National University of Science and Technology
POLITEHNICA BUCURESTI
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PHD THESIS ABSTRACT

RESEARCHES REGARDING THE USE OF CNG TO THE CARS DIESEL ENGINE

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Summary

Key words: diesel-gas fueling mode, DF, DG, CNG, compressed natural gas, bi-fuel, indirect injection, lower heating value, octane number, diesel engine, average indicated pressure, carbon dioxide, nitrogen oxides, non-arsenic hydrocarbons, PM particles,

Introduction

The PhD thesis entitled *RESEARCHES REGARDING THE USE OF CNG TO THE CARS DIESEL ENGINE* is part of the concerns of the research team of the Department of Thermotechnics, Engines, Thermal and Refrigeration Equipment (TMETF), Faculty of Mechanical and Mechatronics Engineering (FIMM) of the National University of Science and Technology POLITEHNICA BUCUREȘTI. The thesis contains original contributions in the field of the study of the influence of compressed natural gas in diesel engines fueled in diesel-gas mode. The work also brings novelty in the field of mathematical modelling where, starting from the basic elements of the AMESIM software tool, a numerical model is developed for the analysis of the influence of the use of CNG in diesel engines.

The 185-page paper is divided into six chapters, contains 25 tables and 196 figures, and at the end of the paper there are 109 bibliographical references numbered in the order of their citation in the thesis.

Chapter 1 gives a general overview of the international context that has favored the growth of compression ignition engines used in cars; then the main factors that have led to the decline of the diesel engine and the shift of researchers towards the study of alternative fuels are presented. The chapter also contains a brief description of the physical and chemical properties of compressed natural gases that make them eligible for use in automotive diesel engines. The chapter also includes brief descriptions of the technological processes for obtaining, transporting and storing compressed natural gas as well as the methods of fueling the engine with this fuel.

Chapter 2 makes a detailed investigation of the state of the art of research into the use of natural gas in compression ignition engines. The analysis of theoretical and experimental research was aimed at evaluating the influence of compressed natural gas on combustion (auto-ignition delay time, maximum pressure, heat release rate, specific energy/fuel consumption, thermal efficiency, combustion duration), energy and pollution performance of the compression ignition engine for different operating regimes and different degrees of CNG diesel substitution.

The main objective of **Chapter 3** was to study and analyse the influence of the use of compressed natural gas on the performance of the diesel engine of a diesel-gas fueled car. The results obtained in conventional operation were used as references; the data recorded in operation of the engine fueled in DG mode were compared with the references in order to draw conclusions on energy and pollution performance for different operating regimes and for several degrees of diesel substitution with compressed natural gas.

Chapter 4 presents the process of developing the thermo-geodynamic model using the AMESIM software tool. The modelling activity is divided into two main parts: the part of building the mathematical model from the basic elements available in the AMESIM software tool and the part of parameterization of the obtained model.

In **Chapter 5**, the results obtained by calculation using the AMESIM software tool are compared with those determined experimentally at the loads studied (40%, 55% and 75%) for different energy substitution coefficients of diesel with compressed natural gas. The successful completion of the parameterization and validation stages of the mathematical model makes it possible to further analyze the influence of diesel engine fueling in DG mode; by calculation it is possible to obtain the values of some quantities or parameters that could not be determined experimentally: temperature evolution (in the cylinder, flue gas, fresh charge), quantity of unburned fuel remaining in the cylinder, quantity of flue gas remaining in the cylinder, gas compression force on the piston, etc.

Chapter 6 presents the final conclusions of the PhD thesis; personal contributions are presented and future directions are described.

The paper concludes with a list of published works in extenso and bibliographical references in the order of their citation in the text

Thanks

This work is the culmination of considerable efforts by people on whose support I have always been able to rely.

Thanks are addressed to the scientific leader, ***Prof. Dr. Ing. Constantin PANĂ*** *for his continuous and rigorous guidance throughout this work.*

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Author

Chapter 1 - Relevance of the research topic

1.1. Description of the international framework and identification of the opportunity of using CNG in diesel car engines

The implementation of regulations, [22] which have favored the excessive growth of the number of diesel-powered cars has led to an alarming increase in some pollutant species (NO_x , PM particles) resulting in exhaust gases which have a negative impact on health and even on human life.

According to a study carried out by the World Health Organization (HRAPIE Project (Health risks of air pollution in Europe), after interviewing 100 experts, individuals or companies with interests and activities strictly related to air quality, it was concluded that the most important source of pollutant emissions (out of a total of 16 respondents) is road transport, accounting for 40.7%. The sector of activity of the interviewees is environmental protection or public health, medicine, transport. As can be seen in the diagram below (Figure 1.1), the most harmful elements in engine emissions are nitrogen oxides, fine and ultra-fine particles and metals [23].

In May 2002, the United States Environmental Protection Agency published a very important report, that informs the society about the various diseases that can affect people who come into contact with diesel exhaust gases. The components of exhaust gases that cause the most serious health problems are fine and ultra-fine particulate matter, sulphuric acid particles and sulphates and nitrogen oxides. Studies have been carried out both in laboratories on different categories of animals but have also highlighted social categories whose jobs or homes put them at high risk of diseases directly related to exposure to diesel exhaust (truck maintenance crews, mining workers). IN VITRO studies were also conducted to highlight the severity of the conditions caused by exposure to diesel exhaust. Among the diseases that are caused by exposure to diesel engine emissions are: malignant and benign tumors, genetic mutations, respiratory system diseases, skin diseases, etc, [24].

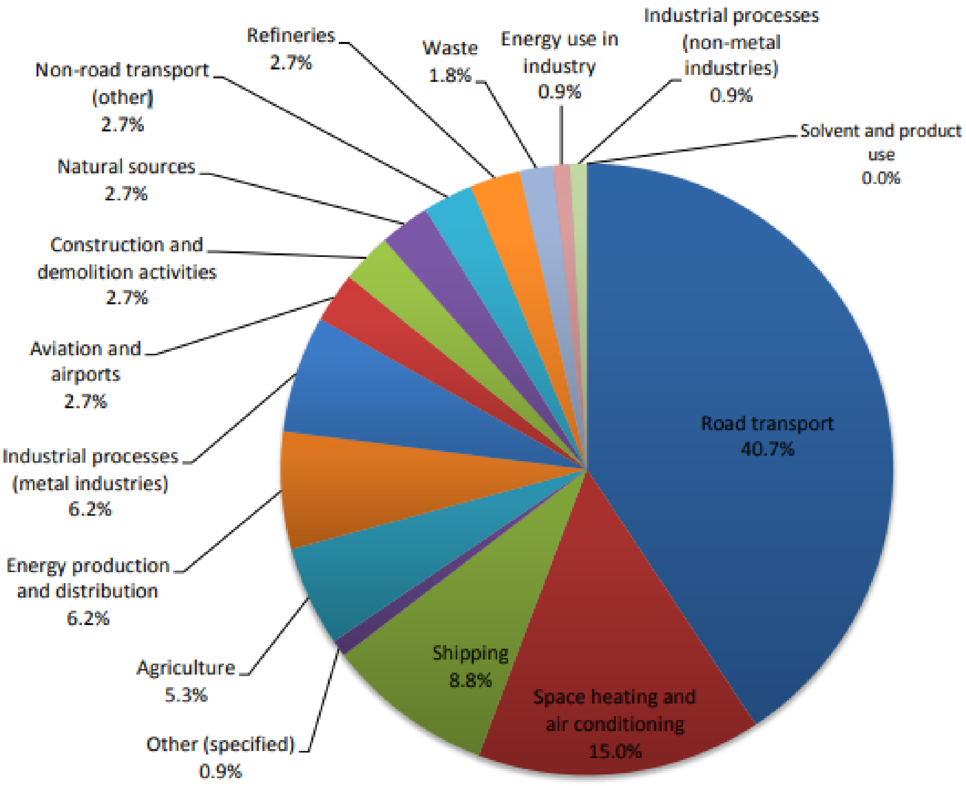

Figure 1.1 Health-risk emissions, [23]

The global focus on the alarming increase in environmental pollution and the main sources of polluting emissions are becoming very important issues. Detailed studies show the impact on the health of people living or working in urbanized or industrialized areas, [2],[3],[4]. In response, governments are implementing increasingly stringent measures for both transport and stationary engines; new procedures and equipment for measuring vehicle emissions are being developed (e.g. Real Driving Emission with PEMS - portable emission measurement system). In this global reality, researchers are looking on the one hand to improve combustion and exhaust gases treatment and on the other hand to identify alternative fuels that are less polluting and have better combustion properties than conventional ones.

The growing concern for reducing nitrogen oxides and PM emissions from compression ignition (CI) engine exhausts and the ever-increasing demand for alternative energy for automotive propulsion make compressed natural gas an attractive alternative for converting CI engines, making more accessible the automotive industry's path towards hydrogen, hybrid and electric propulsion.

Compressed natural gas is a viable alternative not only because it is widely available, but also because of its low price, the possibility of fueling the car in households and its very "clean" combustion compared to conventional fuels. Compared to diesel engines fueled with diesel, the exhaust gas emissions of CO_2 , PM and nitrogen oxides are significantly reduced when burning bi-fuel (diesel-CNG), but the percentages of HC and CO can increase in certain speed ranges and loads by up to 100 times. Compressed natural gas releases less CO_2 when burned because it has the fewest carbon atoms per unit of energy of all fossil fuels.

The literature presents performances, emissions and highlights the benefits of fueling a diesel engine in dual mode with multiple fuels: Aklouche, [14] summarizes the benefits of fueling the engine with CNG and biogas. Egúsquiza, [15], presents the energy performance and emissions of a CNG fueled supercharged engine, taking as a benchmark the operation of the engine when it is conventionally fueled. Mahla, [16], demonstrates that the negative impact on unburned hydrocarbon emissions can be reduced by using the Exhaust Gases Recirculation System. The behavior of a CNG stationary engine fueled in DG mode is analyzed by Jamrozik, [17], while M. Mbarawa, [18], presents the influences of bi-fueling with compressed natural gas on auto-ignition delay and exhaust gas temperature.

The increased interest in compressed natural gas is justified by the following factors: lower carbon content (76% carbon compared to diesel which has 86% carbon), higher lower heating value than conventional fuels (48.6MJ/kg), very high resistance to detonation (octane number 130) and ease of procurement.

The high lower heating value of compressed natural gas and its gaseous state lead to significant reductions in specific energy consumption.

The high-octane number gives compressed natural gas a very good resistance to detonation and thus favors its use in engines with high compression ratios.

The high auto-ignition temperature of CNG imposes the need to initiate combustion either by self-ignition of a diesel pilot, by spark from a spark plug or by the mixture coming into contact with a hot surface (glow plug); when the engine is fueled in DG mode, compressed natural gas is injected into the intake manifold to mix with the air introduced into the cylinder; the air-CNG mixture is ignited in the cylinder by a diesel pilot.

In the exhaust gas, a significant decrease of CO_2 , PM and nitrogen oxides is observed in the bi-fuel combustion (diesel-CNG); the low carbon content in CNG (75% according to [26]) explains the presence of a lower percentage of CO_2 and PM per energy unit in the exhaust gases; according to [27], temperatures of 1930-2080°C in the cylinder are the most favorable for the appearance of nitrogen oxides; the use of compressed natural gas with a maximum flame temperature of 1790°C, [28], can lead to lower cylinder gas temperatures and thus lower NO_x levels in the exhaust gas.

The higher specific heat of compressed natural gas than the specific heat of air [29], may result in a reduced temperature at the end of compression stroke due to the higher specific heat of the homogeneous air-CNG mixture favoring a longer self-ignition delay time.

At the other end of the spectrum, HC and CO percentages can increase in certain low and medium speed ranges and loads by up to 100 times compared to similar tests done for standard operating mode; flame quenching at the cold wall is one of the reasons for the increased HC levels in the exhaust; CO emission is determined by cylinder oxygen concentration, cylinder gas temperature, eddy current intensity; the influence of CNG on these factors, (decreases oxygen concentration, decreases cylinder temperature), can increase CO levels.

1.2. Objectives of the work

The main objectives of the PhD thesis are:

- Analysis of the international context.
- Analysis of the physical and chemical properties of CNG compared to diesel and determination of the impact of CNG use on diesel engine functionality.
- Analysis of the current state of research in the field.
- Optimization of the experimental engine test bench.

- Conducting experimental investigations on the test stand.
- Modeling numerical processes in the cylinder of CNG-fueled diesel engine.
- Validation of theoretical investigation results.
- Dissemination of the results of the theoretical and experimental investigations carried out.
- Establishing new research directions in the field.

Chapter 2 - Analysis of the state of research

2.1. Analysis of the results of experimental research in the field

The influence of natural gas use on ***peak pressure*** is the subject of many scientific articles. S. Imran shows that in DG mode the maximum cylinder pressure is lower than in diesel mode and is reached later on the cycle, especially at low and medium loads and speed ranges, due to reduced diesel injection advance and reduced cylinder filling, [8]. Liu Shenghua and co-workers conclude that the maximum pressure is up to 24% lower than in standard fueling due to too high energy substitution coefficient not adapted to the engine speed and load regime, inadequate advance and diesel pilot, [11]. K. Suresh Kumar and co-workers will demonstrate that for all operating regimes analyzed, the maximum pressure reached in DG fueling mode is lower than that recorded in diesel fueling. The authors attribute this result to the lower combustion rate of the air-gas mixture; oxidation reactions are slower and tend to be incomplete at low and medium loads, [37].

Heat release and heat release rate are some of the quantities considered when the engine is powered in DG mode. The heat release rate in DG fueling mode is lower in terms of maximum value but also delayed by at least 7°CA, [11]. In standard fueling, the main injection combustion occurs with a certain delay compared to the start of pilot burn (due to the injection delay and the time required for vaporization) which can be observed by a decrease in the heat release rate; in DG fueling mode, the homogeneous air-CNG mixture already exists in the cylinder at the appearance of the flame nuclei due to the diesel pilot; the flame propagates rapidly in the volume of the homogeneous air-CNG mixture, [11]. F.Z. Aklouche, presents the negative impact of CNG use; the heat release in diesel-gas fueling mode is lower than in standard operation, but reaches the threshold of 90% of the total quantity faster per cycle; in DG fueling mode the rate of pressure rise loses its intensity because by reducing the diesel pilot fewer flame nuclei will result from which the flame propagates, [14].

The auto-ignition delay time is 3-4°CA longer than it is standard fueling mode due to the reduction in the quantity of air admitted into the cylinder; the author of the paper [37] suggests that methane has a chemical inhibiting effect on diesel fuel by reducing the cetane number which can lead to an increase in auto-ignition delay.

Specific energy consumption is identified as having higher values in the low load area due to faulty combustion control in diesel-gas fueling mode. From loads above 40%, operation in DG mode is preferable. Increased engine efficiency in DG fuel mode results in decreases of up to 50%

of the total cost when using diesel as fuel, [19]. Specific energy consumption is higher in DG power mode at low engine speeds, decreases by up to 8% in the 1200-2000 rpm range, and at high engine speeds increases due to the flame quenching, [13]. The author points to the lower heating value as the main factor causing a decrease in specific energy consumption. At low loads, low cylinder temperatures as well as wall flame quenching may be some of the causes of increased specific energy consumption.

Engine power will increase by up to 5.2% and ***engine torque*** by up to 5.8% with increasing CNG flow rate used; the increase in power and engine torque are attributed to the high lower heating value of natural gas and increased homogeneity of the air-fuel mixture, [13].

According to the paper [8] ***the NO_x emission*** when the engine is fueled in DG mode, is lower than in standard operating mode for two reasons: the quantity of air inside the cylinder is lower and the higher specific heat of CNG than that of air causes a lower temperature in the cylinder at the end of compression; the author shows with the help of the REFPROP program that the temperature of the homogeneous air-CNG mixture at the end of compression stroke is reduced by up to 100K. In DG fueling mode, once the medium load and speed regimes are reached, decreases in NO_x concentration of up to 50% compared to the diesel fueled engine can be recorded, [8]. In both of the fueling modes, the NOx emission increases with increasing load, but the lack of a precise correlation between the flow rates of the two fuels can lead to an increase in NO_x emission of up to 1500 ppm in DG fueling mode at high loads; the author implies that NO_x emissions may also be related to the occurrence of knock. At high loads, a large pilot injection will generate a high number of nuclei that will increase heat releasing rate. Increasing in-cylinder pressure and temperature above a certain threshold favors the occurrence of knock. In the area of leaner mixtures, very high temperatures favor the triggering of the Zeldovich mechanism, [11].

F. Königsson estimates that 50% of ***HC emissions*** are due to fuel blockage in the crevices between piston, cylinder and piston rings, [43]. The swirl effect can reduce up to 20% of emissions. When the excess air index increases above 1.8, flame quenching due to too lean mixture becomes the main cause for the increase in HC concentration, [42]. HC emissions are mainly higher when the engine is fueled in DG mode primarily due to the lack of air but also due to flame quenching at cylinder wall. At partial load, when 45% of the energy is provided by CNG, HC emissions increase by up to 800% compared to standard operation mode; at full load (when more than 65% of the energy is provided by CNG) HC emissions are 250% higher than at standard fueling mode. Increased engine load leads to high in-cylinder temperature and high intensity tumble - swirl currents and these factors positively influence combustion quality, [8].

Diesel engine fueled in DG mode has a big advantage in terms of ***carbon dioxide emissions***, which are reduced by up to 12% at an average CNG diesel substitution ratio of 35%, [12]. The low carbon content of compressed natural gas is the main reason for the reduction of carbon dioxide emissions, [41].

Carbon monoxide emission is negatively influenced by CNG injection up to an average indicated pressure of 0.6MPa because, at low loads, reduced in-cylinder temperature favors incomplete combustion, [11]. At medium loads the in-cylinder temperature increases, combustion improves and CO concentration decreases. Throughout the load range, the CO emission concentration is higher in DG mode due to the smaller quantity of air in the cylinder [19], [43], [14]. Carbon monoxide emission is controlled by the mixture quality, lack of air leads to incomplete combustion. Over the entire engine speed range, the carbon monoxide emission concentration is lower in the DF fueling mode due to the lower carbon content in the CNG, figure 2.43, [13].

PM emission is lower throughout the entire load range when the engine is fueled in DG mode, [14]. The author mentions about the linear carbon bonds, C-C, present in diesel fuel which in the phase of diffusive combustion dissociate at high temperatures determine high particles emission. Compressed natural gas does not have these carbon-carbon bonds and thus the PM emission tends to very low values in DG fueling mode. The main reasons for the reduction of smoke emission are the low carbon content of CNG as well as the reduction of the percentage of heavy fractions on the cycle. The low carbon content as well as the higher heating value of CNG leads to the reduction of carbon per energy unit, which favors the reduction of the smoke emission concentration when fueling the engine in DG mode, [11].

Mohamed Y.E. Selim, [49], draws conclusions from the analysis of experimental data on the ***noise level*** of the engine fueled in diesel-gas mode with CNG compared to standard operating mode. The author demonstrates a direct relationship between the pressure rise rate (dp/dα) and the noise level produced by the engine. The noise pollution of the engine fueled in DG mode is also studied in [50], [51], [52].

2.2. Conclusions Chapter 2

The following conclusions can be drawn from the analysis of the influence of compressed natural gas on diesel engine performances when it is fueled in the diesel-gas mode:

- **Maximum in-cylinder pressure→** The maximum in-cylinder pressure increases with increasing CNG diesel substitution due to the increased proportion of fast combustion. By changing the advance of the diesel pilot injection, the maximum pressure can be reduced below the value for standard fueling mode.
- ***Auto-ignition delay→*** The auto ignition delay duration of the diesel pilot increases with rise of substitution ratio of diesel fuel with CNG due to the reduction in the quantity of air in the cylinder, the in-cylinder temperature at the end of the compression process and the chemical inhibition effect of diesel in the presence of methane which may suggest a decrease in cetane number.
- ***Heat release rate→*** The heat release rate in DG fueling mode is higher because longer auto-ignition delay favors the vaporization of a larger quantity of diesel, increasing the homogeneity of the mixture and increasing the fast-burn phase percentage. By modifying the advance of the diesel pilot injection, the heat release rate can be reduced.
- ***Specific consumption→*** The specific fuel/energy consumption is higher in the low load area due to flame quenching at the wall, air-CNG mixture escape in the exhaust manifold during valve overlap.

From loads above 40%, CNG operation is more efficient due to improved combustion.

- ***Engine power and torque*** → The lower heating value of compressed natural gas causes the engine power and torque to increase in DG fueling mode for all operating modes.
- ***Emission of nitrogen oxides*** → NO_x concentration drops due to a reduction in the quantity of air in the cylinder and the gas temperature.
- **Emission of unburned hydrocarbons** → Unburned hydrocarbons are up to 800% higher in DG fueling mode than in standard operation at low and medium loads. At high loads, although lower, the hydrocarbon emission still has a higher concentration than when using diesel only due to the reduced quantity of air in the cylinder.
- ***Carbon dioxide emissions*** → The low carbon content of CNG leads to lower CO_2 emissions; the higher heating value of methane compared to diesel makes carbon dioxide emissions even lower.
- ***Carbon monoxide emissions*** → Carbon monoxide can increase its concentration by up to 20% compared to burning diesel fuel alone due to the reduction of air in the cylinder.
- ***Smoke emission*** → The quantity of PM decreases due to the lower carbon content in the CNG molecule.
- ***Optimizing diesel engine operation in DG fueling mode***

When using CNG as alternative fuel are the main objectives: reducing specific fuel/energy consumption, reducing emissions concentration, increasing power and engine torque. This can be achieved by changing the pilot injection advance, diesel pilot quantity, coolant temperature.

Increasing the quantity of diesel pilot has the effect of increasing in-cylinder pressure, decreasing auto-ignition delay and combustion duration, reducing CO concentration in the exhaust gas, but causes an increase of up to 52% in the concentration of nitrogen oxides and 150% in the concentration of hydrocarbons.

Reducing the advance on diesel pilot injection results in a reduction of autoignition delay and NO_x concentration in the exhaust gas but will increase CO and HC concentration in the exhaust gas and the specific consumption.

Disadvantages of using CNG

- Clogging the diesel injector orifices is a problem that occurs when the injector injects only 10% of the required quantity 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. Adding a copper jacket around the injector tip ensures its thermal protection.
- Compliance with pollution standards requires the development of a high-performance electronic diesel and CNG injection control system that can set the optimum ratios for the two fuels according to engine speed and load so that both pollution standards and engine power and torque requirements are met.
- CNG direct injection, although it solves the problem of pollutant emissions, still requires extensive research to perfect the diesel/gas injector.
- The in-cylinder pressure rise rate when engine is fueled 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 injected can lead to detonation.

- Storing CNG at 240 bar requires a high cylinder mass and a large occupied volume; the small space and low payload of cars make them less eligible for retrofitting with this type of system compared to the LPG system.

Chapter 3 - Experimental Investigations of CNG-fueled Diesel Engine

The first paragraphs of this chapter reviews the laboratory equipment with which the experimental investigations were carried out: the compressed natural gas supply system in the intake manifold, the Schenck E90 electric eddy current brake, the compression ignition engine with the specific modifications for dual mode fueling, the monitoring and control panel, the pollutant emission measurement equipment, the air and fuel flow measurement equipment, the diesel fueling system, the compressed natural gas supply system.

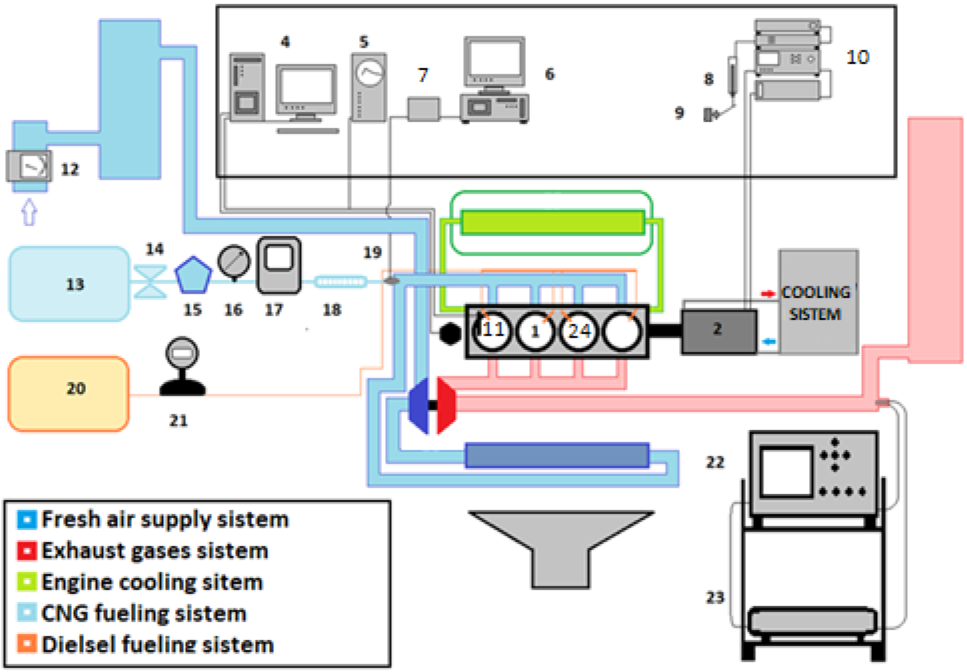

Figure 3.4 General layout of the engine test bench

Table 3.2 General composition of the experimental test stand

Crt. no.	Element
1	Engine
2	Electric eddy current brake
3	Cooling unit for the braking system
4	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 dynamometer
12	Air volumetric flow meter
13	Pressure vessel 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 CNG consumption
18	Flame extinguisher
19	Block of compressed natural gas injectors
20	Diesel fuel tank
21	Mass flow meter for measuring diesel fuel consumption
22	Gas analyzer
23	Smoke emission measurement enclosure
24	Ventilator
25	Crankshaft position translator
26	Pressure transducer in cylinder
27	Diesel injector
28	Turbocharger
29	Water cooler

The diesel engine is fueled in diesel-gas mode: this procedure involves injecting compressed natural gas into the intake manifold; this produces the air-CNG mixture which, once in the combustion chamber, is ignited at the end of compression by a diesel pilot, Figure 1.6.

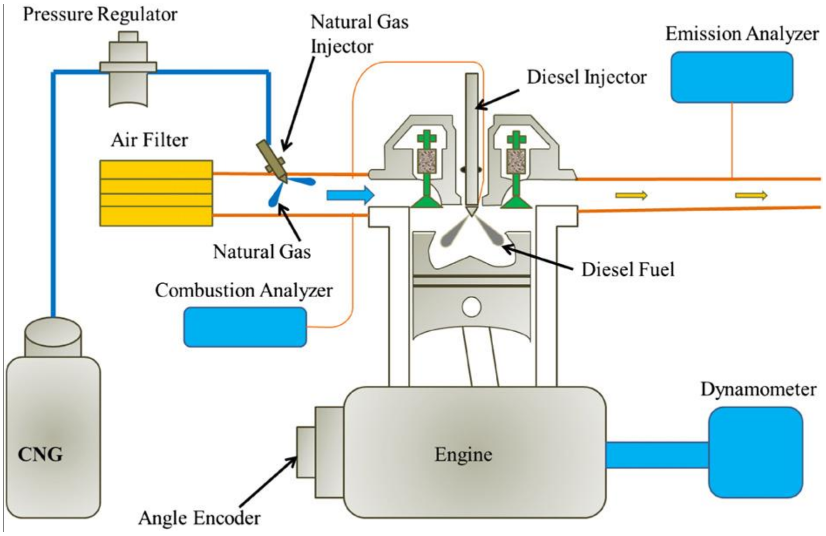

Figure 1.6 Schematic diagram of the main elements of a diesel-gas engine test bench for performance and stability testing, [26].

The results experimentally determined on a Renault diesel engine K9K K792 for the studied regimes (40%, 55% and 70% loads) at 2000 rpm and for different CNG-diesel energy substitution coefficients were presented.

The duration of ***self-ignition delay*** decreases in all cases studied. The greatest reduction in auto-ignition delay is found at high loads (11°CA for the maximum CNG-diesel energy substitution coefficient).

As the energy substitution coefficient of diesel fuel with CNG increases, the ***in-cylinder pressure*** diagram will show an increase in the proportion of preformed mixture combustion due to the increased homogeneity of the air-fuel mixture in the cylinder.

Cylinder ***pressure*** increases by up to 10% for all loads studied when the substitution coefficient reaches its maximum value; this increase is due to the higher net heating value and increased homogeneity of the air-fuel mixture in the cylinder. ***The maximum rate of pressure rise*** is positively influenced when fueling the engine in DG fueling mode; for all energy substitution coefficients the proportion of preformed mixture that will burn in the fast burn phase increases.

Specific energy consumption decreases by up to 50% at low and medium loads and by up to 38% for 70% loads; for all studied operating regimes, specific energy consumption decreases significantly, which is in line with the intent of all vehicle manufacturers: maximum effective efficiency with the aim of protecting resources and the environment, [93], [94]. The decrease in specific energy consumption is due to the higher lower heating value of compressed natural gas and the increased percentage of preformed mixtures combustion.

The duration of the fast-combustion phase decreases with increasing engine load due to the increase in the number of flame nuclei from which combustion will propagate into the preformed mixture. CNG injection will increase the duration of this phase and make it less sensitive to increasing loads.

The duration of the diffusive combustion will increase with increasing engine load due to a higher quantity of diesel burned in this phase. The injection of CNG will shorten this phase by reducing the main diesel dose per cycle and make it more sensitive to increasing load.

For all the studied regimes the injection of compressed natural gas will increase the ***quantity of heat*** released per cycle.

CNG intake will has a positive impact on the ***heat release rate*** of the preformed mixture that is formed from diesel pre-injection vaporization; DG fueling mode has a negative impact on the ***maximum heat release rate***.

For all regimes studied, compressed natural gas injection has a negative effect on the ***stability of the auto-ignition delay***, ***the end of the fast-burn phase*** and ***the end of the diffuse-burn phase***. If for $\alpha_{5\%FMA}$ stability the influence of CNG is high, the CoV for the end of the diffuse combustion phase has low values.

Increased engine load leads to improved combustion stability.

The injection of compressed natural gas has a predominantly negative influence on the ***coefficient of variation of the maximum in-cylinder pressure***; this phenomenon can occur due to imprecise control of the quantity of CNG admitted into the cylinder. Fueling the engine in DG mode has very little impact on the CoV_{pmax} .

The mean indicated pressure is positively influenced by CNG injection for all the regimes studied; reducing the species variation of the fuel dose per cycle can give similar values of the specific mechanical work done on different cycles.

CNG injection causes a decrease in ***carbon dioxide*** emissions for all studied engine operating regimes; increasing engine load causes a reduction in CO_2 concentration when using CNG; while at low loads the CO_2 concentration decreases by 20% at 70% load it does not decrease by more than 7%. The decrease in CO_2 emissions is due to the low carbon concentration in the composition of the alternative fuel. Considered a major contributor to the greenhouse effect, carbon dioxide is also currently setting the threshold for charging companies for both vehicle production and engine emission levels; current studies show methods of reducing carbon dioxide in the atmosphere by capturing it [95].

At low and medium loads, the emission of ***nitrogen oxides*** is up to 10% higher when the engine is fueled in DG mode; at 70% load, CNG injection has a positive influence, with the engine emitting up to 33% less NO_x. The following factors can positively influence the NOx concentration: less air available per cycle (substituted by CNG), lower temperature of the flame produced by CNG and shorter formation time (due to the increased percentage of the fast combustion phase).

When the engine is fueled in DG mode, the emission of ***unburned hydrocarbons*** is higher for all studied engine speeds (conclusion also confirmed by [96] for the studied engine speeds). The main factors are: CNG trap in the piston-cylinder crevices and CNG passing directly into the exhaust manifold during valve opening overlap. For low loads lean-burn flame quenching may be another reason for increased emission of unburned hydrocarbons.

Smoke emission is influenced in different ways:

- At low loads the compressed natural gas supply increases the smoke emission, primarily due to incomplete combustion promoted primarily by the low engine thermal regime.
- At medium loads, against the background of increasing cylinder temperature, the general trend is a decrease in smoke emission with increasing substitution ratio x_c.
- At high loads there is a 30% decrease in smoke emissions with increasing substitution ratio x_c,

Chapter 4 - Modelling of numerical processes in the compression ignition engine cylinder

In order to build a model that would generate data with values similar to those determined experimentally, we started from a predefined AMESIM system: Engine_SingleCylinder_Diesel. This model underwent a number of modifications: the in-cylinder combustion model was replaced by one using a 12-gas fluid; the models of the intake manifold respectively exhaust manifold were replaced by models for constant volume and pressure enclosures also using 12-gas fluid; injectors were added for more accurate simulation of diesel injection (pre-injection, main and post injection), a new injection system for compressed natural gas supply was added; although the initial modification represented the physical system (indirect injection into the intake manifold), the limitations of the AMESIM software tool (natural gas admitted to the cylinder together with the air required for combustion is not considered fuel but burnt gas) led to the addition of a direct fuel injection system for which injection was done at 120 °CA before PMI, Figure 4.2; taking advantage of the model parameterization that all fuel injected before the start of combustion will generate by vaporization preformed mixture and burn in the fast combustion phase, we can say that with CNG injection the share of preformed mixture will increase and the combustion in the cylinder will acquire features similar to the combustion of homogeneous mixtures; the model built is representative for further investigations.

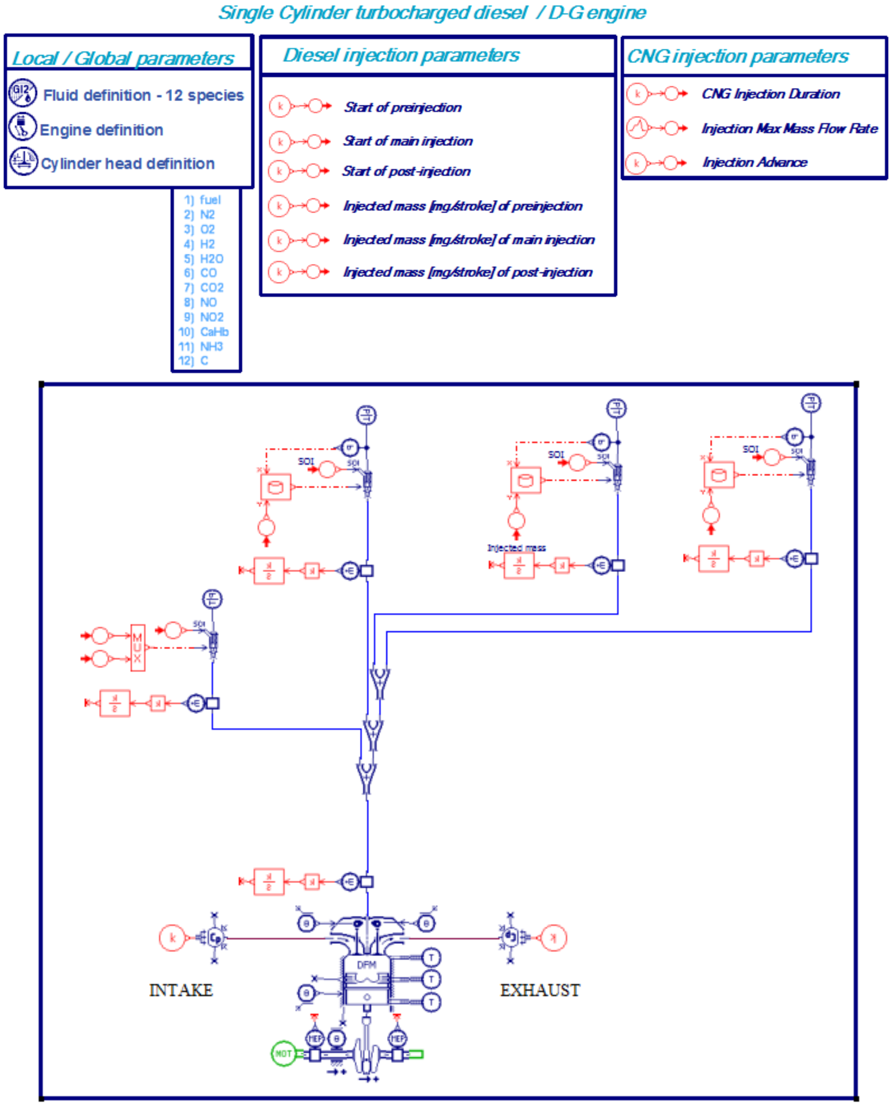

Figure 4.2 Numerical model for combustion simulation in standard and DG mode single-cylinder diesel engine

After optimization, the system contains the following submodels:

- the generator for engine speed (PM000);
- model for measuring the indicated mean pressure (ENGMEPSE11);

- model for the calculation of the engine torque (ENGCRK31);
- source for zero torque (T000);
- model for simulating combustion in a diesel engine cylinder (ENG12DFM00);
- model for the lower part of the engine head where heat transfer, the quantity of air admitted to the cylinder and the quantity of exhaust gases are calculated) (ENG12CYLH030);
- the model for the upper part of the engine head where the valve lift law and the angular position synchronization of the crankshaft (ENGCYLH010) are implemented;
- constant temperature and pressure sources (ENGCS001);
- multiple injection joints (ENGMINJ01);
- angular position sensor (ENGGLBAS21);
- crankshaft position generator (ENGGLBA11);
- pressure sensor (ENGTFPSE02);
- volume with heat input according to the use of 12-gas engine fluid (ENG12CH03);

The global calibration of the model is achieved through the following categories of parameters:

- ***definition of the fluid*** involved in the combustion process (air, diesel, CNG, and exhaust gas). These parameters represent the physical and chemical properties of the engine fluid (air, fuel, exhaust gas) on which the mathematical model will operate. This submodel uses 12 gases (Fuel, N_2 , O_2 , H_2 , H_2 O, CO, CO_2 , NO, NO_2 , HC, NH_3 , PM particles) and one liquid (for the liquid the values x, y respectively z in CxHyOz will be parameterized to calculate the fuel vaporization time). The main fuel parameters used by the mathematical model are: lower heating value, carbon, hydrogen, oxygen content, fuel density in liquid state, specific heat of fuel in liquid state, latent heat of vaporization, specific heat at constant pressure, viscosity, thermal conductivity, perfect gas constant.
- ***the engine definition*** contains the physical characteristics of the engine that influence its performance.
- ***the definition of the intake / exhaust valve***, provides the possibility to modify the dimensions, the opening/closing moments as well as the valve lift laws.
- ***global parameterization*** to increase efficiency in working with the AMESIM software tool: for example, if a general temperature used by several submodels is required, it can be entered in a set of global parameters; this temperature will be updated simultaneously in all submodels using it.
- ***local parameterization for each subsystem*** (e.g.: with the PM000 engine speed was set, model for in-cylinder combustion simulation: initial temperature and pressure conditions, injector physical characteristics, parameters specific to auto-ignition delay calculation, parameters specific to combustion calculation, parameters specific to pollutant emission calculation, parameters specific to heat loss calculation).

Optimal calibration of the mathematical model has resulted in obtaining calculated values very similar to those obtained by experimental investigation. Hourly fuel and air mass consumption were used to calibrate the model. In the following figure the in-cylinder pressure diagrams for engine operating in standard mode at studied loads are presented. They represented benchmark and were compared to the in-cylinder diagrams obtained when the engine was fueled in D-G mode.

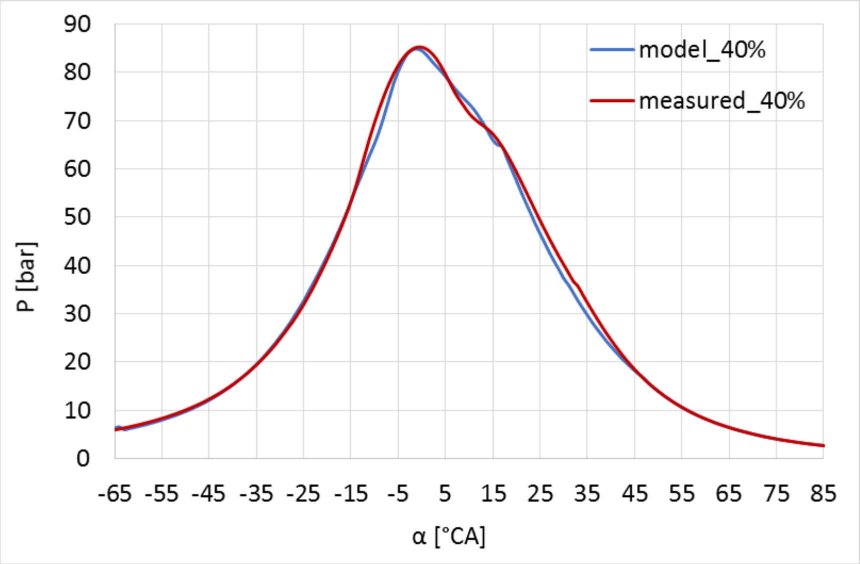

Figure 4.17 In-cylinder pressure evolution calculated / obtained by experimental investigation at 40% load

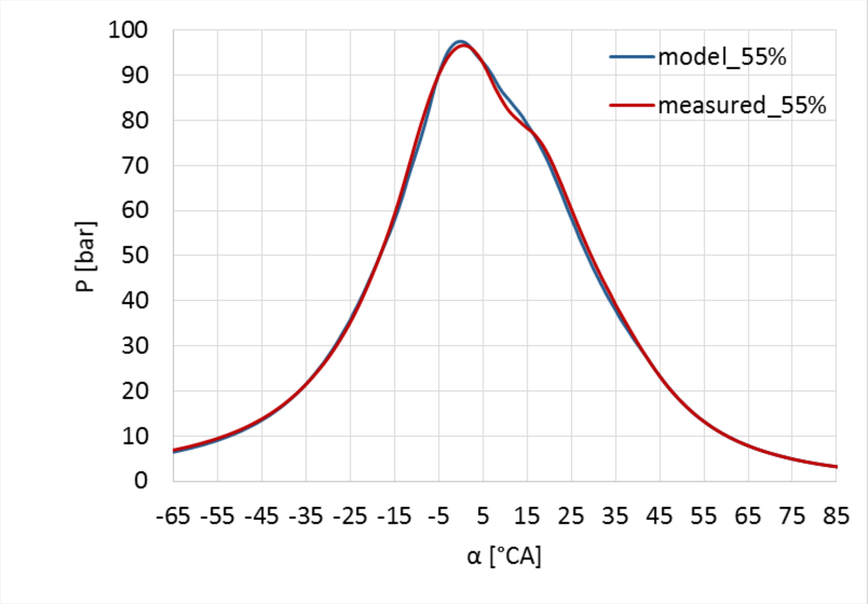

Figure 4.18 In-cylinder pressure evolution calculated / obtained by experimental investigation at 55% load

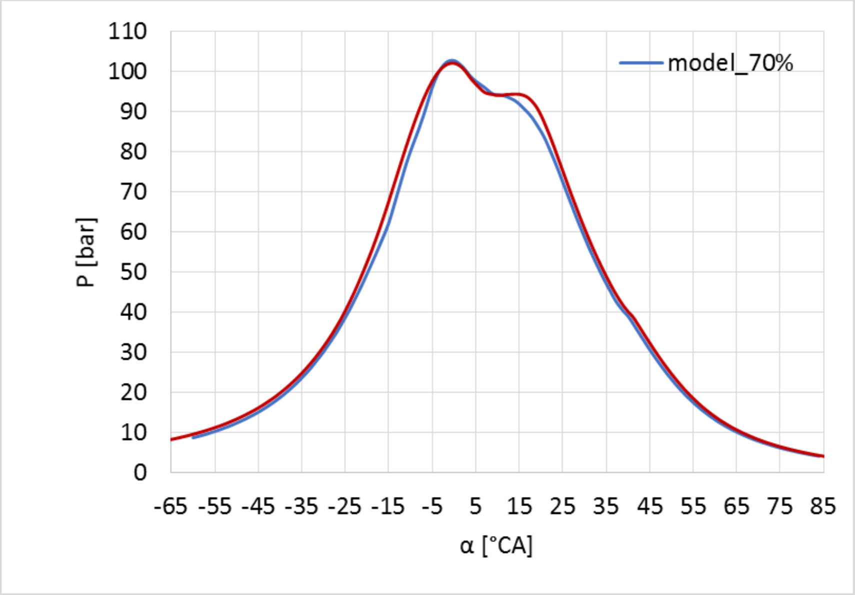

Figure 4.17 In-cylinder pressure evolution calculated / obtained by experimental investigation at 70% load

Chapter 5 - Comparative analysis of the results of experimental and theoretical investigations

Based on the mass shares of each fuel injected per cycle, values for the equivalent parameters used by the model were identified:

- lower heating value;
- the fraction of carbon and hydrogen atoms in the fuel molecule;
- the density of the fuel in liquid form;
- the specific heat of the fuel in liquid form;
- reference temperature for the latent heat of vaporization of the fuel;
- specific heat at constant pressure;
- absolute viscosity;
- thermal conductivity;
- specific gas constant.

For each of the 15 cases experimentally investigated, a version of the mathematical model was developed for the calibration of which, in addition to the parameters mentioned in the previous paragraph, the following parameters were used: quantity and temperature of air admitted to the cylinder, boost pressure, exhaust gas temperature, mass of each fuel per cycle.

Among the advantages of using a precisely constructed and parameterized mathematical model are the reduction of the cost of experimental tests and possible failures due to operating errors of the physical system (exceeding certain temperature, pressure or speed thresholds, etc.); at the same time, with the help of the mathematical model, the engineer can make a very large number of iterations for different operating regimes; of these he will subject to experimental investigation only those of interest; this reduces the time spent in the cell for experimental tests; also among the advantages is the physical protection of the cell for experimental investigations by identifying critical operating regimes and avoiding them during the tests.

The model used to simulate combustion in compression ignition engine, both standard and DG fueled, was based on an existing model in the AMESIM library but underwent a number of modifications to bring the calculated data closer to the experimentally determined data.

The following conclusions have been made about the performance of the thermo-geodynamic model:

The cylinder pressure variation was calculated using the following parameters: air quantity per cycle, quantities of each fuel per cycle, boost pressure, intake air temperature, exhaust gas temperature. For all three loads analyzed it was observed that the model manages to calculate in-cylinder pressure values very close to those determined experimentally. Also for all the studied regimes it is observed a lack of accuracy in the calculation of the pressure drop due to the heating of the main dose droplets (the heat lost for the preheating of the diesel droplets is neglected) and the increase of the calculated cylinder pressure towards the end of the combustion above the experimentally determined one (due to the lower heating value calculated on the basis of the mass shares of each fuel); these drifts have very little impact on other quantities.

The quantity of heat release and the maximum heat release rate obtained by calculation have small deviations from the experimentally determined values. The heat quantity will not show dispersions greater than 10%; with increasing engine load the calculation of the maximum heat release rate becomes more accurate reducing from 20% errors at low loads to 5% errors at high loads; increasing engine running stability makes it easier to determine the maximum heat release rate by calculation.

PM particle concentration and opacity

The assessment of the smoke emission is based on the calculation of the weight of PM particles in the exhaust gas. By comparing these plots with the experimentally determined opacity value plots it can be seen that the model confirms the trends observed during the experimental investigation;

The carbon dioxide concentration shows similar trends to those determined experimentally in all cases studied. Drifts of less than 5% can be identified for all the regimes studied.

The concentration of nitrogen oxides is accurately determined by the mathematical model for all the regimes studied.

The carbon monoxide concentration analysis determined by the model shows up to 6-fold increases in carbon monoxide emissions once the maximum CNG-diesel energy substitution coefficient is reached independent of the engine speed studied.

Influence of engine load on oxygen concentration in the exhaust gas

Theoretical values of O_2 concentration show a reduction in the quantity of oxygen in the combustion gases with increasing load both at standard engine fueling and DG mode fueling.

Further use of the mathematical model

Successful completion of the parameterization and validation stages of the mathematical model makes it possible to analyze the influence of fueling the diesel engine in DG mode in greater depth; through calculation it is possible to obtain the values of some quantities or parameters that could not be determined experimentally: the evolution of temperatures (in-cylinder, of the burnt gases, of the fresh charge), the quantity of unburned fuel remaining in the cylinder, the quantity of burnt gases remaining in the cylinder, the force of pressure of the gases on the piston, etc.

The optimizations to be made to the thermo-geodynamic model are:

- identification of each fuel used;
- use of fuel injected into intake manifold close to the inlet valve;
- transforming input quantities (e.g. temperatures, pressures, injection times, or flow rates) from constant values into charts that take into account variable engine parameters;
- the use of a complete engine with all four cylinders in order to take into account influences (e.g. gas-dynamic influences from intake/exhaust manifolds);
- activation of the blow-by function (loss of gas past the piston in the lower crankcase);

development and activation of the non-aqueous hydrocarbon concentration scale.

Chapter 6 - **Conclusions, personal contributions and future research directions**

6.1 FINAL CONCLUSIONS

The main objective of this work was to analyze the influence of the use of compressed natural gas in a diesel engine fueled in diesel-gas mode.

Theoretical and experimental research on the supply of the diesel car engine with compressed natural gas in D-G mode allows the following conclusions to be drawn:

- Reduced auto-ignition delay duration at increased energy substitution of diesel with CNG at all investigated engine loads due to increased homogeneity of the air-fuel mixture.

- Reduced combustion duration when increasing the degree of energy substitution of diesel with CNG due to increased percentage of preformed blends combustion.

- Reduction of the maximum heat release rate by 12% at 70% engine load when increasing the degree of energy substitution.

- 25% increase in maximum heat release rate at 55%.

- At low engine loads the influence of CNG on the maximum heat release rate is negligible.

- Increased maximum in-cylinder pressure due to increased quantity of pre-formed mixture.

- Increase of the maximum rate of pressure rise for all CNG diesel energy substitution coefficients due to an increase in the share of preformed mixture.

- Decrease in effective specific consumption by up to 50% at low and medium loads and by up to 38% for 70% loads due to the increased percentage of the preformed mixtures and the higher lower heating value of compressed natural gas than diesel.

- The increase in mean indicated pressure an increase in the degree of energy substitution of diesel with CNG for all the studied regimes due to the lower heating value of compressed natural gas and the increase in the percentage of the fast combustion phase.

- Reduction of carbon dioxide concentration in exhaust gas by 7% at high loads and 20% at low loads when increasing the degree of energy substitution of diesel with CNG due to lower carbon content of natural gas.
- Reduction of nitrogen oxide emissions by up to 33% at high engine loads when increasing the degree of energy substitution of diesel with CNG due to the reduction of the quantity of air in the cylinder and the reduction of the gas temperature. At low and medium engine loads, the concentration of nitrogen oxide emissions is up to 10% higher with increasing energy substitution of CNG diesel.
- Increased concentration of unburned hydrocarbons as an effect of preformed mixture blockage in cylinder crevices, direct CNG discharge during overlapping valve opening and possibly flame extinction at low loads.
- At low loads the compressed natural gas supply increases the smoke emission, primarily due to incomplete combustion promoted by the low engine thermal regime.
- At medium loads, as cylinder temperatures rise, the general trend is for smoke emissions to decrease as the energy substitution ratio of diesel to CNG increases.
- At high loads there is a 30% decrease in smoke emissions with an increase in the energy substitution ratio of diesel to CNG.

The use of compressed natural gas in D-G fueling mode to power diesel car engines, with its positive influence on pollutant and greenhouse gas emissions and on the indicated mean pressure, is an alternative with a positive impact on air quality in urban or highly industrialized areas, contributing to an increased quality of life.

6.2 PERSONAL CONTRIBUTIONS

The main personal contributions to the development of the PhD thesis are:

- Analysis of the international context on the further reduction of pollutant emissions and greenhouse gases by using CNG as an alternative fuel for the diesel car engine.
- Analysis of the physical and chemical properties of the two fuels used to power the diesel engine under investigation and determination of the implications for its operation.
- Analysis of some technological processes for obtaining, storing and transporting compressed natural gas in order to establish more efficient production solutions.
- Analysis of methods of fueling the automotive engine with compressed natural gas.
- Analysis of the current state of research in the field and its development with new information obtained through theoretical and experimental research.
- Upgrading the engine test bench in order to carry out experimental investigations specific to the general objective of the PhD thesis - fueling a car diesel engine in D-G mode with diesel and compressed natural gas.
- Establishment of a suitable procedure for conducting experimental investigations of the compressed natural gas-fueled automotive diesel engine in D-G mode.
- Processing and interpretation of the results of experimental investigations.

- Development and parameterization of an AMESIM numerical model for simulation of numerical processes in the cylinder of compressed natural gas-fueled automotive diesel engines. A major activity has been the identification of a method to overcome the limitation of the standard AMESIM numerical model (lack of possibility to model diesel-gas fueling).
- Validation of the developed numerical model.
- Dissemination of theoretical and experimental research results in journals with national and international circulation and in volumes of prestigious international conferences.
- Participating in development programs in engineering related fields organized by the National University of Science and Technology POLITEHNICA BUCHAREST, as a PhD student, gave me new perspectives and the opportunity to apply the knowledge acquired in other fields: developing a business plan based on the technical knowledge acquired during the thesis.

6.3 FUTURE RESEARCH DIRECTIONS

The theoretical and experimental research carried out by the author opens new research directions on the efficient use of compressed natural gas in automotive diesel engines:

- CNG injection into the inlet/direct valve gate in the engine cylinder and individual and synchronized control of the compressed natural gas injectors.
- Efficient interfacing of the two control units (standard diesel engine electronic control unit and CNG injection electronic control unit) at all operating speeds.
- Optimize engine tuning (diesel injection advance, diesel pilot size, CNG consumption, dosage, etc.) at all engine operating speeds.
- Conduct experimental investigations under real conditions, at operating regimes commonly used in service.
- Parameterization optimization of the AMESIM thermo-geodynamic model when using CNG in D-G mode.
- Activating the blow-by function.

DISSEMINATION OF RESEARCH RESULTS

The results of the theoretical and experimental research carried out by the author during the elaboration of the PhD thesis have been published in prestigious edited journals/volumes of international conferences.

Papers published in journals:

1. Silviu ROTARU, Constantin PANA, Niculae NEGURESCU, Alexandru CERNAT, Dinu FUIORESCU, Cristian Nikolaos NUȚU, „*CNG INFLUENCE ON COMBUSTION IN AN AUTOMOTIVE DIESEL ENGINE FUELED IN DIESEL-GAS MODE*"**,** U.P.B. Sci. Bull, Series D, Vol. 82, Iss. 4, 2020, pp. 67-78, ISSN (print): 1454-2358 / (online): 2286-3699, Journal category B+, CNCSIS Code 102**,** indexed in BDI: ULRICHS INTERNATIONAL, PERIODICALS DIRECTORY, SCOPUS **(https://www.scopus.com/sourceid/21639)**, INSPEC **(www.theiet.org/publishing/inspec/support/docs/loj.cfm)**, METADEX **(http://www.csa.com/ids70/serials_source_list.php?db=metadex-set-c)**, ELSEVIER SCIENCESS BIBLIOGRAPHIC DATABASES, ENGINEERING VILLAGE , CAMBRID-GE SCIENTIFIC ABSTRACTS **(http://www.csa.com/ids70/serials_source_list.php?db=mechtrans-set-c)**, COMPENDEX paper indexed in BDI SCOPUS at https://www.scopus.com/record/display.uri?eid=2-s2.0-85097111593&origin=resultslist

2. Silviu Rotaru, Constantin Pana, Niculae Negurescu, Alexandru Cernat, Cristian Nutu, Dinu Fuiorescu and Gheorghe Lazaroiu, CNG impact on combustion quality of a diesel engine fueled in diesel-gas mode - Helyon - in review.

Papers presented at international conferences:

1. **S. Rotaru**, C. Pana, N. Negurescu, Al. Cernat, D. Fuiorescu, Cr. N. Nutu, *Experimental investigations of an automotive diesel engine fueled with natural gas in dual fuel mode*, IOP Conference Series: Materials Science and Engineering, 2020, 997(1), 012130, ACME code 6-22, Session ACME-06-01: Automotives. Engine and Transmission. Road Safety, indexed in BDI SCOPUS https://www.scopus.com/authid/detail.uri?authorId=57218549774 , respectively https://www.scopus.com/record/display.uri?eid=2-s2.0-85099246948&origin=resultslist

2. **Silviu Rotaru,** Constantin Pană, Nicolae Negurescu, Alexandru Cernat, Dinu Fuiorescu, Cristian Nikolaos Nutu, *Experimental study on combustion of an automotive diesel engine fueled with CNG* IOP Conference Series: Materials Science and Engineering, Volume 1262, The 10th International Conference on Advanced Concepts in Mechanical Engineering (ACME 2022) 09/06/2022 - 10/06/2022 Online. Citation S Rotaru 2022 IOP Conf. Ser.: Mater. Sci. Eng. 1262 012072. DOI 10.1088/1757-899X/1262/1/012072,

3. **Silviu Rotaru**, Constantin Pană, Nicolae Negurescu, Alexandru Cernat, Dinu Fuiorescu, Cristian Nikolaos Nutu, *Effects of CNG quantity on combustion characteristics and emissions of a dual fueled automotive diesel engine*, E3S Web of Conferences **180**, 01008 (2020), published by E3S Web-of-Conferences Open Access proceedings in Environment, Energy and Earth Sciences (eISSN: 2267-1242), and indexed in *Conference Proceedings Citation Index (Web of Science), Scopus, DOAJ, EBSCO* and other prestigious scientific databases. (ISSN 2359-7941), pp. 10, , published online 24 July 2020, Journal E3S Web of Conference, eISSN:2267-1242, Publisher EDP Sciences, https://doi.org/10.1051/e3sconf/202018001008, also indexed in SCOPUS https://www.scopus.com/authid/detail.uri?authorId=25229963900
indexed in BDI SCOPUS https://www.scopus.com/authid/detail.uri?authorId=57218549774 , respectively https://www.scopus.com/record/display.uri?eid=2-s2.0-85089497390&origin=resultslist

4. **Silviu Rotaru**, Constantin Pană, Niculae Negurescu, Gheorghe Lăzăroiu, Alexandru Cernat, Dinu Fuiorescu, Cristian Nuțu, Researches *regarding the CNG use at an automotive diesel*

engine", Part I - Advanced Powertrain and Propulsion, Book of Abstracts, The 30th SIAR International Congress of Automotive and Transportation Engineering SMAT 2019, under the aegis of FISITA, Editors Răcilă D L, Ilie D, Editura Universitaria, ISBN 978-606-14-1548-9, Craiova, October 23-25, 2019

Scientific contracts and reports:

1. Fellowships for entrepreneurship education among PhD students and postdoctoral researchers (Be Antreprenor), ! MYSM CODE 124539, IMPLEMENTATION: 10.07.2019 - 09.01.2021. , POCU: PRIORITY AXIS 6. Grant of 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.

Selective bibliography

[1] Atkinson S., Skinner G., Gebrekal T., What worries the world, https:/www.ipsos.com/sites/default/files/ct/news/documents/2019-11/what-worries-the-world-september-2019.pdf, World Wories, Ipsos 2019.

[2] Seagrave J., McDonald J.D., Bedrick E., Edgerton E.S., Gigliotti A.P., Jansen J.J., Ke L., Naeher L.P., Seilkop S.K., Zheng M., Mauderly J.L., Lung toxicity of ambient particulate matter from southeastern U.S. sites with different contributing sources: relationships between composition and effects. Environ Health Perspect. 2006 Sep;114(9):1387-93. doi: 10.1289/ehp.9234. PMID: 16966093; PMCID: PMC1570075.

[3] Schultz E.S., Litonjua A.A. & Melén E., Effects of Long-Term Exposure to Traffic-Related Air Pollution on Lung Function in Children. Curr Allergy Asthma Rep 17, 41 (2017). https://doi.org/10.1007/s11882-017-0709-y.

[4] Cazacu M.M., Timofte A., Balin I., Dimitriu D.G., Gurlui S., Complementary Atmospheric Urban Pollution Studies In The North-East Region Of Romania, Iasi CountyCazacu, Marius & Timofte, Adrian & Balin, Ioan & Dimitriu, Dan-Gheorghe & Gurlui, Silviu. (2011). Complementary atmospheric urban pollution studies in the north-east region of Romania, Iasi county. Environmental engineering and management journal. 10. 139-145. 10.30638/eemj.2011.020.

[8] Imran S., Emberson D.R., Diez A., Wen D.S., Crookes R.J., Korakianitis T., Natural gas fueled compression ignition engine performance and emissions maps with diesel and RME pilot fuels,Applied Energy,Volume 124,2014,Pages 354-365,ISSN 0306-2619,https://doi.org/10.1016/j.apenergy.2014.02.067.

[11] Shenghua L., Longbao Z., Ziyan W., Jiang R., Combustion characteristics of compressed natural gas/diesel dual-fuel turbocharged compressed ignition engine. Proceedings of the

Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering. 2003;217(9):833-838. doi:10.1177/095440700321700909.

[12] Napolitano P., Guido C., Beatrice C., and Del Giacomo N., Application of a Dual Fuel Diesel-CNG Configuration in a Euro 5 Automotive Diesel Engine, SAE Technical Paper 2017-01-0769, 2017, https://doi.org/10.4271/2017-01-0769.

[13] Muralidharan, M., Srivastava, A., and Subramanian, M., 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):393-411, 2022, https://doi.org/10.4271/03-15-03-0020.

[14] Aklouche F.Z.. Characteristic study and development of diesel engine combustion in Dual-Fuel mode: optimization of pilot fuel injection. Thermal [physics.class-ph]. Ecole nationale supérieure Mines-Télécom Atlantique, 2018. French ⟨NNT: 2018IMTA0072⟩ .

[15] Egúsquiza J. & Braga S., 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. 10.1590/S1678-58782009000200007, 2009.

[16] Mahla, S. K. 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.

[17] Jamrozik A., Tutak W., Grab-Rogaliński K., An Experimental Study on the Performance and Emission of the diesel/CNG Dual-Fuel Combustion Mode in a Stationary CI Engine. Energies 2019, 12, 3857. https://doi.org/10.3390/en12203857.

[18] Mbarawa M., Milton B.E., An Examination of the Maximum Possible Natural Gas Substitution for Diesel Fuel in a Direct Injected Diesel Engine, R & D Journal, 2005, 21 (1) incorporated into The SA Mechanical Engineer.

[19] Wan Mansor W. N., Dual fuel engine combustion and emissions - an experimental investigation coupled with computer simulationDoctor of Philosophy Colorado State University Fort Collins, Colorado, Fall 2014.

[22] ***CO2 Based Motor Vehicle Taxes In The EU In 2016, http://www.acea.be.

[23] Health risks of air pollution in Europe, United States Environmental Protection Agency, www.eea.europa.eu, 2022.

[24] Health assessment document for diesel engine exhaust, U.S. Environmental Protection Agency (EPA) (2002), Prepared by the National Center for Environmental Assessment, Washington, DC, for the Office of Transportation and Air Quality; EPA/600/8-90/057F. Available from: National Technical Information Service, Springfield, VA; PB2002-107661, and <http://www.epa.gov/ncea>.

[26] Lijiang Wei, Peng Geng, A review on natural gas/diesel dual fuel combustion, emissions and performance,Fuel Processing Technology,Volume 142,2016,Pages 264-278,ISSN 0378-3820,https://doi.org/10.1016/j.fuproc.2015.09.018.

[27] Flynn P. F., Hunter G. L., Durrett R. P., Farrell L. A., & Akinyemi W. C. Minimum Engine Flame Temperature Impacts on Diesel and Spark-Ignition Engine NOx Production. SAE Transactions, 109, 1286-1297. http://www.jstor.org/stable/44634306.

[28] Reed R. J., North American Combustion Handbook, Volume 1, 3rd edition, North American Mfg Co., 1986. Archived from the original on 2011-07-16. Retrieved 2009-12-09.

[37] 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).

[41] Grigoratos T., Fontara G., Martini G., Peletto C., A Study of Regulated and Green House Gas Emissions from a Prototype Heavy-Duty Compressed Natural Gas Engine under Transient and Real Life Conditions, Energy 103 (2016): 340-355, http://doi.org/10.1016/j.energy.2016.02.157.

[42] Belgiorno G., Di Blasio G., Beatrice C., Parametric Study and Optimization of the Main Engine Calibration Parameters and Compression Ratio of a Methane-Diesel Dual Fuel Engine, Fuel 222, no. 15 (2018): 821-840, https://doi.org/10.1016/j.fuel.2018.02.038.

[43] Königsson F., On Combustion in the CNG-Diesel Dual Fuel Engine, PhD paper, 2019.

[49] Selim M. Y.E, Pressure-time characteristics in diesel engine fueled with natural gas, Renewable Energy, Volume 22, Issue 4, 2001, Pages 473-489, ISSN 0960-1481, https://doi.org/10.1016/S0960-1481(00)00115-4, https://www.sciencedirect.com/science/article/pii/S0960148100001154).

[50] Schaberg P.W., Priede T., Dutkiewicz R.K., Effects of a rapid pressure rise on engine vibration and noise, SAE paper 900013, 1990.

[51] Galinsky G., Reader G.T., Potter I.J., Gustafson R.W., Effect of various working fluid compositions on combustion noise in diesel engines, AIAA-94-3996-CP, 1994:1157-1162.

[52] Imoto K., Sugiyama S., Fukuzawa Y., Reduction of combustion-induced noise in IDI diesel engine (1st report, target of cycle and low-noise combustion). Trans of JSME, B 1997;63(605):329-35.

[87] **Rotaru, S.**, Pana, C., Negurescu, N., Cernat, A., Fuiorescu, D. and Nuțu, C.N., 2020. Effects of CNG quantity on combustion characteristics and emissions of a dual fueled automotive diesel engine. In E3S Web of Conferences (Vol. 180, p. 01008) EDP Sciences.

[88] **Rotaru, S.**, Pana, C., Negurescu, N., Cernat, A., Fuiorescu, D. and Nuțu, Experimental investigations of an automotive diesel engine fueled with natural gas in dual fuel modeACME 2020 / IOP Conf. Series: Materials Science and Engineering 997 (2020) 012130 / IOP Publishing / doi:10.1088/1757-899X/997/1/012130.

[89] **Rotaru, S.**, Pana, C., Negurescu, N., Cernat, A., Fuiorescu, D. and Nuțu, Researches regarding the CNG use at an automotive diesel engine, SMAT 2019.

[90] **Rotaru, S.**, Pana, C., Negurescu, N., Cernat, A., Fuiorescu, D. and Nuțu, CNG INFLUENCE ON COMBUSTION IN AN AUTOMOTIVE DIESEL ENGINE FUELED IN DIESEL-GAS MODEU.P.B. Sci. Bull., Series D, Vol. 82, Iss. 4, 2020 ISSN 1454-2358.

[92] **Rotaru, S.**, Pana, C., Negurescu, N., Cernat, A., Fuiorescu, D. and Nuțu,, Experimental study on combustion of an automotive diesel engine fueled with CNG, Automotives. Engine and Transmission. Road Safety. The 10th International Conference on Advanced Concepts in Mechanical Engineering, ACME 2022, June 9-10, 2022, Iasi, Romania (The ACME2022 Conference Proceedings will be published by IOP Conference Series: Materials Science and Engineering, an open-access proceedings journal, with abstracting and indexing in ISI Web of Science (Conference Proceedings Citation Index), Scopus, EI Compendex, among others (as a proceedings journal, an Impact Factor is not assigned) - under indexing.

[93] Andreescu C., Course Notes - Environmental and Resource Protection, Faculty of Transport, UBP, 2014.

[94] Aramă C., Apostolescu N., Grunwald B., Air pollution by internal combustion engines, Tehincă Publishing House, ISBN:168IPOLTPO, 1975.

[95] James C.S., Howard J.J., Experimental hydrate formation and gas production Scenarios based on CO2 sequestration, Fuel 2019, 235, 763-774.

[96] Nirendra N. M., Robert R. R. Verhelst S., Combustion and emissions characteristics of a dual fuel engine operated on alternative gaseous fuels, Fuel, Volume 109, 2013, Pages 669-678, ISSN 0016-2361, https://doi.org/10.1016/j.fuel.2013.03.007.

[108] Rotaru S., Business Plan: Development of a company providing DG power solutions for stationary generator ignition engines for BeAntrepreneur 2019 - 2020.