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PH.D. THESIS

Study on performance, efficiency and pollutant emissions of a spark ignition engine fuelled with compressed natural gas and hydrogen

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Content

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CHAPTER 1. INTRODUCTION AND TOPIC CHOICE MOTIVATION

With increasingly stringent requirements on pollution regulations, car manufacturers are trying to adapt alternative propulsion solutions using new energy sources other than fossil fuels. Thus, a possible alternative solution is natural gas stored in pressure tanks (200-250 bar), called compressed natural gas (CNG), used as fuel for vehicles with thermal engines.

Another alternative solution is hydrogen (H_2), a tasteless, colorless, and odorless gas. This gas does not include carbon atoms in its molecule; thus, after combustion (oxidation), no polluting gases such as carbon dioxide (CO_2), hydrocarbons (HC), and carbon monoxide (CO) are produced [1, 2].

The mixture of hydrogen and natural gas in different fractions called HGNC (Hydrogen-Natural Gas Mixture) can be considered vehicle fuel without requiring significant modifications to the internal combustion engine. The benefits of these fuels would be that they are less polluting, renewable, and more economically viable than gasoline [3].

This paper aims, starting from the current situation of the compressed natural gas (CNG) and hydrogen supply infrastructure to the adaptation of internal combustion engines for these alternative fuels in different proportions, to highlight the changes in performance, economy, and pollutant emissions produced by them under the conditions in which one would switch to these alternative fuels.

The results of experimental studies on the use of natural gas mixed with hydrogen as a fuel for spark ignition engines are highlighted, taking into account the current legislation on polluting emissions. The results show the advantages of improved combustion and combustion rates in the engine fuelled with natural gas blended with hydrogen.

Hydrogen enrichment extends the combustion limit of compressed natural gas-hydrogen (HGNC) mixtures. The addition of hydrogen (H2) in volumetric fractions of 20-30% in natural gas can be an effective short-term solution to the greenhouse gas problem, without requiring major changes to the current technologies used in engines. In order to achieve significantly improved performance characteristics, the compression ratio of the engine can be increased when using CNG and H2 due to the higher octane number than gasoline.

This work presents the results of an experimental and theoretical investigation into the performance, economy, and pollutant emissions carried out on the Renault HR09DET spark-ignition engine, four-stroke, 3-cylinder, multi-point fuel injection fuelled with compressed natural gas and compressed natural gas mixed with hydrogen. Objective: highlighting the influence of hydrogen additions of various fractions mixed with compressed natural gas on performance, efficiency, and pollutant emissions under the conditions in which the maximum power of the engine is maintained when switching from gasoline to CNG fuelling.

To carry out the theoretical investigation, a simulation model was created with the AVL Boost program, which was calibrated using experimental data obtained for the gasoline engine. The simulation model allowed the addition of hydrogen in parallel with the natural gas supply. The results highlight changes in performance and emissions of regulated pollutants such as unburnt hydrocarbons (HC), carbon monoxide (CO), and nitrogen oxide emissions (NO_x).

The impact of increasing the compression ratio using 2 heat release laws (Wiebe 2 Zone and Fractal) was studied on this spark ignition engine at different ratios of alternative fuels namely compressed natural gas and hydrogen. Given the higher octane number of CNG and hydrogen compared to gasoline, the thermal efficiency of the engine has been improved by increasing the compression ratio without knocking.

CHAPTER 2. THE STUDIED FUELS

With increasingly strict regulations, car manufacturers are obliged to find new alternative propulsion solutions using energy sources other than fossil fuels. The main reasons are ecological, economic, and political.

Gasoline and diesel are classic (conventional) fossil fuels of petroleum origin, but there are also alternative (non-conventional) fuels that are not of petroleum origin. Among them, it is appreciated that hydrogen has an open future for fuelling internal combustion engines. Another non-conventional fuel of interest is compressed natural gas (CNG) which is becoming more widely used with increasingly stringent CO_2 emissions regulations.

2.1. Compressed natural gas

One of the alternative solutions is CNG (Compressed Natural Gas) or CNGV (Compressed Natural Gas for Vehicles). CNG is "natural gas stored in containers under pressure, by compression, to use it as fuel for vehicles with thermal engines", according to Energy Law no. 123/2012. After compression to approx. 1% of the volume occupied under normal conditions, natural gas remains in a gaseous state and the pressure at which it is sold is 200-250 bar, in special containers. Natural gas can be liquefied at
-163°C and stored under the name of Liquefied Natural Gas (LNG).

Natural gas (CNG) is considered an alternative fuel for vehicles because of its economic and environmental advantages [4]. Compressed natural gas is composed primarily of methane (CH4), but frequently contains traces of ethane, propane, hydrogen sulfide, nitrogen, helium, carbon dioxide, and water vapor [5].

However, due to the slow-burning speed of CNG and lean combustion, CNG spark-ignition engine still has some disadvantages, such as low thermal efficiency, lower burning speed, reduced engine power, and increased fuel consumption [6].

The advantage of natural gas is the high octane number of 130, which allows an engine to operate with a high compression ratio without knocking. In addition, gasoline and diesel engines can be easily converted to CNG engines without major structural changes.

At the end of 2021, it was estimated that more than 30 million vehicles powered by compressed natural gas were used worldwide, which gives this fuel an increasingly defined place in the automotive industry [7]. Of these, over 13 million vehicles powered by compressed natural gas are in Europe [7]. 4159 CNG stations and 648 LNG stations are reported for Europe on updated infrastructure in 2023.

There are three types of natural gas-powered vehicles:

1) Dedicated: Vehicles designed to run on natural gas only.
2) Bi-Fuel: These types of vehicles have two separate fuel systems. They allow operation on either natural gas or gasoline.
3) Dual fuel: In the case of heavy vehicles, a diesel pilot injection is used to ignite the natural gas.

2.2. Hydrogen

Hydrogen (H_2) is an odorless, colorless, and tasteless gas. It is lighter than air and burns with an invisible flame. It is the only combustible gas that does not contain carbon atoms in the molecule and thus, following combustion (oxidation), no polluting gases such as carbon monoxide (CO) and carbon dioxide (CO_2) are produced. H_2 has the highest thermal conductivity of all gases. Combined with oxygen, the hydrogen flame reaches a temperature of 2834°C. It has a mass calorific value 2.8 times higher than gasoline, namely 121 MJ/kg. The maximum flame propagation speed is 8 times higher and the hydrogen vapors are non-toxic [4].

Due to the burning speed of hydrogen, considerably higher compared to gasoline, the duration of the combustion phase in the engine is reduced. For this reason, the thermal efficiency of an internal combustion engine using hydrogen is superior to internal combustion engines using gasoline [8]. From the point of view of ignition, hydrogen has a higher resistance to self-ignition (RON > 130), so it can be used on engines with a high compression ratio. However, the flammability limit in air occurs at very lean mixtures (lambda > 10) and for this reason, the air-hydrogen mixture can auto-ignite relatively easily (compared to gasoline) from engine parts that have high temperatures. [8] The use of hydrogen as a fuel for internal combustion engines or fuel cells can be an alternative to fossil fuels. The high cost of the mass unit of liquid H_2 is a disadvantage of using hydrogen in internal combustion engines.

In July 2020, the European Commission proposed a hydrogen strategy for a climate-neutral Europe, which aims to accelerate the production of clean hydrogen and ensure its role as the basis of a climate-neutral energy system by 2050 [9].

Hydrogen can be extracted from multiple sources, such as by reforming hydrocarbons or by electrolysis of water. The most promising technology, in the long term, seems to be water electrolysis (decomposition of water into hydrogen and oxygen using electric current) because it uses water as a raw material and the electric current can be obtained from renewable sources (solar, wind) [8].

At the end of 2022, 814 hydrogen fuelling stations were in operation worldwide, and another 315 stations are planned to be built. Of these, there are 254 hydrogen stations in Europe.

CHAPTER 3. POLLUTANT EMISSIONS AND LEGISLATION

Pollutant emissions are harmful to health and affect air quality. Air quality standards are defined by the World Health Organization (WHO) and applied in different regions of the world. These emissions are regulated in the regions of the world by different legislative packages known as EU5, EU6 (Europe), ULEV, LEVII, LEVII (USA), etc.

CHAPTER 4. DRIVING CYCLES

With the development of technology and changing traffic conditions, the laboratory test for fuel consumption and pollutant emissions also had to be updated to reflect reality. Due to the evolution in technology and driving conditions, the old laboratory test called New European Driving Cycle (NEDC) has become obsolete. In this regard, the European Union has developed a new test called the Worldwide Harmonized Light Vehicle Test Procedure (WLTP)

The new EU6d emissions regulation has implemented real driving emissions testing as an additional requirement from 2017. Real Driving Emissions (RDE) legislation through regulation (EU) 2017/1151 adds the road as an environment for emissions testing and certification [9].

To meet these new RDE challenges, a well-designed, compact, modular, and easy-to-install Portable Emission Measurement System (PEMS) is needed in the vehicle whose pollutant emissions are to be tested.

4.1. WLTP

Under the conditions defined by EU law, the WLTP laboratory test is used to measure the fuel consumption and CO2 emissions of passenger cars as well as their emissions pollutants.

The new WLTP procedure is based on the new driving cycles Worldwide harmonized Light-duty vehicles Test Cycles (WLTC) to measure average fuel consumption, CO_2 emissions as well as pollutant emissions by passenger cars and light commercial vehicles.

The WLTP driving cycle is divided into four parts with different average speeds: low, medium, high, and very high. Each part contains a series of driving, stopping, accelerating, and braking phases. For a given car type, each engine configuration is tested with WLTP for the lightest (most economical) and heaviest (least economical) versions.

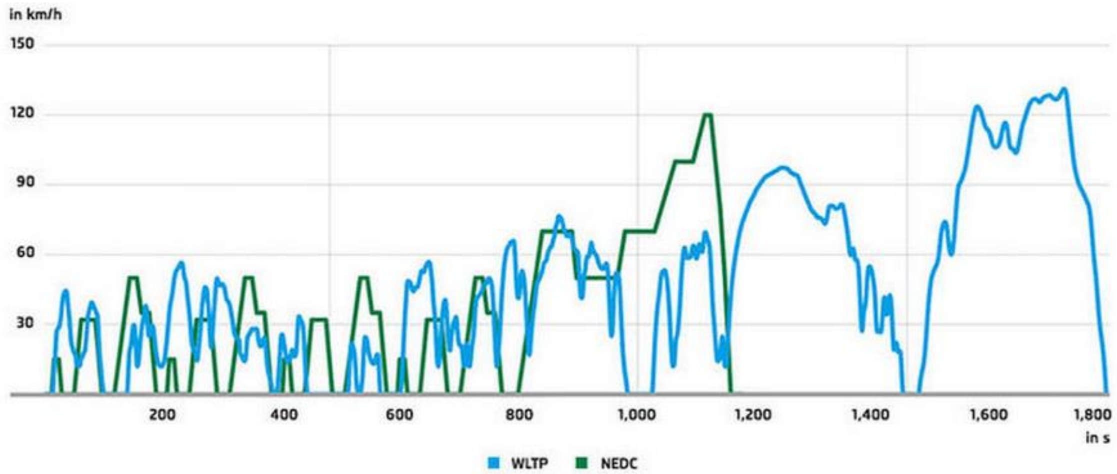


Figure 4.1: Differences between the phases of the two NEDC and WLTP cycles [10]

4.2. RDE

Even though the WLTP cycle has much more complex test conditions compared to the old NEDC cycle, they still do not take into account all the parameters of the actual operation of a vehicle. That is why the test for the real level of emissions in traffic RDE was added. It is carried out on public roads, under real operating conditions, and complements the WLTP certification by checking the actual level of consumption and pollutant emissions.

Under the RDE, a vehicle is driven on public roads under a wide range of different conditions. Specific equipment installed on the vehicle collects data to check that legally declared pollutant emissions, such as NO_x, are not exceeded.

4.3. PEMS

PEMS is a device small and light enough to be attached to the vehicle whose pollutant emissions are to be tested. The use of PEMS is extensive, but in recent years it has focused on checking and optimizing engine pollutant emissions under real-world conditions. This system can determine the pollutants level of a car, as well as the density and number of emitted particles (PM and PN). The regulatory emissions currently measured using PEMS are CO, HC, NO_x, NMHC, PN + CO_2.

The purpose of using PEMS, along with the increasingly strict rules, has become a mandatory system for the competent authorities, to verify compliance with the emission limits imposed by the pollutant emissions regulations, in real conditions, not only in the laboratory.

CHAPTER 5. RDE PROCEDURE AND RESULTS WITHIN THE RENAULT GROUP

At the Titu Technical Center of the Renault group, RDE testing for different types of vehicles and specific engines with the new WLTP driving cycle also takes place. To perform these tests is a complex and well-defined procedure.

After the mass calculation for the vehicle to be tested, the correlation tests performed in the dyno with rollers according to the WLTC cycle intended for the validation of the PEMS measuring device are needed. The tests are carried out in parallel with the roller bench, analyzing the results obtained by comparing with PEMS, aiming not to exceed the limits imposed by the regulation.

Within the Renault group, there is an engine powered by compressed natural gas. It was fitted to a supercharged 898cc petrol internal combustion engine. The compressed natural gas version with a total power of 66 kW, maximum torque of 140 Nm, Euro6b pollution standard on a Logan body, with a 5-speed manual transmission.

The comparative results regarding the most important pollutant emissions obtained on the roll bench and the results obtained on the vehicle in the street tests with the help of PEMS for the two cases of gasoline and compressed natural gas are presented in Figures 5.1, 5.2, and 5.3. The emissions compared are CO_2, NO_x, and CO with the mention that the vehicle at the time of the tests has a test calibration that differs from the official one used in the homologation tests and with which the production vehicle is equipped.

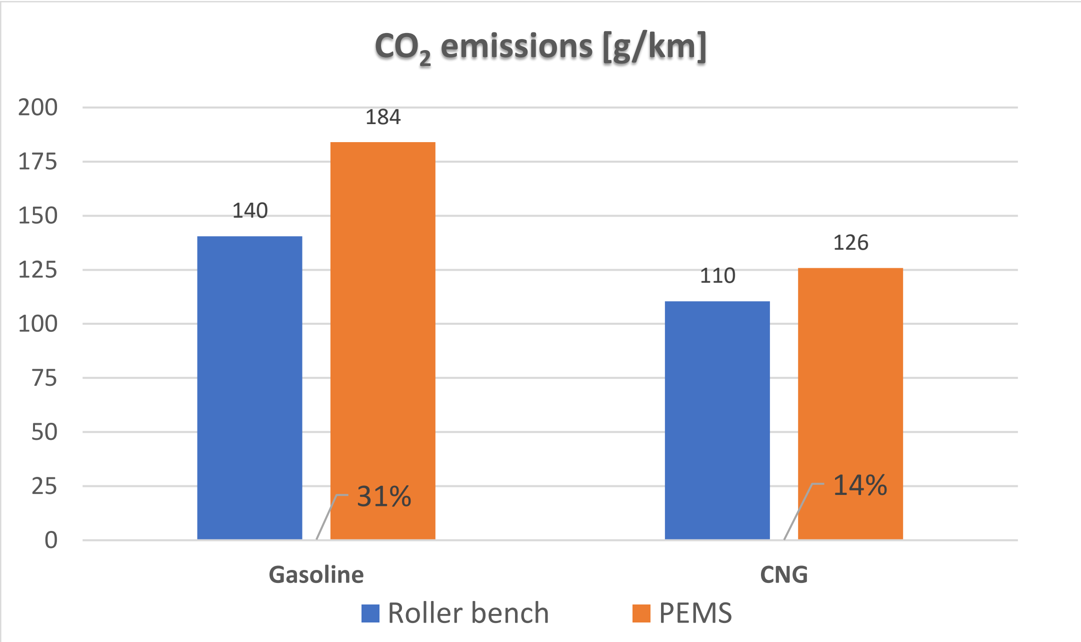


Figure 5.1: Comparison of CO_2 emissions [11]

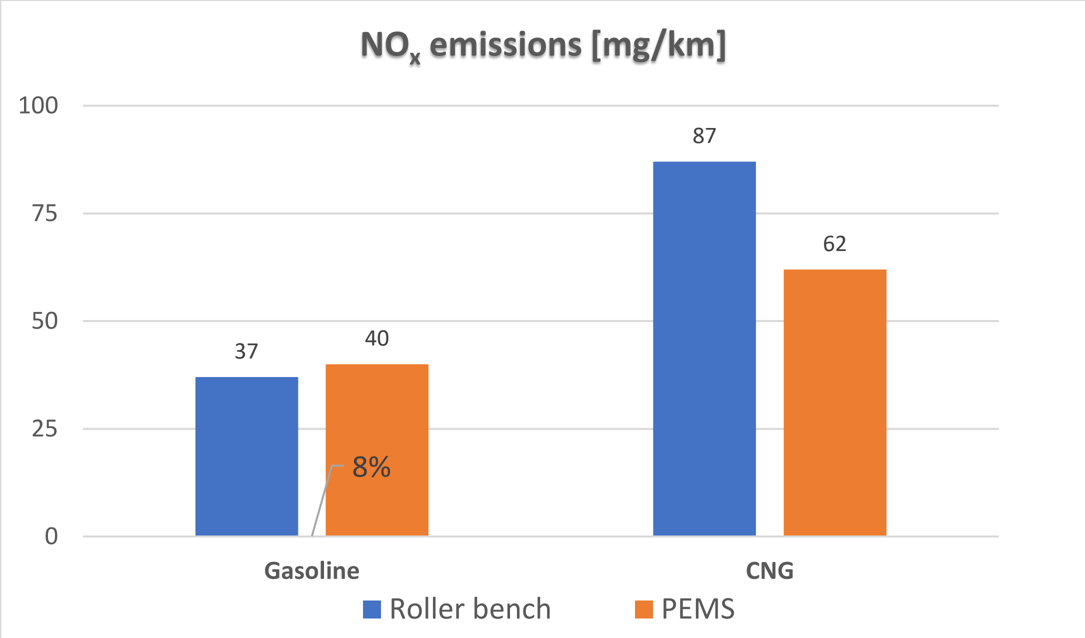


Figure 5.2: Comparison of NO_X emissions [11]

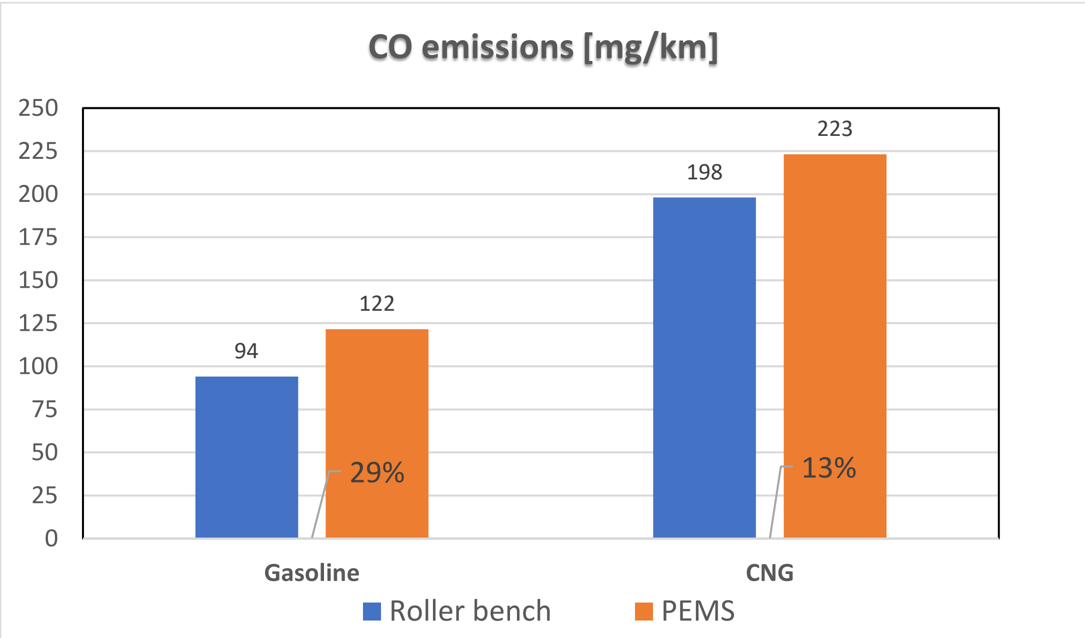


Figure 5.3: Comparison of CO emissions [11]

CHAPTER 6. THE STUDY OF THE INFLUENCE OF NATURAL GAS MIXED WITH HYDROGEN

The most used test procedure for vehicle homologation is called WLTP and is based on the WLTC cycle. In this sense, the most used operating points of the engine on a WLTC cycle were determined, resulting in 4 operating regimes of interest, which have the highest weights and are indicated in figure 6.1 (engine speed / Brake Mean Effective Pressure): [12]

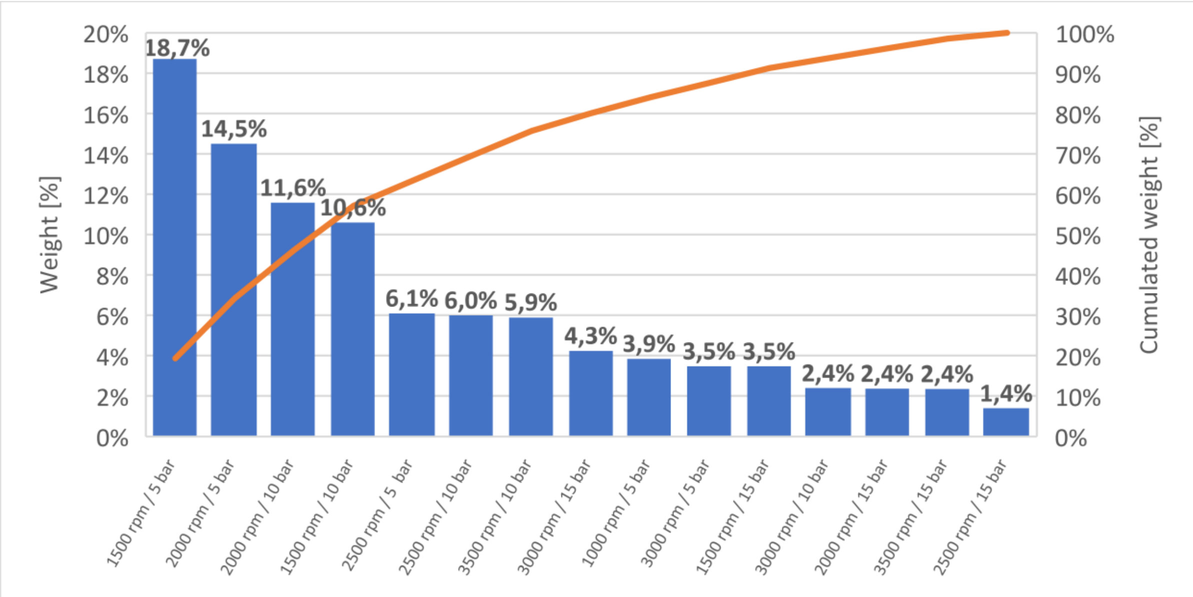


Figure 6.1. Histogram with engine operating conditions (Engine speed / BMEP) in which the most time was spent in WLTP cycle [12]

6.1. Methodology and data acquisition

For this study, the turbocharged gasoline engine manufactured by the Renault group with the name HR09DET was considered. Experimental tests were carried out on an engine bench at the Titu Technical Center with the automatic acquisition of all parameters necessary to perform the calibration of the theoretical model.

6.2. Theoretical model calibration

The engine operation was simulated using the AVL Boost v2019.1 (Figure 6.2) tool through a thermodynamic model based on the Fractal and Wiebe 2 Zone heat release characteristics. According to the manufacturer's specifications, the model calibration was performed. The model has the following main components: C1, C2, C3 - Engine cylinders, TH1 – Throttle, PL1 – Intake manifold, PL2 - Exhaust manifold, TC1 – Turbo-charger, SB1 and SB2 – system boundaries, CO1 – Charge air cooler, CL1 - Air Cleaner, CAT1 - Catalyst, WG1 - Waste Gate.

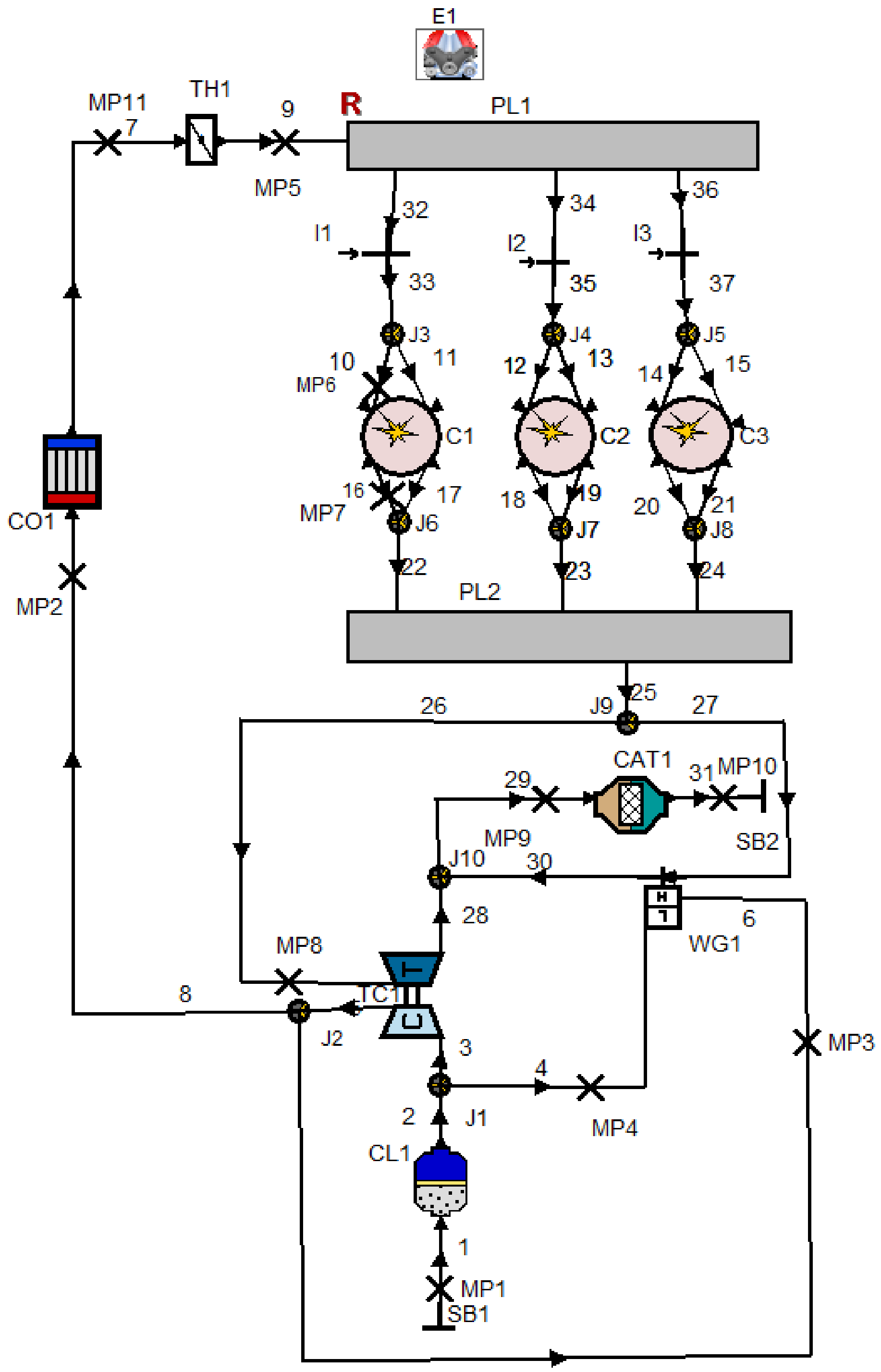


Figure 6.2 The engine symbolic layout in AVL Boost [13]

The calibration was made, when the engine was fuelled with commercial gasoline (with 7% ethanol), by comparing the results obtained on simulation with the experimental results obtained on the engine test bench. The air mass flow, the throttle angle, the friction mean effective pressure (FMEP), the fuel consumption, the manifold pressure, lambda (λ=1), and the start of combustion (SOC) were kept constant for the model development and its calibration. The next parameters like combustion duration (CD), shape parameter (SHP), kinetic multiplier for CO emissions, NOx post-processing multiplier, and HC post-oxidation multiplier were varied in the calibration stage.

Model calibration performance based on experimentally obtained data is accurate, and accuracy is within 5% for Brake Mean Effective Pressure, peak pressure, and peak pressure angle for selected operating conditions. Power calibration was performed with relative differences of up to 2% at both 1500 rpm and 2000 rpm.

Calibration for regulated emissions of HC, CO, and NOx was achieved with good accuracy for all 4 operating conditions with relative deviations of up to 1%. Resulting in a simulation with relative differences of less than 2% between the experimental data and the results of the simulations, it was possible to appreciate that the model is viable and predictive and in this way, it can be used for simulations other than the calibration ones.

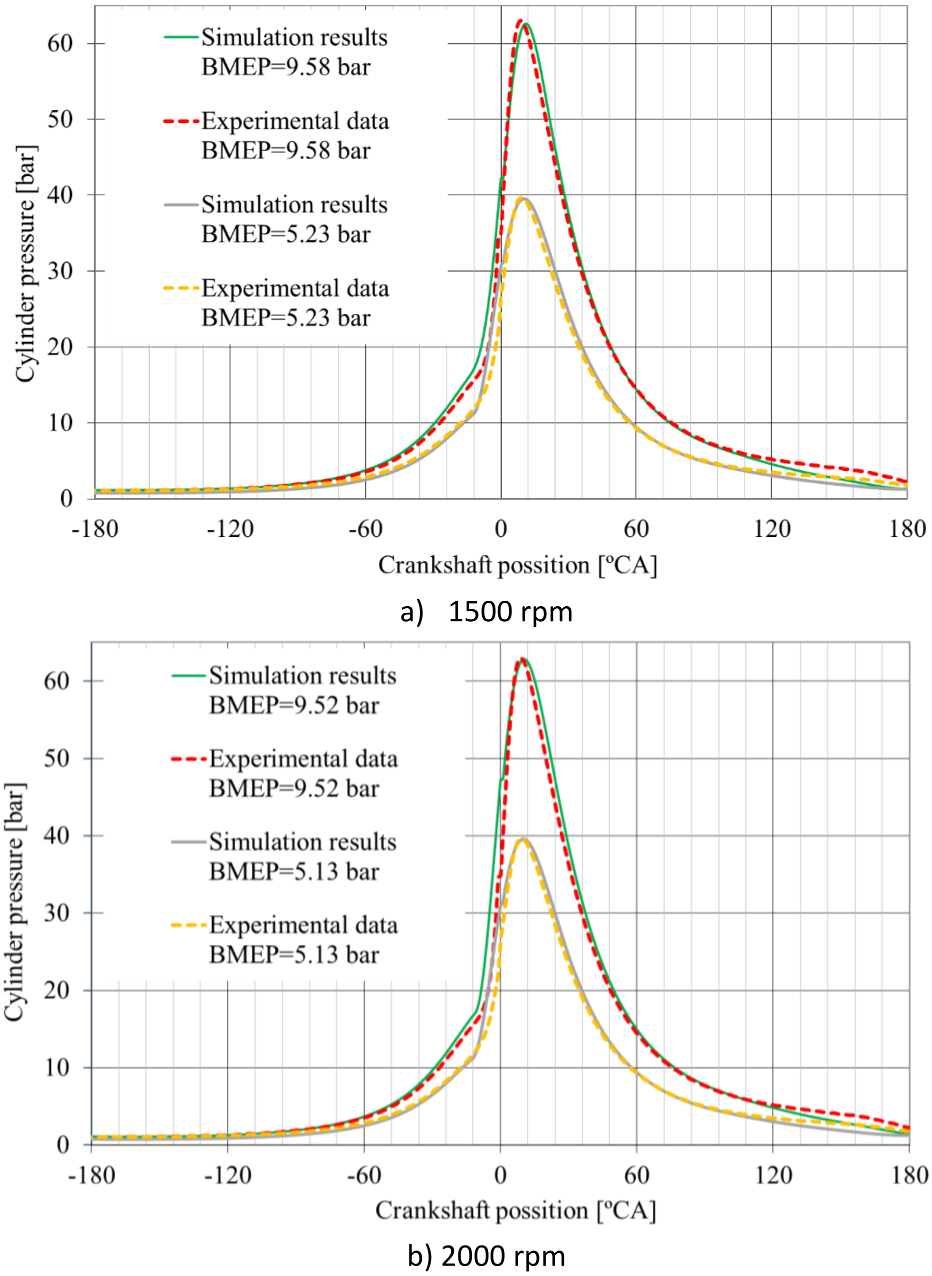


Figure 6.3. Experimental and simulated cylinder pressure a) at 1500 rpm with BMEP of 5.23 and 9.58 bar, b) at 2000 rpm with BMEP of 5.13 and 9.52 bar

6.3. Results

After calibration of the model for gasoline operation, a simulation study was performed to understand the influence of fuelling the engine with natural gas and hydrogen on the engine performance and pollutant emissions compared to the results obtained by gasoline fuelling. The simulations were made keeping constant the relative air-fuel ratio (λ=1) for the 4 fuels used: E7 gasoline, 100% methane, 20% v/v hydrogen-enriched methane, and 30% v/v hydrogen-enriched methane. The same relative air-fuel ratio (λ=1) was kept constant by changing the mass of fuel injected without changing the other parameters.

Figure 6.3 shows the results obtained for the effective power; a decrease of up to 15% can be observed, being more obvious as the amount of hydrogen is higher. This difference is due to the decrease in the amount of air entering the engine, the air being replaced by the gaseous fuel drawn inside the cylinder through the valve port (figure 6.4); the trend of the mass air flow is similar to that one of the brake power.

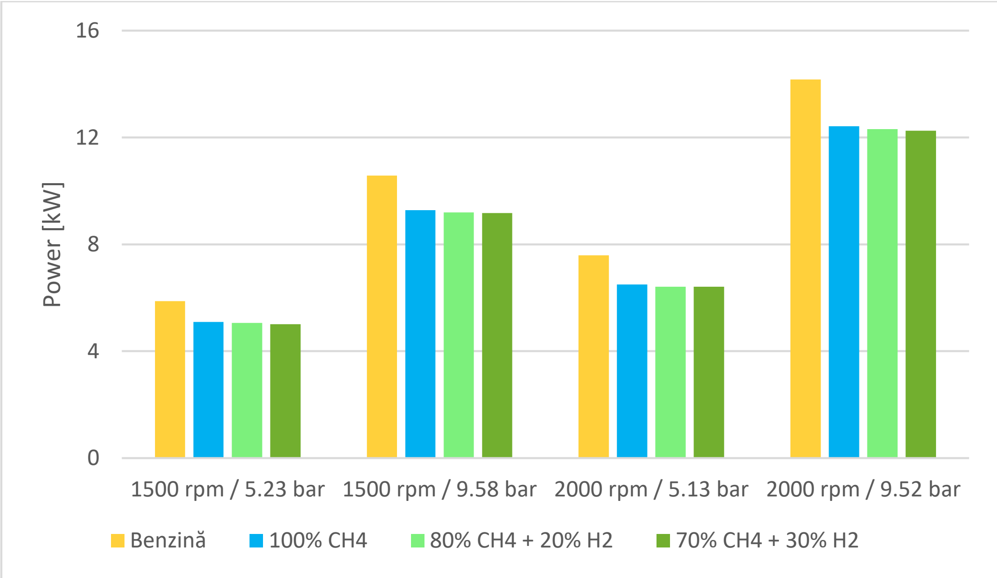


Figure 6.3. Evolution of the effective power according to the fuel used for the 4 operating conditions

From Figure 6.4 it can be remarked that the higher the hydrogen fraction is, the more pronounced the phenomenon of replacing the intake air with gaseous fuel is, the effect is evident because hydrogen has the lowest density.

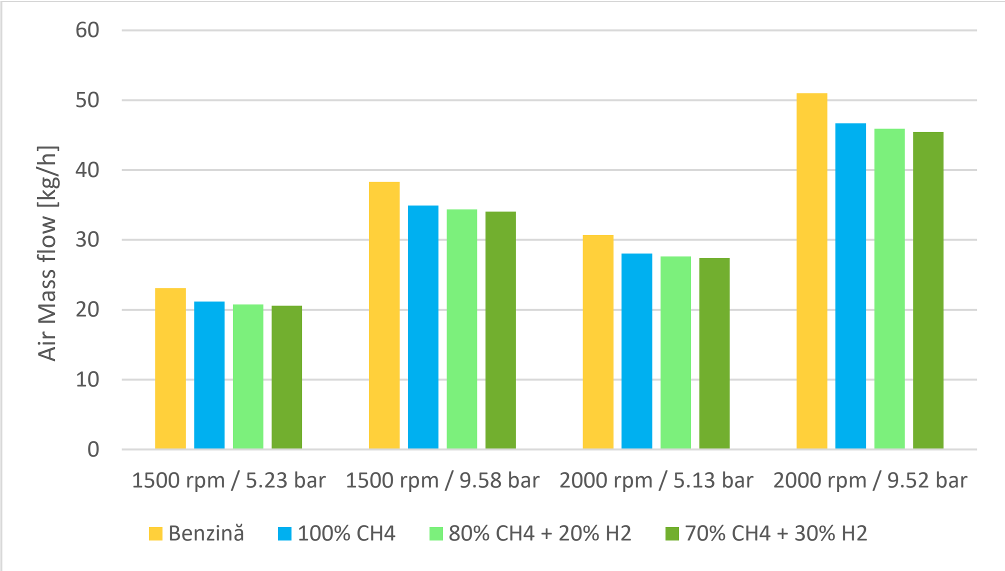


Figure 6.4. Evolution of the Air Mass flow according to the fuel used for the 4 operating conditions

The importance of gaseous fuel direct injection can be thus highlighted when the engine performance obtained in gasoline fuelling must be maintained using the same airflow inducted into the engine cylinders.

The figures below, 6.5 and 6.6 show the results for HC and CO regulated emissions. Significant decreases up to 65% for HC and 55% for CO can be noticed. These decreases can be attributed to a better homogeneity in the case of the "gaseous fuel-air" mixture (for CNG and H_2 fuels) compared to the "liquid fuel-air" mixture (for gasoline).

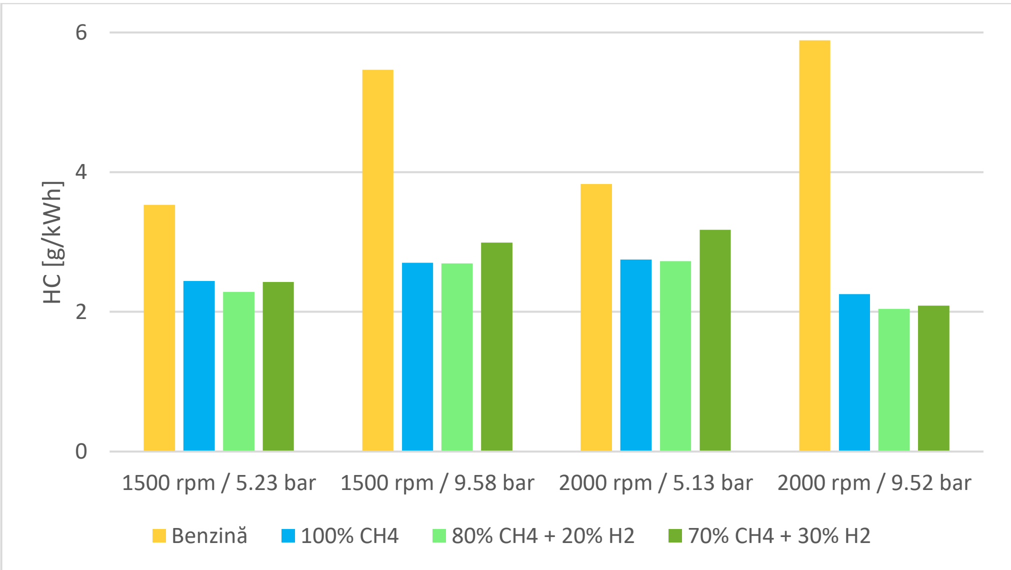


Figure 6.5. Evolution of the HC according to the fuel used for the 4 operating

A small increase in HC emissions could also be observed when the amount of hydrogen increases from 20% to 30% v/v. This may be due to the higher hydrogen combustion speed compared to natural gas which diminishes the available time necessary for the oxidation reactions of hydrocarbons.

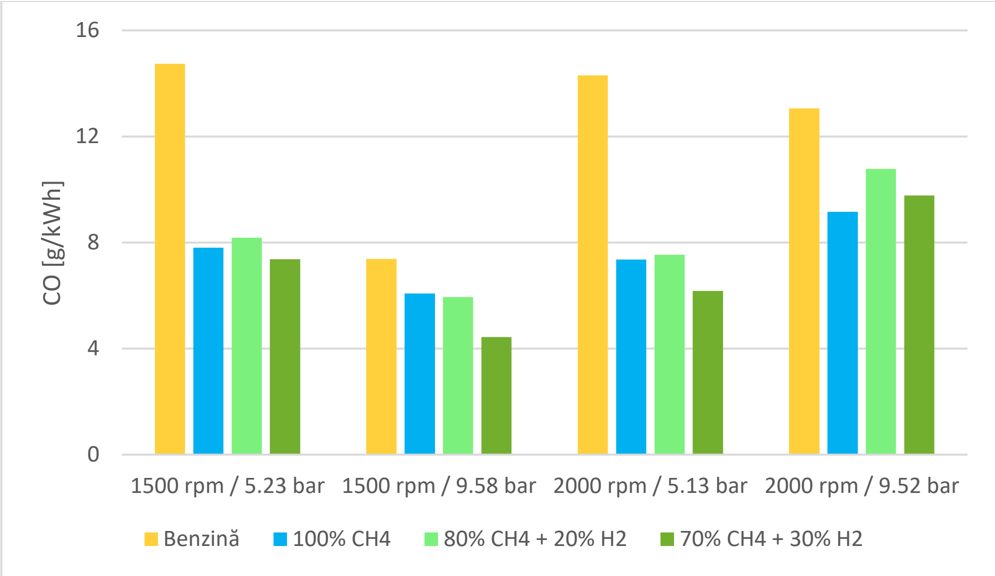


Figure 6.6. Evolution of the CO according to the fuel used for the 4 operating conditions

The decrease in CO emissions shown in figure 6.6 by load increasing and by a higher amount of hydrogen enrichment is attributed to the higher thermal effect which accelerates wet CO chemical kinetics oxidation at high temperatures for all gaseous fuels. This effect seems to be not so evident at a low fraction of 20% hydrogen. Similar results have been reported by Keshavarz [14].

NO_x emissions are dependent on the peak fire temperature inside the cylinder, the amount of oxygen available, and the residence time (combustion duration at a high level of temperature). An increase in NO_x emissions is observed in Figure 6.7 at higher BMEP values for both engine speeds of 1500 rpm and 2000 rpm; similar results have been obtained by Agarwal [3].

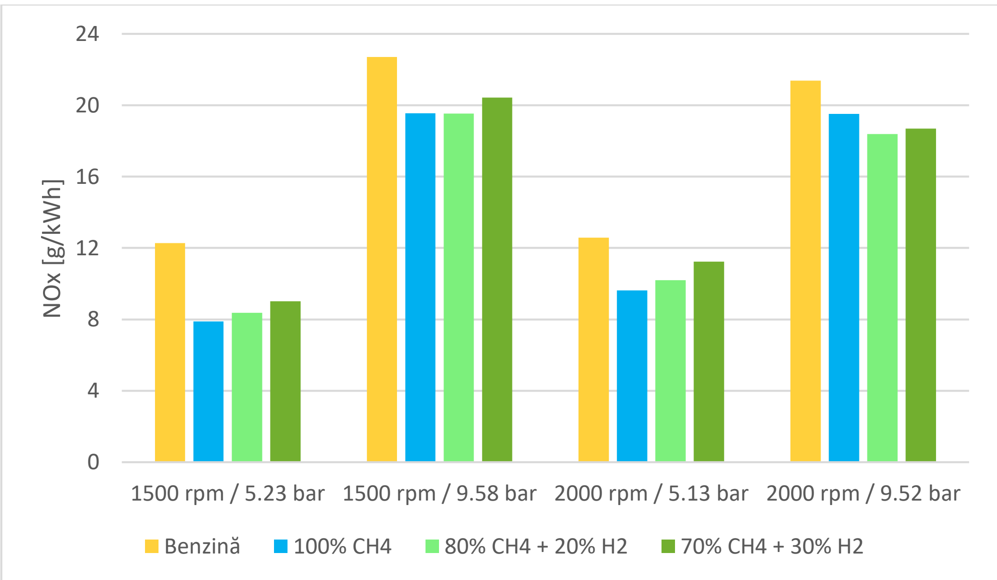


Figure 6.7. Evolution of the NO_x according to the fuel used for the 4 operating conditions

There is a decrease in NO_x emissions by an average of 15% when the fuel was changed from gasoline to natural gas and then a slight increase of NOx by hydrogen enrichment (figure 6.7).

These variations are well correlated with the variation of the peak fire temperatures (figure 6.8) because there is no change in the amount of oxygen for stoichiometric mixtures at lambda = 1. The increase in the temperature as well as NO_x emissions, when the engine runs on a higher hydrogen fraction, is attributed to the higher rate of heat release; the same conclusion is reported also by Mehra [15].

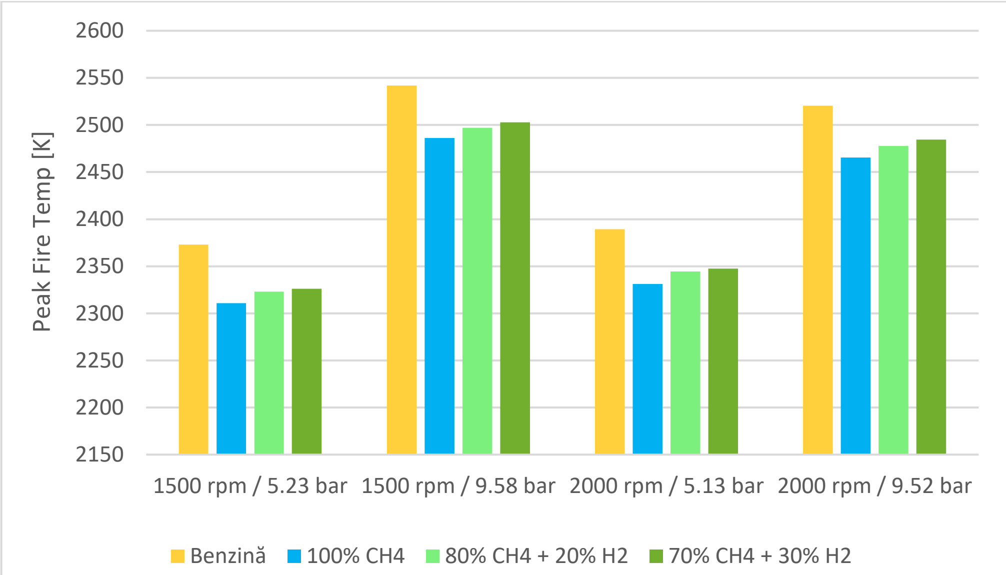


Figure 6.8. Evolution of the Peak Fire Temperature according to the fuel used for the 4 operating conditions

CHAPTER 7. STUDY OF THE INFLUENCE OF THE COMPRESSION RATIO ON THE FUNCTIONING OF THE CNG-H_2 ENGINE

A solution to increase the efficiency of thermal engines is to increase their compression ratio, which can also compensate for the decrease in power. Depending on how much you want to increase this compression ratio, you need to change the architecture of the piston. This can only be achieved by using fuels with a higher octane number to avoid the unwanted knocking phenomenon. Two of the most studied fuels with a higher octane rating than gasoline are natural gas and hydrogen. For a thermal engine to be able to work with gaseous fuels, the fuel system needs to be adapted. Several studies have been conducted through simulation and experimental investigations to highlight the advantages and disadvantages of these modifications. [16]

7.1. Simulation setup

It has been studied the fuelling impact on hydrogen and compressed natural gas in different mass fractions: 0%, 20%, 30%, 40%, 50%, 60%, 70, 80%, 90%, and 100% H2. For each fuel mixture, a parametric study on the influence of compression ratio on the engine performance and emissions was conducted considering the following values: 9.5, 9.7, 10, 10.5, 11, and 11.5. The study was performed using the AVL Boost v2019.1 simulation tool.

The operation of the engine was simulated using the AVL Boost program using the same model presented previously but with a heat release law (Fractal) that allows coupling with the architecture (piston geometry, cylinder head) combustion chamber shape, spark plug location different from the previous one (Wiebe 2 Zones).

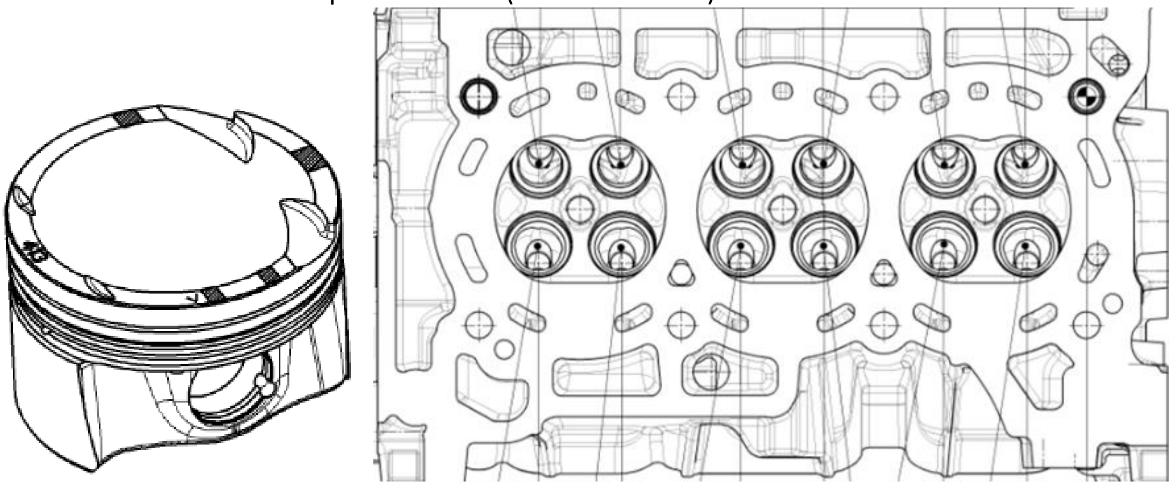


Figure 7.1. Real engine piston and cylinder head geometry [11]

The main components of this model remained the same as in the previous study. The simulation model was made based on the same real Renault production HR09DET engine.

The two-zone thermodynamic combustion model is defined in the Combustion Models - Wiebe 2 Zones section. Gas characteristics are calculated using the two-zone model for the remaining fresh charge (unburned zone) and combustion products (burned gas zone).

Table 1 shows the effective calibration values with the relative deviations for the regulated emissions of CO, NOx, and HC and effective power. After the calibration differences of up to 4% for effective power, up to 1.7% for HC, up to 9.5% for CO, and 2.3% for NOx were obtained.

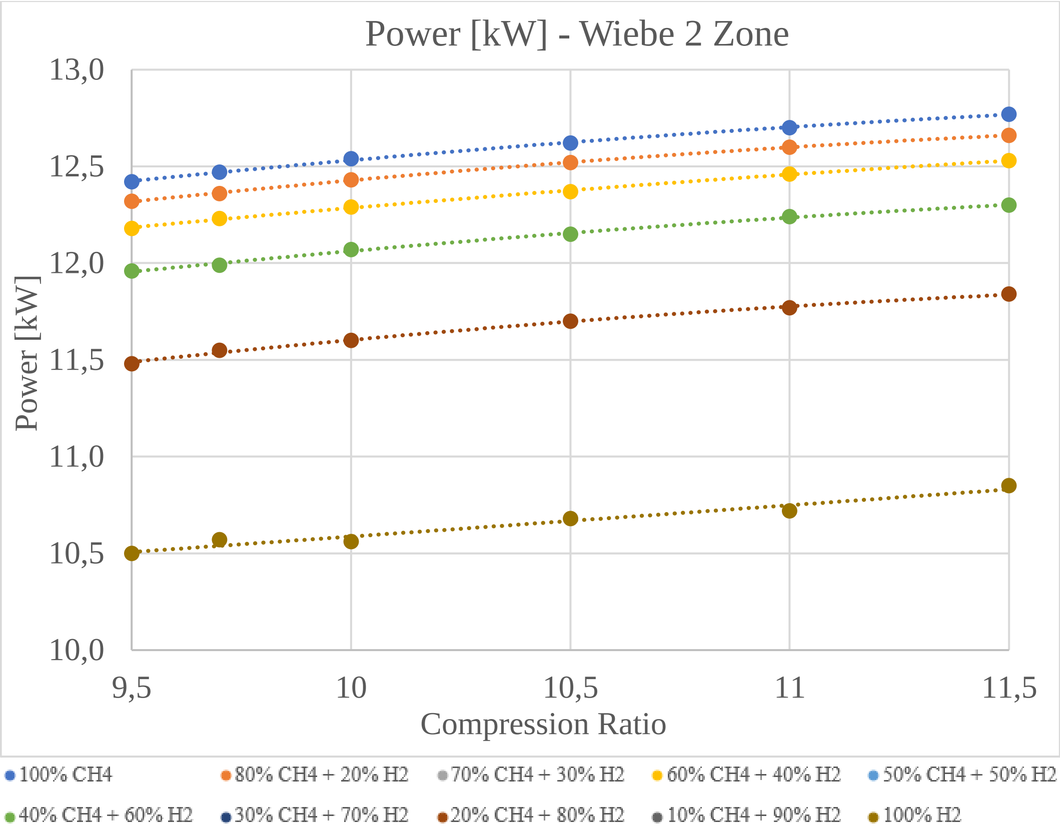
Table 1. Calibration results

2000 rpm / 9.52 bar	Experimental data	Simulation results Wiebe 2 zone	Simulation results Fractal	Relative deviation Wiebe 2 zone	Relative deviation Fractal
Power [kW]	14,27	14,17	14,84	-0,7%	4,0%
CO [g/kWh]	13,06	13,06	14,30	0,0%	9,5%
HC [g/kWh]	5,93	5,89	6,03	-0,7%	1,7%
NOx [g/kWh]	21,54	21,37	21,05	-0,8%	-2,3%
BMEP [bar]	9,52	9,47	9,91	-0,5%	4,1%
Peak Fire Pressure [bar]	63,01	62,87	63,31	-0,2%	0,5%
Peak Fir.Pres.at Crankangle [deg]	9	9,14	13,5	1,6%	50,0%
BSFC [g/kWh]	258	253	242	-1,9%	-6,2%

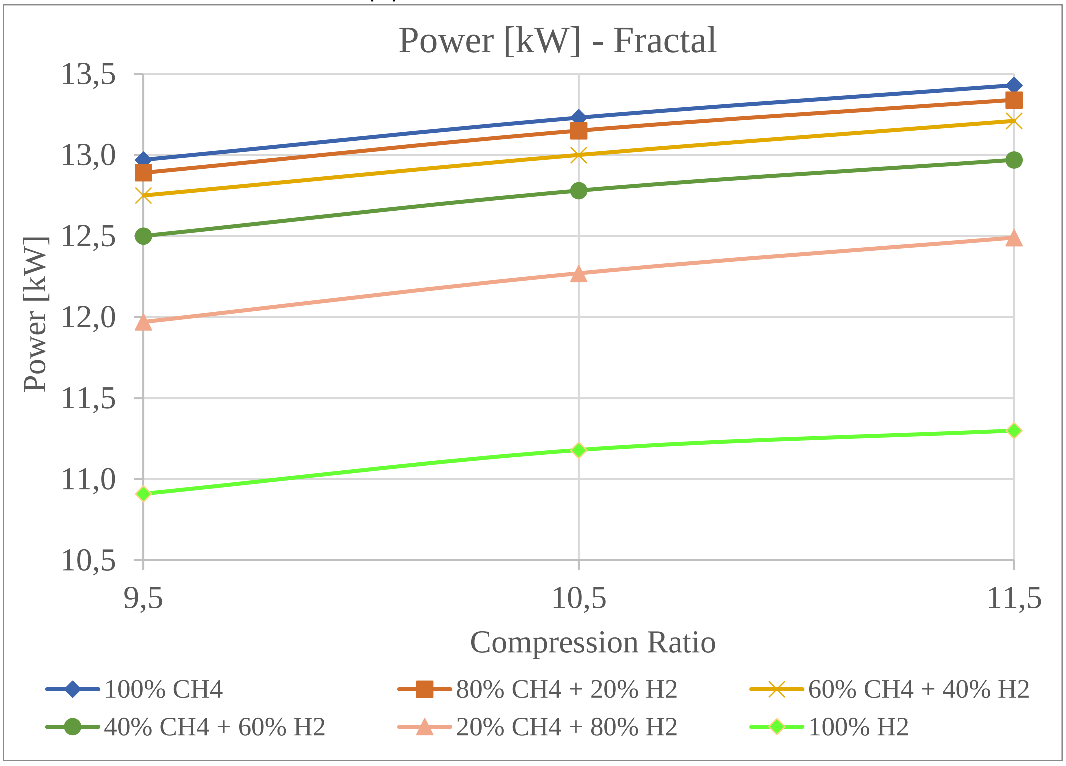
7.2. Results

This section presents the results obtained for each heat release model, namely Wiebe 2 Zone and Fractal.

An increase in the effective power of up to 3.3% was achieved for the Wiebe 2 Zone and up to 4.3% for the Fractal, between compression ratios of 9.5 and 11.5, for all fuels, shown in Figure 7.2 a and b. The increase in power is due to the increase in the compression ratio which induces a faster combustion.



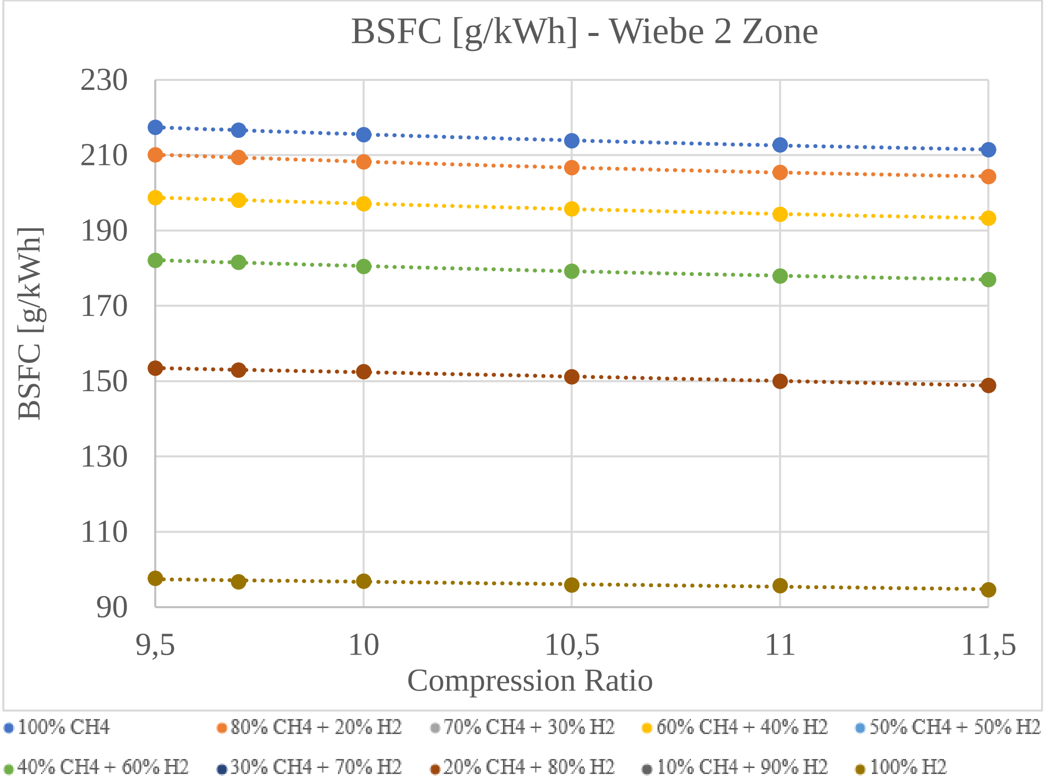
7.2. (a) Heat release Wiebe 2 Zone



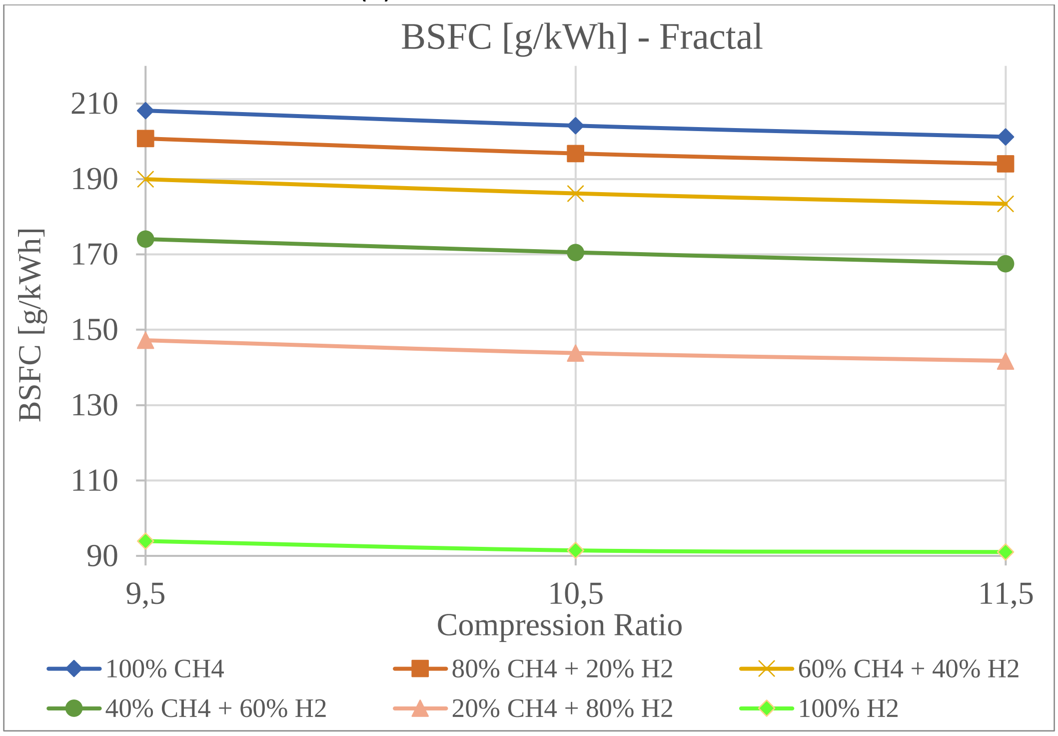
7.2. (b) Heat release Fractal

Figure 7.2. Evolution of effective power for the 10 and 6 types of fuels respectively at different compression ratios

Figure 7.3 a and b show the evolution of Brake Specific Fuel Consumption (BSFC) with increasing compression ratios. A decrease of up to 3.1% was obtained for the Wiebe 2 Zone heat release law and up to 3.7% for the Fractal heat release law, comparing compression ratios of 9.5 and 11.5, for all types of fuels. The decrease in BSFC is due to the increase in the compression ratio that leads to an increase in engine efficiency by shortening the duration of combustion and increasing the maximum temperature per cycle more evident in the case of the Fractal combustion model.



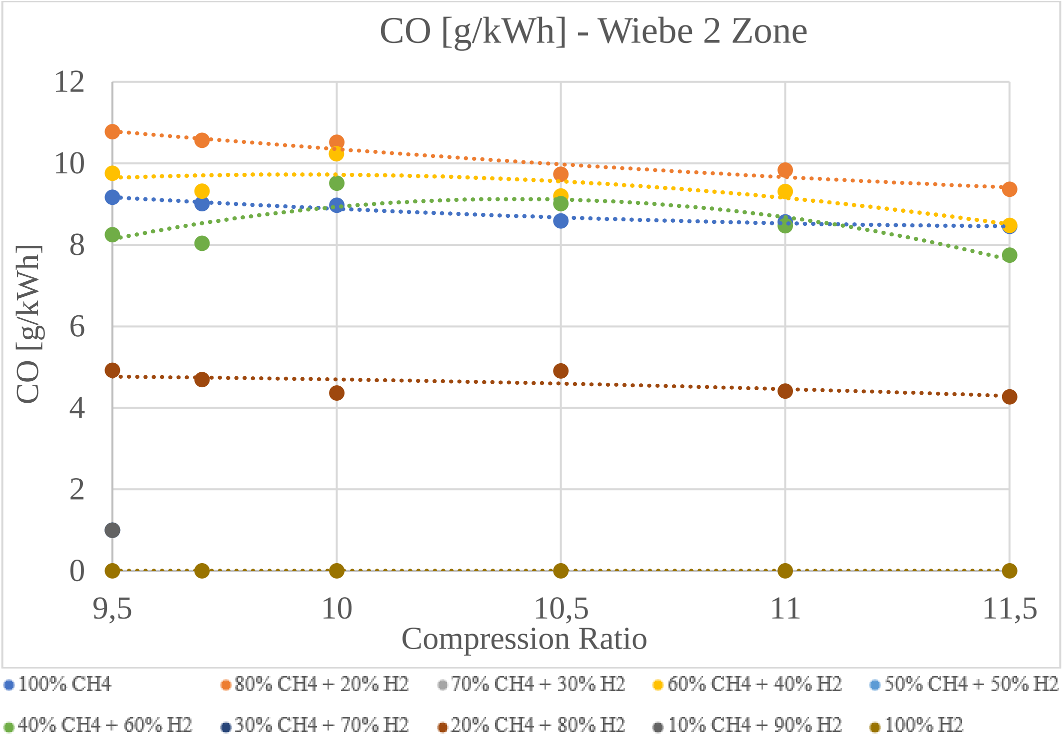
7.3 (a) Heat release Wiebe 2 Zone



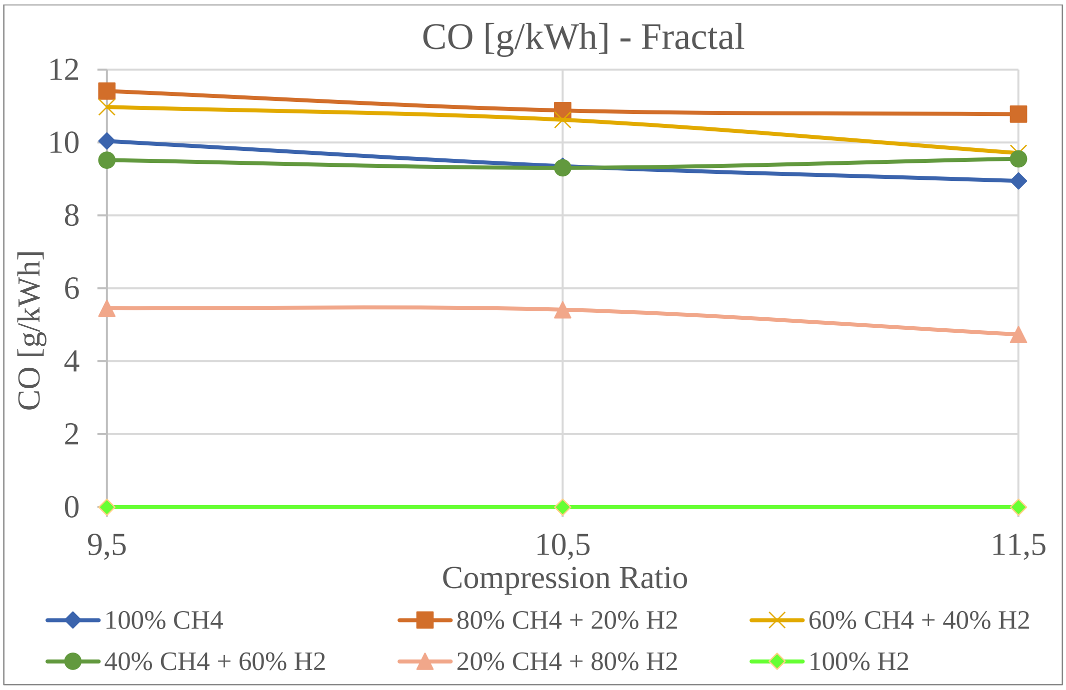
7.3 (b) Heat release Fractal

Figure 7.3. Evolution of BSFC for the 10 and 6 types of fuels respectively at different compression ratios

Figure 7.4 a and b shows the evolution of CO with increasing compression ratios. A reduction of up to 19.7% was obtained for the Wiebe 2 Zone heat release law and up to 13.2% for the Fractal heat release law, comparing the compression ratio of 9.5 and 11.5, for all types of fuels. Reducing the burning time can reduce the level of CO emissions because the oxidation time of carbon to CO_2 is shortened.



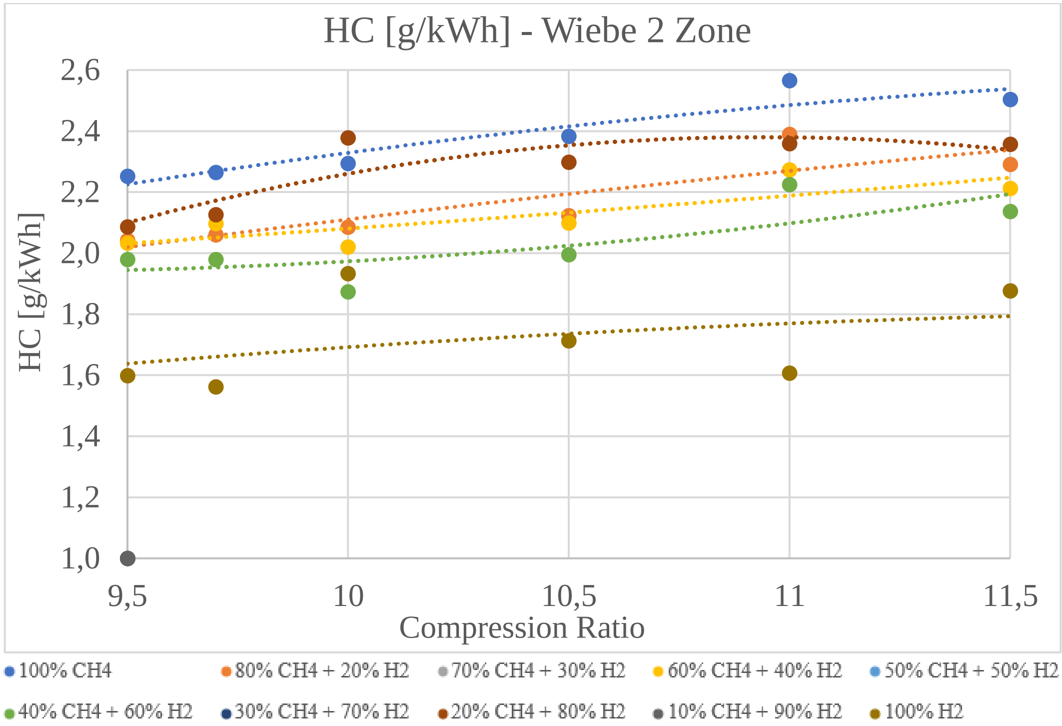
7.4. (a) Heat release Wiebe 2 Zone



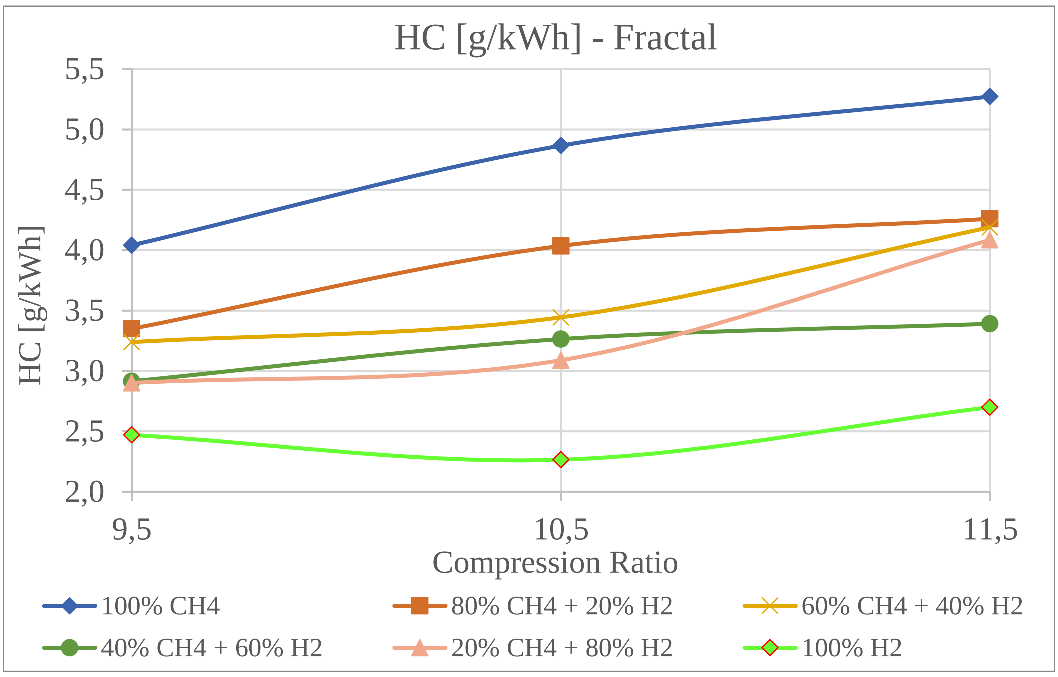
7.4. (b) Heat release Fractal

Figure 7.4. Evolution of CO for the 10 and 6 types of fuels respectively at different compression ratios

Figures 7.5 a and b show the evolution of HC with increasing compression ratios. An increase of up to 17.4% was achieved for the Wiebe 2 Zone heat release law and up to 40.8% for the Fractal heat release law, comparing the compression ratio of 9.5 and 11.5, for all types of fuels. Reducing the duration of combustion can increase the level of HC emissions by reducing their oxidation time.



7.5. (a) Heat release Wiebe 2 Zone

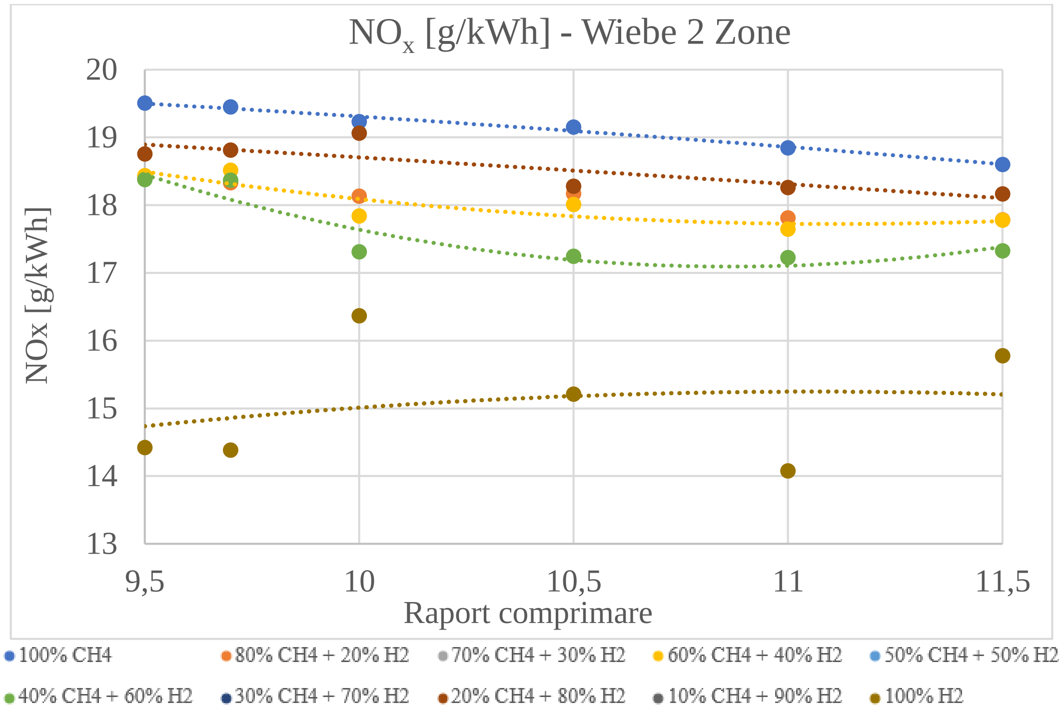


7.5. (b) Heat release Fractal

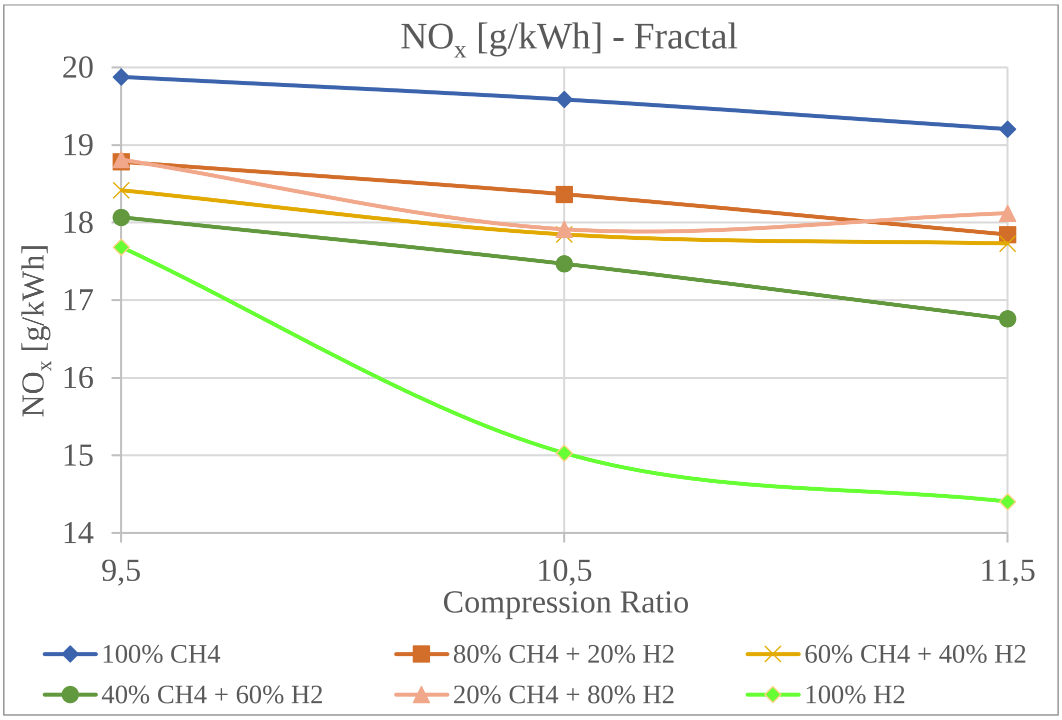
Figure 7.5. Evolution of HC for the 10 and 6 types of fuels respectively at different compression ratios

Figures 7.6 a and b show the evolution of NO_x with increasing compression ratios. A reduction of up to 5.7% was achieved for the Wiebe 2 Zone heat release law and up to 18.6% for the Fractal heat release law, comparing the compression ratio of 9.5 and 11.5 for all types of fuels.

There is a slight decrease in NO_x reported in g/KWh possibly due to the increase in NO_x in ppm (or g/h) but the greater increase in effective engine power in KW.



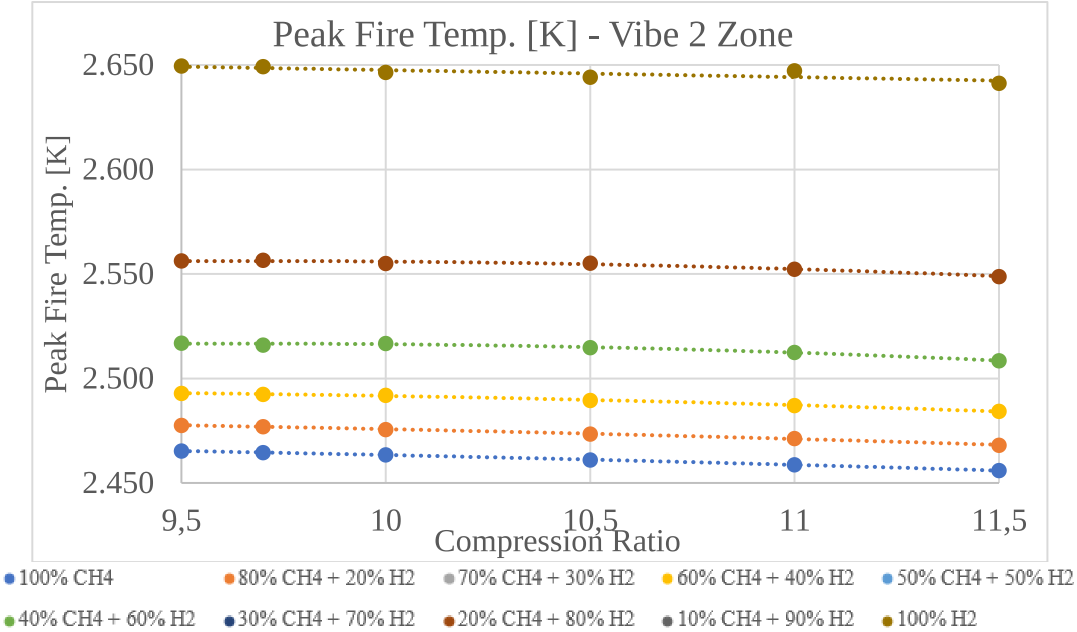
7.6. (a) Heat release Wiebe 2 Zone



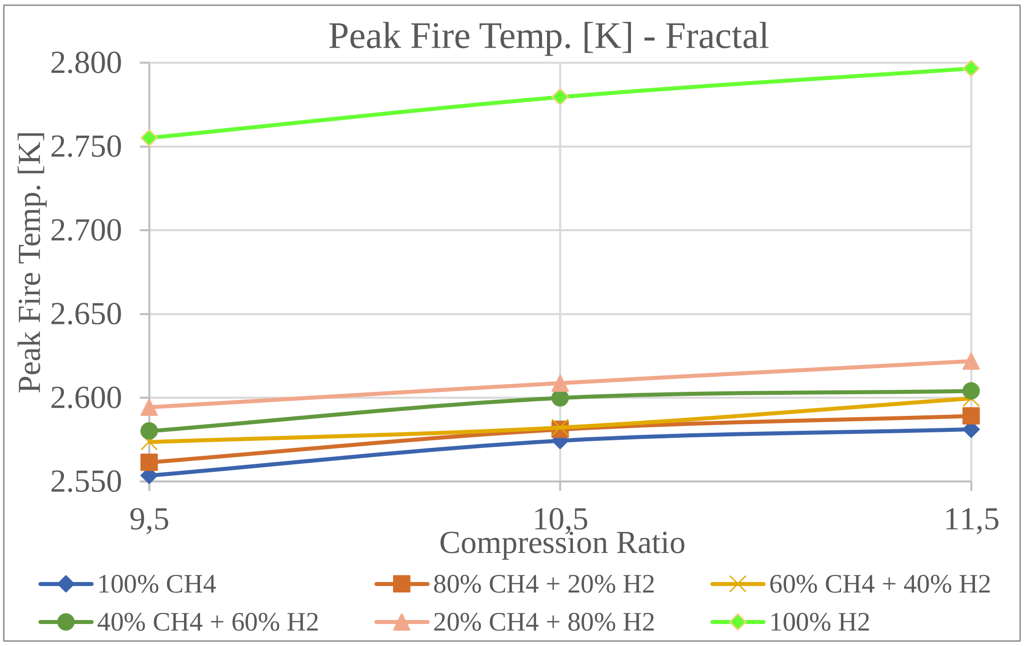
7.6. (b) Heat release Fractal

Figure 7.6. Evolution of NO_x for the 10 and 6 types of fuels respectively at different compression ratios

The reduction in NO_x emissions is attributed to lower maximum cylinder temperatures in the case of the Wiebe 2 Zone. Figure 7.7 a and b shows the evolution of the maximum temperature in the cylinder with increasing compression ratios. A decrease of up to 0.4% was achieved for the Wiebe 2 Zone heat release law, comparing compression ratios of 9.5 and 11.5, for all fuels. In the case of Fractal, NO_x emissions decrease because the decrease in the amount of air has a greater weight compared to the increase in the maximum temperature in the cylinder.

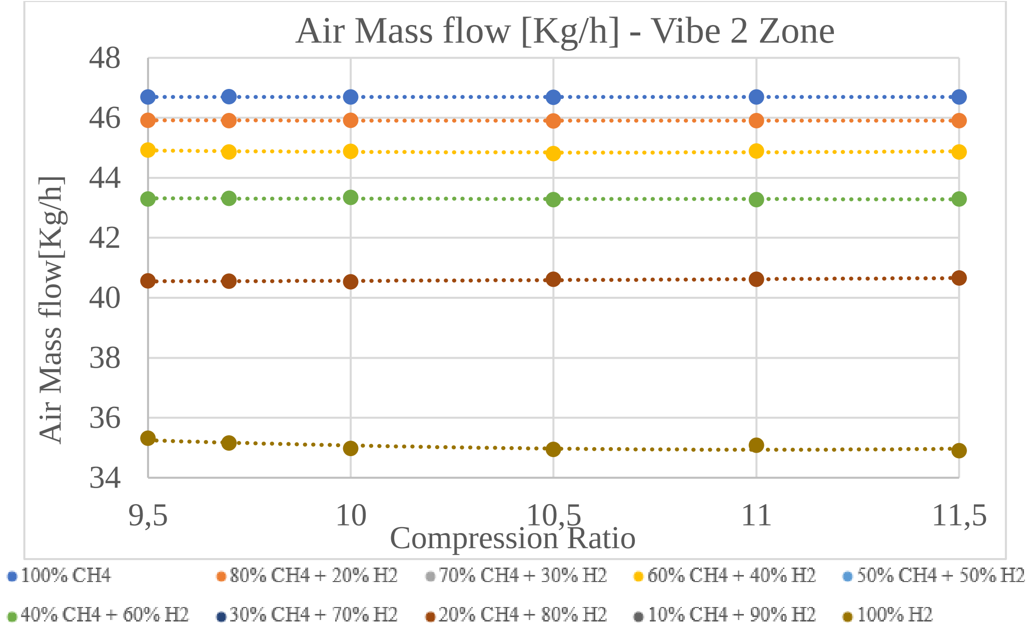


7.7 (a) Heat release Wiebe 2 Zone

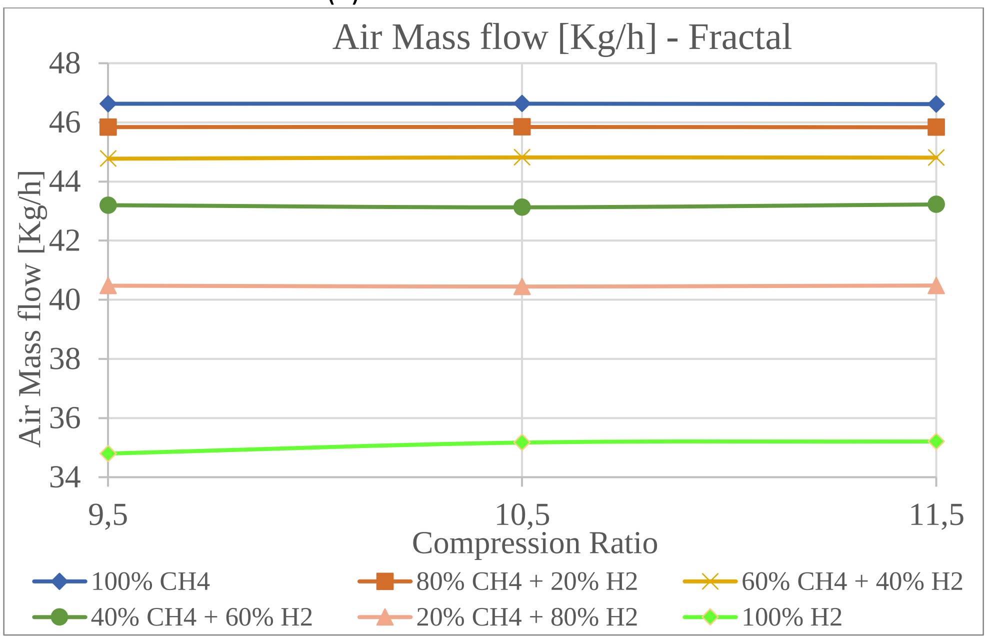


7.7. (b) Heat release Fractal

Figure 7.7. Evolution of Peak Fire Temperature for the 10 and 6 types of fuels respectively at different compression ratios



7.8. (a) Heat release Wiebe 2 Zone



7.7 (b) Heat release Fractal

Figure 7.8. Evolution of Air Mass flow for the 10 and 6 types of fuels respectively at different compression ratios

FINAL CONCLUSIONS

The current study highlights the influence of hydrogen-enriched compressed natural gas compared to conventional gasoline liquid fuel on the performance and emissions of a spark ignition engine. The conclusions can be summarized as follows:

- By changing the liquid fuel with the gaseous one a better homogeneity of the mixture with the air is obtained, ensuring thus more complete combustion with significant reductions in HC and CO emissions.

- A decrease in brake power was obtained due to the intake air replacement by gaseous fuels for the same stoichiometric ratio (λ=1).
- A decrease in NOx emissions by an average of 15% when the fuel was changed from gasoline to natural gas was obtained.
- The slight increase of NOx and decrease of CO emissions normally occurred with higher fractions of hydrogen due to elevated cylinder charge temperatures.
- Hydrogen enrichment extends the combustion limit of HCNG mixtures; this way the engine efficiency can be improved by operating with lean mixtures.
- Significantly improved performance characteristics can be achieved with a higher compression ratio of the engine when using CNG and H2 due to their higher-octane number compared to gasoline.
- The addition of H_2 (up to 20-30% by volume) to natural gas can be an effective short-term solution to the problem of greenhouse gas emissions.

The study also showed that the simulation results in AVL Boost software, using 2 heat release laws, "Wiebe 2 Zone" and "Fractal", can very well simulate the behavior of a spark ignition engine under different operating conditions. Engine operating conditions are a constant speed of 2000 rpm, a constant load of 9.52 bar brake mean effective pressure, and a stoichiometric mixture λ=1. The influence of fuelling compressed natural gas and hydrogen in different volumetric proportions was also studied: 0%, 20%, 30%, 40%, 50%, 60%, 70, 80%, 90%, and 100% H_2. For each fuel mixture, a compression ratio study was performed for the following values: 9.5, 9.7, 10, 10.5, 11, and 11.5 in the case of Wiebe 2 Zone and 9.5, 10.5, and 11.5 in the case of Fractal.

With increasing compression ratio, the effective power is observed to increase proportionally for both heat release models, Wiebe 2 Zone and Fractal up to 4.3%. This fact is correlated to the decrease of CSC to 4.4%. The reduction in NO_x emissions by up to 18.6% can be attributed to lower maximum cylinder temperatures. A decrease of up to 19.7% was achieved for the Wiebe 2 Zone heat release law for CO emissions.

Among the results obtained between minimum and maximum compression ratios (9.5 and 11.5), for all types of fuels, some conclusions can be listed:

- An increase in the effective power of up to 3.3% was achieved for Wiebe 2 Zone and up to 4.3% for Fractal.
- A decrease in BSFC of up to 3.1% was achieved for the Wiebe 2 Zone heat release law and up to 3.7% for the Fractal heat release law.
- A reduction in CO emissions of up to 19.7% was achieved for the Wiebe 2 Zone heat release law and a decrease of up to 13.2% for the Fractal heat release law.
- An increase in HC emissions of up to 17.4% was achieved for the Wiebe 2 Zone heat release law and up to 40.8% for the Fractal heat release law.
- A reduction in NO_x emissions of up to 5.7% was achieved for the Wiebe 2 Zone heat release law and up to 18.6% for the Fractal heat release law, attributed to lower maximum cylinder temperature values.

Following the study of the compression ratio influence, it can be seen that the trends are an increase in effective power, a decrease in BSFC, and a decrease in CO and NO_x emissions. Thus, the expectations regarding the improvement of performance and pollutant emissions of the studied engine, when fuelled with fuels having a high octane number are confirmed.

PERSONAL CONTRIBUTIONS

1. Obtaining and processing experimental results at the Renault Technologie Roumanie engine test bench for the gasoline-powered engine.

2. Obtaining and processing the experimental results at the Renault Technologie Roumanie roller bench following the WLTP procedure for the engine studied for the two cases of gasoline and compressed natural gas.

3. Obtaining and processing the experimental results on the vehicle within Renault Technologie Roumanie following the RDE driving cycle for the two cases of gasoline and compressed natural gas.

4. Obtaining and processing the simulation results of the most used operating regimes in the WLTC cycle within Renault Technologie Roumanie for the studied engine.

5. Creating the simulated model using the AVL Boost program for the gasoline engine, so that we achieved the performance and emission characteristics of the real Renault 0.9 liter engine within the maximum limit of relative deviations of 1.9%.

6. Adaptation of the AVL Boost model for the supply of two fuels, Compressed Natural Gas and Hydrogen in various volumetric proportions, in the engine version with spark ignition.

7. Carrying out the numerical simulation study with AVL Boost using the Wiebe 2 Zone heat release law for engine operation at different speeds and loads.

8. Realization of the study by numerical simulation with the AVL Boost program using the Fractal heat release law that takes into account the engine architecture.

9. Realization of the numerical simulation study with the AVL Boost program of the effect of increasing the compression ratio for the two Wiebe 2 Zone and Fractal heat release laws.

PUBLISHED ARTICLES

1. **M.C. Barbu**; A. Birtaș; R. Chiriac; "The impact of different heat release models on performance and emissions of a spark ignition engine operating with hydrogen and natural gas mixtures at different compression ratios"; in U.P.B. Sci. Bull., Series D, Vol. xx, Iss. xx, 2023 (în curs de publicare)

2. **M.C. Barbu**; A. Birtaș; R. Chiriac; "On the improvement of performance and pollutant emissions of a spark ignition engine fuelled by compressed natural gas and hydrogen"; Energy Reports Volume 8, Supplement 9, November 2022, Pages 978-991; https://doi.org/10.1016/j.egyr.2022.07.136

3. **M.C. Barbu**; R. Chiriac; "The use of natural gas mixed with hydrogen as fuel for spark-ignition engines"; SIAR - Ingineria automobilului, nr. 60; ISSN 1842 – 4074 (pp.8-15); September 2021; http://siar.ro/wp-content/uploads/2021/08/rIA-60.pdf

4. R. Chiriac; B. Radu; **M.C. Barbu**; "Computational elements for designing

a piston steel type"; SIAR - Ingineria automobilului, nr. 38; (pp.17-19); March 2016; http://siar.ro/wp-content/uploads/2016/03/rIA-nr.38-2016_1-martie.pdf

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