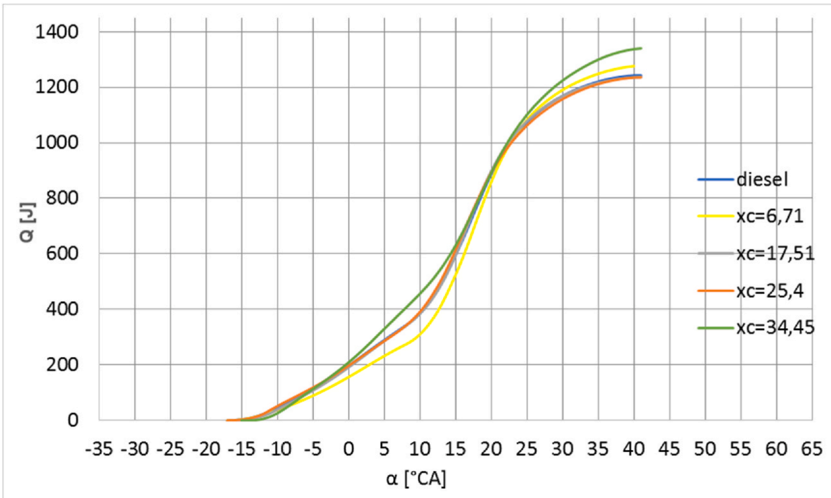

Fig. 9. Variation of heat release with crankshaft angular position at 55 % engine load.

interval, for low x_c. For the highest x_c, the HRR increases with 15 % mostly due to a closer to stoichiometric preformed air-diesel-CNG mixture. The maximum HRR is recorded on 15°CA – 20°CA interval for all specific energetic substitution coefficients and in standard operating mode.

At medium loads, similar behavior to low engine loads can also be observed for the maximum rate of heat release: at the lowest value of the specific energetic substitution coefficient the heat release rate reaches the highest level; high maximum HRR can lead to higher in-cylinder temperatures, and this may explain the increase in nitrogen oxide emissions recorded in Ref. [40] for this x_c value. As x_c increases, the HRR will reduce its value; when the specific energetic substitution coefficient reaches 25 %, the HRR will have a lower value than that recorded when the engine runs in standard mode; the main dose of diesel fuel will burn in the diffusive phase and this will have a negative impact on maximum HRR, Fig. 11.

For medium loads, when the engine is fueled in DG mode, the specific mechanical work produced has higher values. The lower heating value of the CNG and the gaseous state of CNG which will increase fast burning phase and reduce heat losses at the cylinder wall, have a good influence on the indicated mean pressure, Fig. 12.

The decrease of the exhaust gas temperature in DG mode for medium loads, demonstrates that the diffusive combustion phase is getting shorter; this phenomenon was also observed at low loads and is mainly due to the increase of the proportion of preformed mixture; increasing x_c coefficient will cause a reduction of the main dose of diesel fuel; this will shorten the diffusive combustion phase, Fig. 13.

The amount of air admitted into the cylinder decreases with the rise of specific energetic substitution of diesel with CNG as more air will be displaced by the alternative fuel, Fig. 14; this will have little impact on the air excess coefficient that varies around the values 1.43; air excess coefficient is also influenced by the quantity of each fuel used: for highest x_c at medium loads the reduction o diesel fuel quantity will determine a reduction of necessary air of 41 % and the injected mass of CNG will need a 32 % higher theoretical mass of

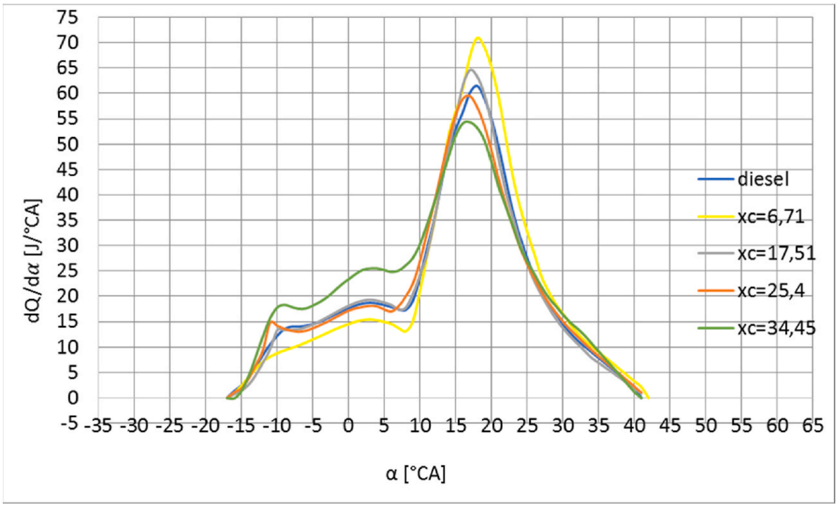

Fig. 10. Variation of heat release rate with crankshaft angular position at 55 % engine load.

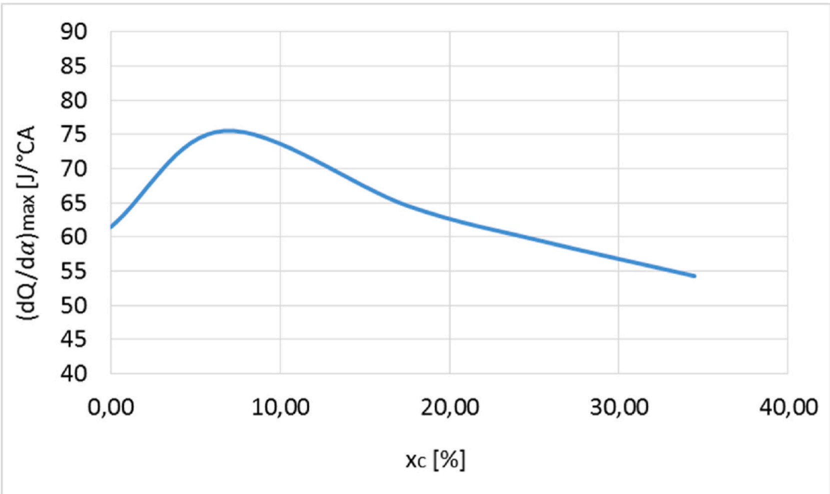

Fig. 11. Variation of maximum heat release rate with specific energetic substitution of diesel with CNG at 55 % engine load.

air; the 10 % drop in air admitted into the cylinder will lead to a 1,42 air excess coefficient.

The duration of the rapid burning phase increases because the injected mass of CNG increases the proportion of preformed mixtures; Reducing the qunatity of the main dose of diesel fuel per cycle results in a decrease in the quantity of fuel that burns during the moderate combustion phase (the percentage of diffuse combustion duration decreases in relation to the total combustion duration), Fig. 15.

3.3. Results at 70 % engine load

When the engine is fueled in DF mode with diesel fuel and CNG, the recorded heat released quantity is higher than that recorded in standard operating mode. The higher LHV and the gaseous state of compressed natural gas increases the percentage of preformed mixture that will burn in fast combustion phase producing more heat per cycle. As the x_c will increase, the quantity of heat released by the diesel fuel pilot will be recorded sooner on the cycle, Fig. 16. This phenomenon can also be observed on heat released rate diagram. As the quantity of CNG admitted into the cylinder is larger, the HRR of the preformed mixture (air-diesel fuel preinjection-CNG) will reach higher values because the preformed mixture is closer to stoichiometric value.

Around 5°CA when the main diesel fuel is injected, the HRR records a small drop (period when the outer layer of the diesel jet fuel vaporizes). The maximum HRR is also recorder in the 15°CA – 20°CA interval for high loads, Fig. 17.

The maximum heat release rate reaches lower values as the specific energetic substitution of diesel with CNG reaches higher values mainly due to the fact that most of the injected GNC quantity burns in the preformed mixture of the preinjection and the combustion of

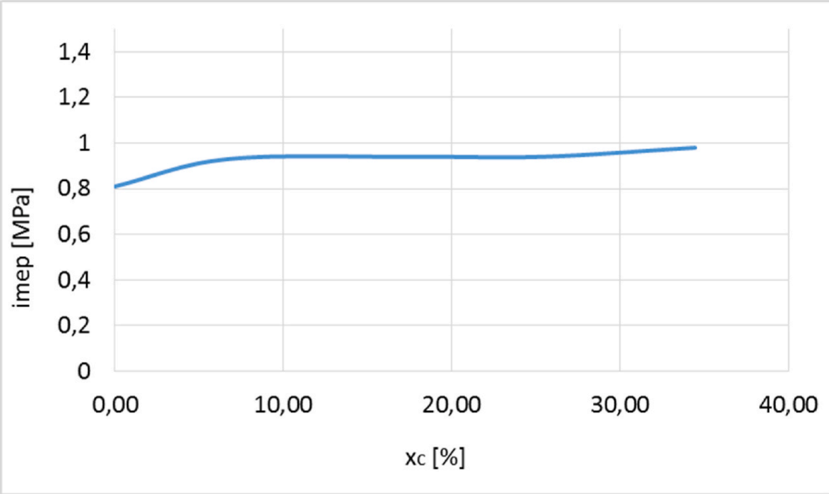

Fig. 12. Variation of indicated mean pressure with specific energetic substitution of diesel with CNG at 55 % engine load.

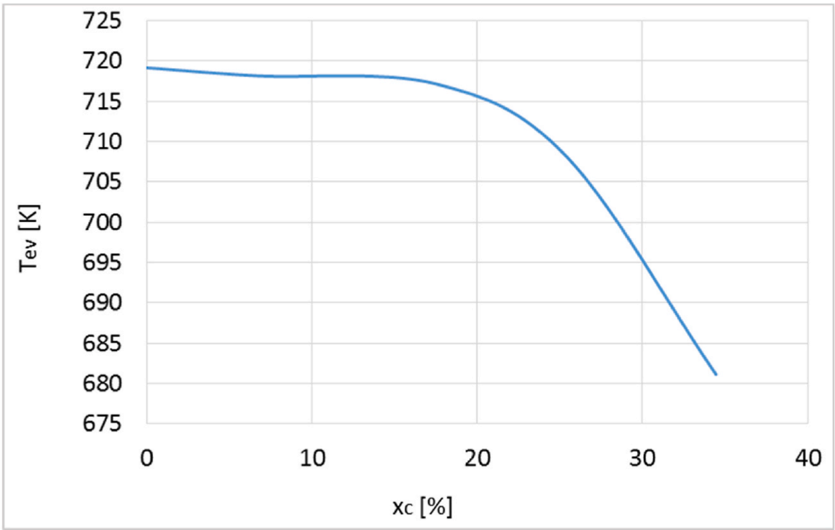

Fig. 13. Variation of exhaust gases temperature with specific energetic substitution of diesel with CNG at 55 % engine load.

the main dose will get a diffusive feature with negative impact on maximum HRR, Fig. 18.

The higher LHV of compressed natural gas helps to increase the amount of heat released per cycle; the gaseous state of the alternative fuel causes an increase in the percentage of preformed mixture; these two factors cause the mean effective pressure to increase, Fig. 19.

Although the amount of air admitted into the cylinder is only slightly influenced by the injection of CNG, the air excess ratio will drop with 5 % due to a larger L_t needed by compressed natural gas, Fig. 20 (observed also in Ref. [41]). This can have positive impact on nitrogen oxides emission.

Injecting CNG into the cylinder increases the amount of preformed mixture; for all specific energetic substitution coefficients the duration of rapid combustion increases. A 6 % drop of diffusive combustion can also be noted for the highest specific energetic substitution of diesel fuel with CNG mainly due to a lower main dose diesel fuel quantity. Total combustion will be 9 % longer in DG mode for maximum $x_{c,}$ Fig. 21.

3.4. Engine load influence when engine is fueled in DF mode with CNG and diesel fuel

Increasing engine load increases the amount of heat released, Fig. 22, as more fuel will be used and higher in-cylinder temperatures will be reached. Injecting compressed natural gas into the intake manifold determines a growth in the amount of heat release per cycle; as the load increases, heat release becomes more sensitive to compressed natural gas injection.

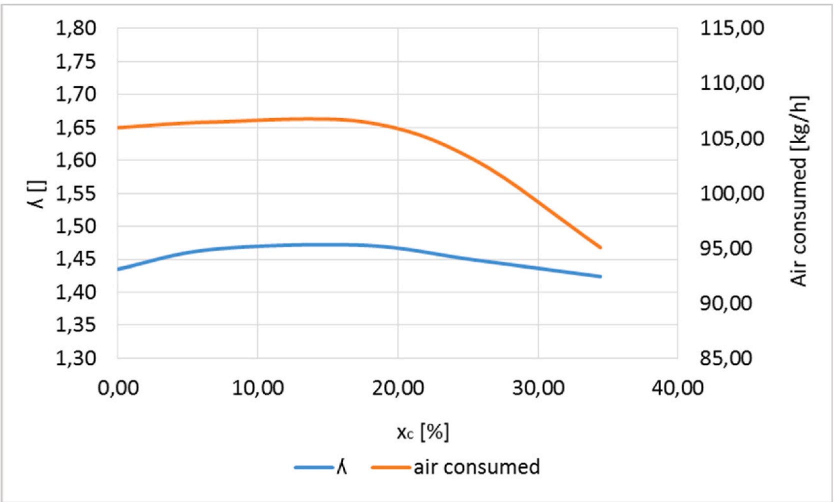

Fig. 14. Variation of coefficient of air excess and air consumption with specific energetic coefficient of diesel with CNG at 55 % engine load.

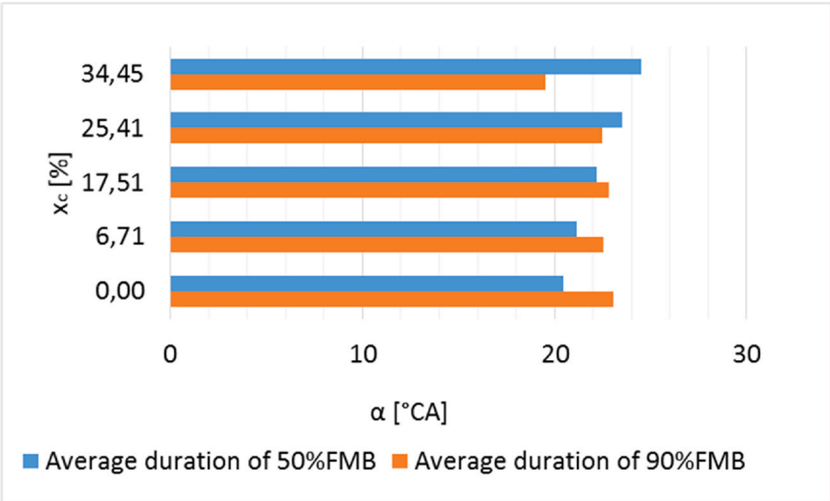

Fig. 15. Variation of average fast/diffusive combustion duration with specific energetic substitution of diesel with CNG at 55 % engine load.

The maximum heat release rate is positively influenced by increasing engine load, Fig. 23. In standard operating mode a 60 % HRR growth is recorded (higher in-cylinder temperature will create optimal condition for combustion); as the specific energetic substitution of diesel fuel with CNG will grow, the maximum HRR will be less sensitive to the engine load; for highest x_c, the maximum HRR will grow with 35 %; this phenomenon happens due to the lower number of flame nuclei that appear in DG fueling mode.

From the analysis of Figs. 24 and 25 the following conclusions can be drawn.

- o when the engine is fueled in standard mode, increasing the load causes a decrease in the rapid combustion phase (20 % drop from 40 % to 70 % engine load); higher temperatures at high loads cause a higher quantity of diesel fuel to vaporize; in the preformed mixture more flame nuclei will appear; the combustion speed thus increases. CNG injection requires a reduction in the amount of diesel fuel; fewer flame nuclei will result, and a lower combustion speed will be recorded, when the engine is fueled in DG mode. The use of CNG makes the fast burn phase less sensitive to increasing engine load (5 % drop is recorded when engine load reaches 70 % from 40 %).
- o increasing the engine load, increases the duration of the diffusive combustion by up to 19 % when engine is fueled in standard mode; a larger quantity of diesel fuel is need due to higher loads; this will not have enough time to vaporize and will burn in the diffusive phase. When fueling the engine in DG mode, the amount of diesel fuel used per cycle is reduced as a part of mechanical work is done with CNG. Shorter average periods for diffusive combustion are recorded because of the gaseous state of CNG (at highest x_c a 22 % drop will be recorded for 70 % engine load). Fueling the engine in DG mode makes diffusive phase more sensitive

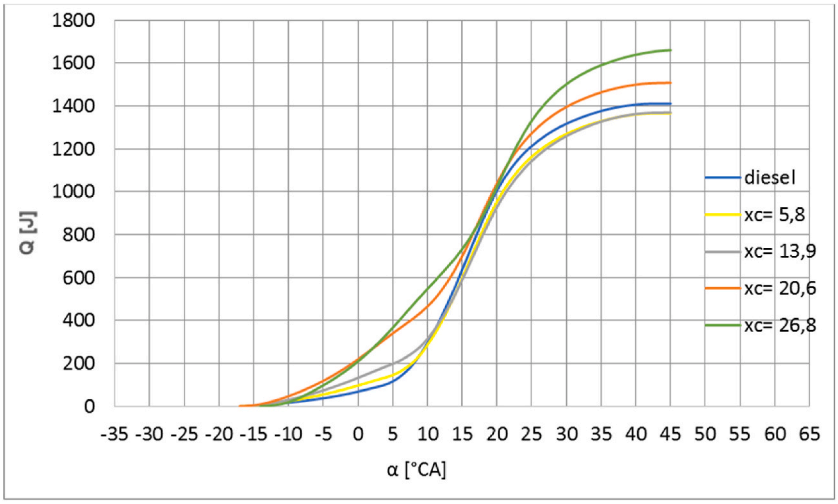

Fig. 16. Variation of heat release with cranckshaft angular position at 70 % engine load.

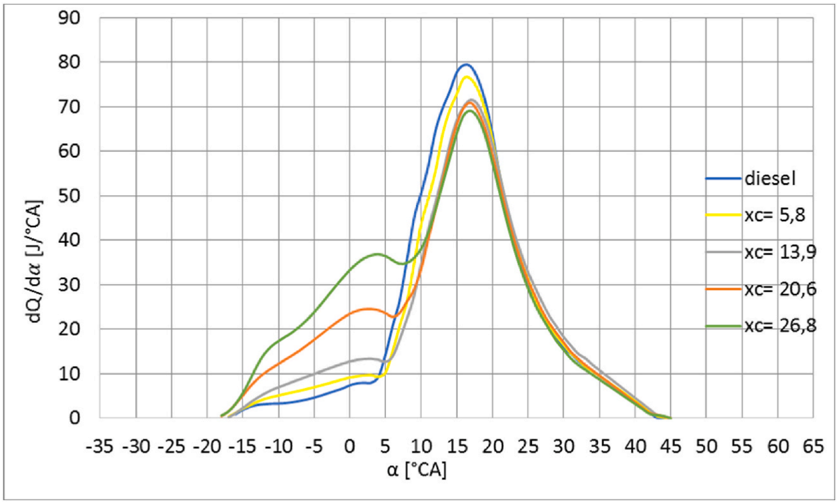

Fig. 17. Variation of heat release rate with cranckshaft angular position at 70 % engine load.

to engine load increase: for standard fueling mode the diffusive combustion phase grows with 20 % when the engine load increases with 30 %

o when the engine is fueled in DG mode the diffusive combustion phase records a 27 % growth for same engine load increase at x_c equal to 26 %.

4. Conclusion

- **Heat release**

For all the studied regimes the released heat quantity is higher when the engine is fueled in DF mode. At low and medium loads the total qunatity of heat released per cycle will increase with 10 % and with 25 % higher for 70 % load. As the load increases, the released heat is higher and it will be more sensitive to CNG injection; for all loads, the injection of CNG will have good influence on combustion mostly because of the lower heating value and the gaseous state of CNG.

- **Heat release rate and maximum heat release rate**

There are two main phases that can be observed on HRR diagrams for each studied regime: the combustion of the diesel fuel preinjection pilot and the combustion of the diesel fuel main injection pilot. For all the studied cases the combustion of diesel fuel

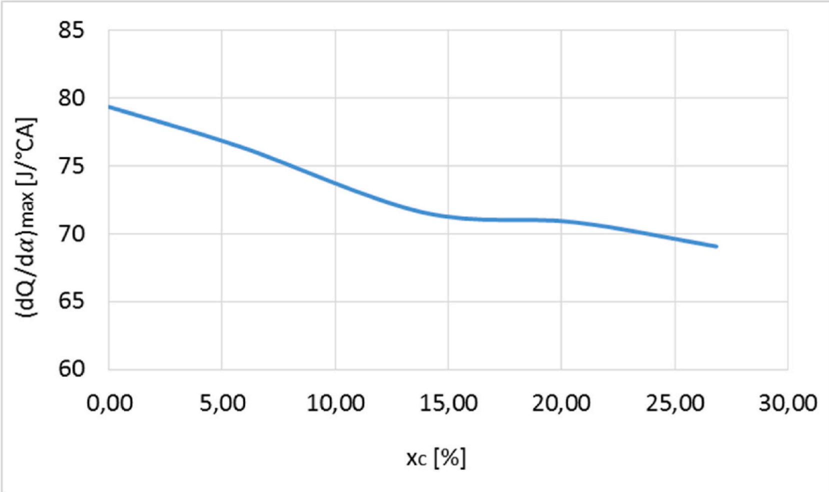

Fig. 18. Variation of maximum heat release rate with specific energetic substitution of diesel with CNG at 70 % engine load.

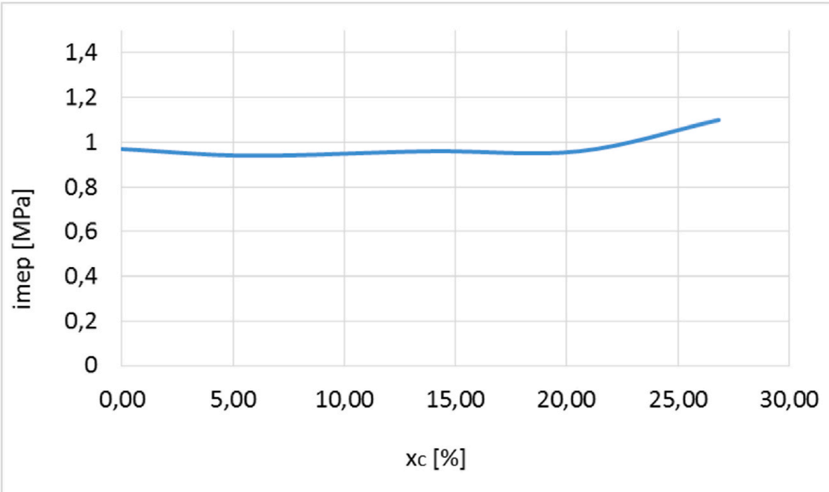

Fig. 19. Variation of indicated mean pressure with specific energetic substitution of diesel with CNG at 70 % engine load.

preinjection is positively influenced by CNG injection because of the gaseous state of the compressed natural gas that will help the premixed mixture to reach stoichiometric value; for all the studied cases the HRR will reach higher value on −15°CA – 5°CA interval; the HRR of the preformed mixture will double its value for low and medium loads and will reach thresholds up to 3.5 times higher. Maximum HRR will be recorded during the combustion of the main dose of diesel fuel. As the most part of the CNG quantity admitted into the cylinder burns in the preformed mixture of the preinjection, the maximum HRR will reach lower values as x_c grows because the quantity of the diesel main dose will decrease; a 10 % drop in maximum HRR is recorded for low loads when the energetic substitution coefficient reaches 36 % and 14 % drop is recorded at high loads when the xc is 26 %.

- **Indicate mean pressure**

Lower heating value and gaseous state of CNG will have a good impact on engine's mechanical work for all loads and for all studied cases when the engine is fueled in DG mode. Increase in fast combustion phase will determine lower in-cylinder retention periods of the combustion fluid; lower heat quantities lost to cylinder wall will increase the amount of mechanical work per cycle; for low and medium loads 30 % and for high loads 20 % increase in indicated mean effective pressure will be recorded.

- **Air excess coefficient**

For all studied cases, ʎ will reduce as the CNG quantity will grow. There are two main reasons for this phenomenon to happen: the

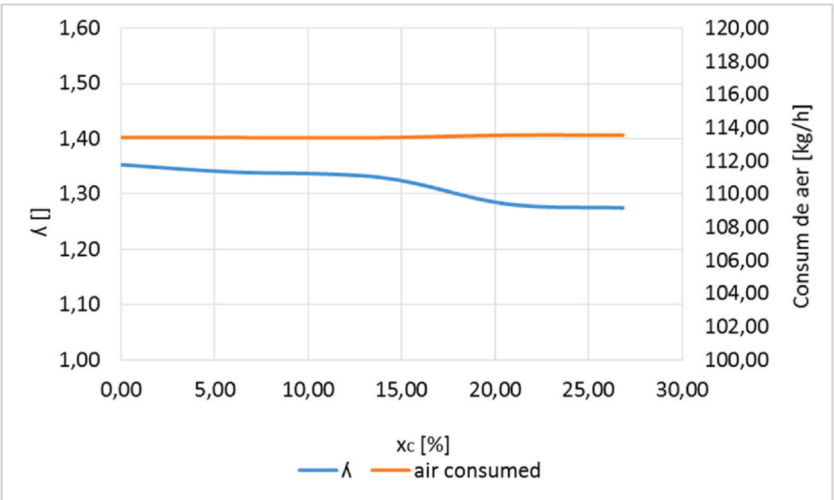

Fig. 20. Variation of coefficient of air excess and air consumption with specific energetic substitution of diesel with CNG at 70 % engine load.

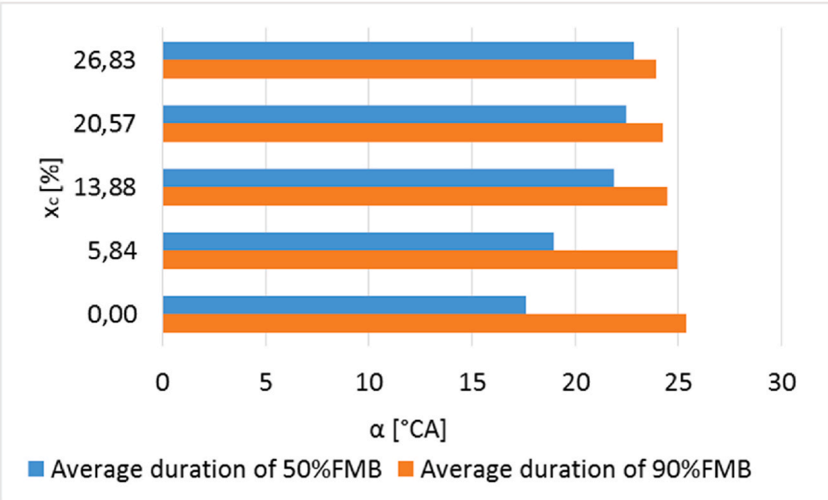

Fig. 21. Variation of fast/diffusive combustion faze average duration with specific energetic substitution of diesel with CNG at 70 % engine load.

quantity of air admitted into the cylinder will drop (being displaced by CNG) and the higher theoretical air qunatity will be necessary as the compressed natural gas quantity will grow. Analyzing air excess coefficient may provide information on combustion quality: at all engine loads a drop in ʎ can have a positive impact on nitrogen oxides emission and a negative impact on CO emission.

- **Exhaust gases temperature**

For the studied engine loads, in DF fueling mode, the exhaust gases temperature will drop for all specific energetic substitution of diesel with CNG (a drop of 10 % is recorded at higher x_c value for low and medium loads); this proves that the diffusive combustion will have shorter periods in DG fueling mode due to lower main dose diesel fuel quantity.

- **Average duration of fast combustion phase**

In standard mode the fast combustion phase will decrease with engine load; due to higher in-cylinder temperatures more flame nucleus will be formed and the premixed mixture will burn faster. Injecting compressed natural gas into the intake manifold will grow the premixed mixture quantity; longer fast combustion phases will be recorded as x_c will be higher (20 % longer for low and medium loads and 30 % for high loads). When the engine is fueled in DF mode, combustion will be less sensitive to engine load increase.

- **Average duration of diffusive combustion phase**

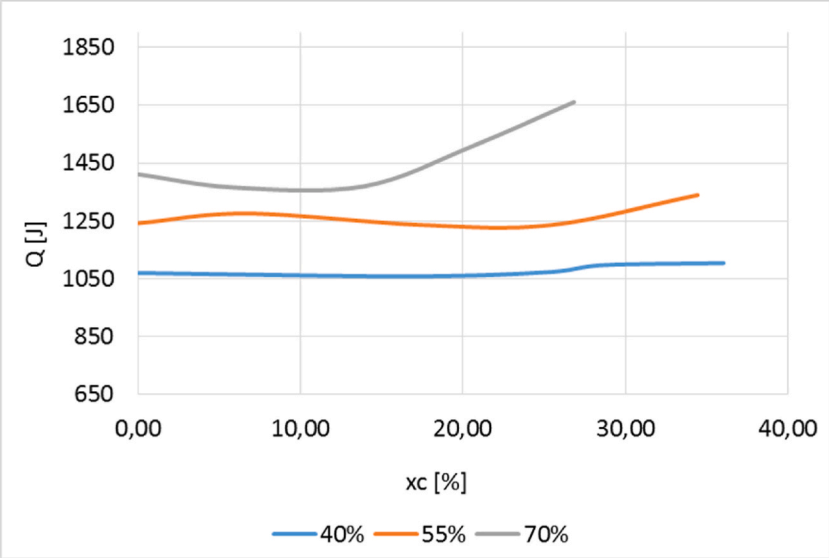

Fig. 22. Variation of heat release per cycle with specific energetic substitution of diesel with CNG for all studied loads.

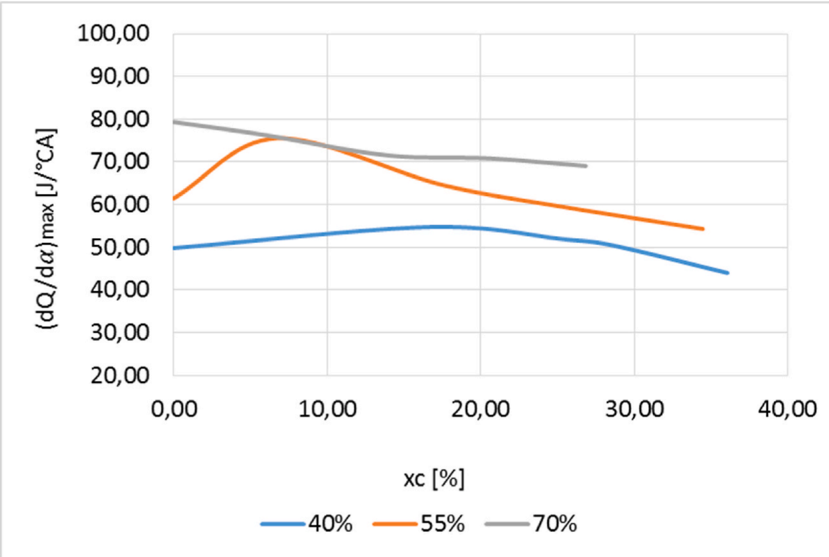

Fig. 23. Variation of maximum heat release rate with specific energetic substitution of diesel with CNG all studied loads.

In standard operating mode, longer diffusive combustion phases will be recorded as the engine loads grows. Injecting CNG in intake manifold will shorten the diffusive combustion phase, for all the studied cases; in DG fueling mode, the engine will produce mechanical work using CNG during the fast combustion phase, and this will reduce the diesel fuel quantity that burns in diffusive combustion phase (10–15 % shorter for low loads and 7 % at high loads). When the engine is fueled in DF mode with diesel fuel and CNG the diffusive combustion is more sensitive to engine load.

Funding statement

Partially, this work was supported by a grant of the Ministry of Research, Innovation and Digitization, CCCDI - UEFISCDI, project number, PN–III–P2-2.1-PED-2021-0427 within PNCDI III.Partially, this work was supported by a grant of the Ministry of Research, Innovation and Digitization, CNCS -, UEFISCDI project number PCE 5/2022, PN–III–P4-PCE-2021-0777, within PNCDI III.

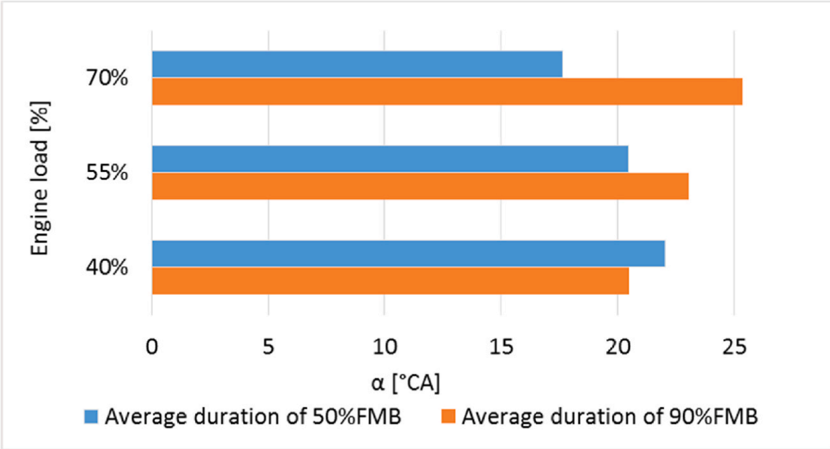

Fig. 24. Variation of fast/diffusive combustion faze average duration with load in standard operating mode.

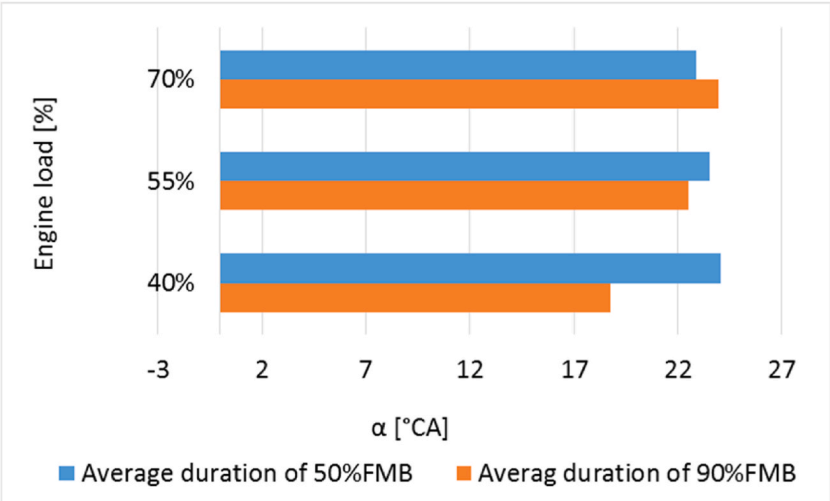

Fig. 25. Variation of fast/diffusive combustion faze average duration with load in DG fueling mode ($x_c = 26$ %).

Additional information

No additional information for this paper.

Data availability statement

The authors certify that the data pertaining to the manuscript is made available on request. data used were specified in the manuscript Data will be made available on request.

CRediT authorship contribution statement

Silviu Rotaru: Visualization, Validation, Software, Methodology, Investigation, Data curation, Conceptualization. **Constantin Pana:** Conceptualization. **Niculae Negurescu:** Conceptualization. **Alexandru Cernat:** Validation. **Cristian Nutu:** Data curation. **Dinu Fuiorescu:** Formal analysis. **Gheorghe Lazaroiu:** Funding acquisition.

Declaration of competing interest

This paper has never been published. The results represent authors new research, the graphics never been published in other journals, magazines, or presented to other conferences.

Acknowledgements

The authors address special thanks to AVL GmbH Graz Austria for providing the necessary equipment's. This work was supported by a grant of the Ministry of Research, Innovation and Digitization, CCCDI - UEFISCDI, project number PN–III–P2-2.1-PED-2021-0427, within PNCDI III. Partially, this work was supported by a grant of the Ministry of Research, Innovation and Digitization, CNCS - UEFISCDI, project number PCE 5/2022, PN–III–P4-PCE-2021-0777 within PNCDI III.

References

[1] J. Seagrave, J.D. McDonald, E. Bedrick, E.S. Edgerton, A.P. Gigliotti, J.J. Jansen, L. Ke, L.P. Naeher, S.K. Seilkop, M. Zheng, J.L. Mauderly, Lung toxicity of ambient particulate matter from southeastern U.S. sites with different contributing sources: relationships between composition and effects, Environ. Health Perspect. 114 (9) (2006) 1387–1393, https://doi.org/10.1289/ehp.9234. PMID: 16966093; PMCID: PMC1570075.
[2] E.S. Schultz, A.A. Litonjua, E. Melén, Effects of long-term exposure to traffic-related air pollution on lung function in children, Curr. Allergy Asthma Rep. 17 (2017) 41, https://doi.org/10.1007/s11882-017-0709y.
[3] Marius Cazacu, Adrian Timofte, Ioan Balin, Dan-Gheorghe Dimitriu, Silviu Gurlui, Complementary atmospheric urban pollution studies in the north-east region of Romania, Iasi County, Environmental engineering and management journal 10 (2011) 139–145, https://doi.org/10.30638/eemj.2011.020.
[4] A. Cernat, C. Pana, N. Negurescu, G. Lazaroiu, C. Nutu, D. Fuiorescu, Hydrogen —an alternative fuel for automotive diesel engines used in transportation, Sustainability 12 (2020) 9321, https://doi.org/10.3390/su12229321.
[5] C. Sandu, C. Pana, N. Negurescu, G. Lazaroiu, A. Cernat, R. Georgescu, C. Nutu, The influence of N-butanol addition in gasoline on the combustion in the spark ignition engine, Sustainability 15 (2023) 14009, https://doi.org/10.3390/su1518140097.
[6] Yousefi Amin, Madjid Birouk, Benjamin Lawler, Ayatallah Gharehghani, Performance and emissions of a dual-fuel pilot diesel ignition engine operating on various premixed fuels, Energy Convers. Manag. 106 (2015) 322–336, https://doi.org/10.1016/j.enconman.2015.09.056. ISSN 0196-8904.
[7] S. Imran, D.R. Emberson, A. Diez, D.S. Wen, R.J. Crookes, T. Korakianitis, Natural gas fueled compression ignition engine performance and emissions maps with diesel and RME pilot fuels, ISSN 0306-2619, Appl. Energy 124 (2014) 354–365, https://doi.org/10.1016/j.apenergy, 2014.02.067.
[8] L. Zhou, Y.-F. Liu, C.-B. Wu, et al., Effect of the diesel injection timing and the pilot quantity on the combustion characteristics and the fine-particle emissions in a micro-diesel pilot-ignited natural-gas engine, in: Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering, vol. 227, 2013, pp. 1142–1152, https://doi.org/10.1177/0954407013480452, 8.
[9] I. Pielecha, K. Wislocki, W. Cieslik, P. Borowski, et al., Analysis of a dual-fuel combustion engine fueled with diesel fuel and CNG in transient operating conditions, SAE Technical (2016), https://doi.org/10.4271/2016-01-2305. Paper 2016-01-2305.
[10] L. Shenghua, Z. Longbao, W. Ziyan, R. Jiang, Combustion characteristics of compressed natural gas/diesel dual-fuel turbocharged compressed ignition engine, in: Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering, vol. 217, 2003, pp. 833–838, https://doi.org/10.1177/095440700321700909, 9.
[11] P. Napolitano, C. Guido, C. Beatrice, N. Del Giacomo, Application of a dual fuel diesel-CNG configuration in a euro 5 automotive diesel engine, SAE Technical (2017), https://doi.org/10.4271/2017-01-0769. Paper 2017-01-0769.
[12] Fatma Zohra Aklouche, Etude caractéristique et développement de la combustion des moteurs Diesel en mode Dual-Fuel : optimisation de l'injection du combustible pilote, Thermique [physics.class-ph]. Ecole nationale supérieure Mines-Télécom Atlantique (2018). Français. ⟨NNT : 2018IMTA0072⟩.
[13] J. Egúsquiza, S. Braga, Carlos Braga, Performance and gaseous emissions characteristics of a natural gas/diesel dual fuel turbocharged and aftercooled engine, Journal of The Brazilian Society of Mechanical Sciences and Engineering - J BRAZ SOC MECH SCI ENG 31 (2009), https://doi.org/10.1590/S1678-58782009000200007.
[14] Mahla, Sunil Kumar et al. Effect of EGR on performance and emission characteristics of natural gas fueled diesel engine, 2010 Jordan Journal of Mechanical and Industrial Engineering 4, pp 524 – 528.
[15] A. Jamrozik, W. Tutak, K. Grab-Rogaliński, An experimental study on the performance and emission of the diesel/CNG dual-fuel combustion mode in a stationary CI engine, Energies 12 (2019) 3857, https://doi.org/10.3390/en12203857.
[16] M. Mbarawa, B.E. Milton, An Examination of the Maximum Possible Natural Gas Substitution for Diesel Fuel in a Direct Injected Diesel Engine, R & D Journal, 2005, p. 21.
[17] https://www.engineeringtoolbox.com/methaned_1420.html.Methane.proprieties.
[18] Wei Lijiang, Geng Peng, A review on natural gas/diesel dual fuel combustion, emissions and performance, Fuel Process. Technol. 142 (2016) 264–278, https://doi.org/10.1016/j.fuproc.2015.09.018. ISSN 0378-3820.
[19] P.F. Flynn, G.L. Hunter, R.P. Durrett, L.A. Farrell, W.C. Akinyemi, Minimum engine flame temperature impacts on diesel and spark-ignition engine NOx production, SAE Trans. 109 (2000) 1286–1297. http://www.jstor.org/stable/44634306.
[20] R.J. Reed, North American Combustion Handbook third ed., vol. 1, North American Mfg Co, 1986. Archived from the original on 2011-07-16, Retrieved 2009-12-09.
[21] Suresh Kumar K., Sudheer Premkumar B., Rajagopal K., Murthy V.S.S., Rao S., NagaRaja C., Effect of pilot fuel quantity on the performance and emission characteristics of a pre-mixed CNG - diesel dual fuel mode engine, IOSR-JMCE, e-ISSN: 2278-1684, p-ISSN: 2320-334X, Volume 9, Issue 2, (Sep.-Oct 2013).
[22] M. Muralidharan, A. Srivastava, M. Subramanian, Full load investigation of CNG–diesel dual- fuel heavy-duty engine with selective catalytic reduction on engine performance and emissions for its potential use, SAE Int. J. Engines 15 (3) (2022) 393–411, https://doi.org/10.4271/03-15-03-0020.
[23] Mansor W.N. Wan, Dual Fuel Engine Combustion and Emissions – an Experimental Investigation Coupled with Computer Simulation, PhD paper, Colorado State University Fort Collins, Colorado, Fall, 2014.
[24] J.C. Egusquiza, S.L. Braga, C.V.M. Braga, Performance and gaseous emissions characteristics of a natural gas/DDF turbocharged and aftercooled engine, J. Braz. Soc. Mech. Sci. Eng. 31 (2) (2009) 142–150, https://doi.org/10.1590/S1678-58782009000200007.
[25] I.A. Resitoglu, K. Altinisik, A. Keskin, The pollutant emissions from diesel-engine vehicles and exhaust aftertreatment systems, Clean Technologies and Environmental Policy 17 (1) (2014) 15–27, https://doi.org/10.1007/s10098-014-0793-9.
[26] F. Königsson, On Combustion in the CNG-Diesel Dual Fuel Engine, Royal Institute of Technology SE-100 44, Stockholm, 2014. PhD paper.
[27] M.Y.E. Selim, Pressure–time characteristics in diesel engine fueled with natural gas, Renew. Energy 22 (4) (2001) 473–489, https://doi.org/10.1016/S0960-1481(00)00115-4. ISSN 0960-1481, https://www.sciencedirect.com/science/article/pii/S0960148100001154.
[28] P.W. Schaberg, T. Priede, R.K. Dutkiewicz, Effects of a Rapid Pressure Rise on Engine Vibration and Noise, SAE paper 900013, 1990, https://doi.org/10.4271/900013. ISSN: 0148-7191, e-ISSN: 2688-3627.
[29] G. Galinsky, G.T. Reader, I.J. Potter, R.W. Gustafson, Effect of various working fluid compositions on combustion noise in diesel engines, The University of Calagary (1994) 1157–1162. Canada, AIAA-94-3996-CP.
[30] Renault -k9k Engine Specification 2004.
[31] Gehandler Jonatan, Lönnermark Anders, CNG Vehicle Containers Exposed to Local Fire, RISE Research Institutes of Sweden, 2020. RISE Rapport 2019:120_rev1, ISBN 978-91-89049-73-4, ISSN 0284-5172, Borås.
[32] ISO 11439, Gas Cylinders — High Pressure Cylinders for the On-Board Storage of Natural Gas as a Fuel for Automotive Vehicles, second ed. 2013-06-01.
[33] https://landirenzo.com/en, CNG fueling system.
[34] Unichip Q00897 Manual, 2007.
[35] N. Negurescu, C. Pană, M.G. Popa, Internal Combustion Engines. Processes, Publisher Matrixrom, Bucharest, 2009.
[36] Marcel Ginu Popa, Niculae Negurescu, Constantin Pana, Diesel Engines, Publisher Matrixrom, Bucharest, 2003.

[37] N. Negurescu, C. Pană, M.G. Popa, Processes in ICE, vol. II, Editura MATRIX ROM, București, 1996.
[38] Alexandru Cernat, Simulation of Thermal Machines Operation, 2019 lecture, UPB.
[39] Y. Karagöz, T. Sandalcı, U.O. Koylu, A.S. Dalkılıç, S. Wongwises, Effect of the use of natural gas–diesel fuel mixture on performance, emissions, and combustion characteristics of a compression ignition engine, Adv. Mech. Eng. 8 (4) (2016), https://doi.org/10.1177/1687814016643228.
[40] Rotaru Silviu, Pană Constantin, Negurescu Nicolae, Cernat Alexandru, Fuiorescu Dinu, Nikolaos Nutu Cristian, Experimental investigations of an automotive diesel engine fueled with natural gas in dual fuel mode, ACME 2020/IOP Conf. Series: Materials Science and Engineering 997 (2020) 012130, https://doi.org/10.1088/1757-899X/997/1/012130. IOP Publishing.
[41] Silviu Rotaru, Constantin Pană, Nicolae Negurescu, Gheorghe Lazaroiu, Alexandru Cernat, Dinu fuiorescu, cristian nikolaos Nutu, researches regarding the CNG use at an automotive diesel engine, SMAT (2019).