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

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This paper presents the results of a theoretical investigation made by simulations on a Renault HR09DET spark ignition engine, four-stroke, 3-cylinders, and multipoint fuel injection fuelled by compressed natural gas and hydrogen. The simulation model, developed with the AVL Boost program, was calibrated using experimental data for the engine fuelled with gasoline. The simulation model allowed the addition of hydrogen in parallel with the fuelling by natural gas. The results highlight the changes in performance and regulated pollutant emissions as unburned hydrocarbons (HC), carbon monoxide (CO), and nitrogen oxide emissions (NOx) by increasing the compression ratio, using 2 laws of heat release (Wiebe 2 Zone and Fractal). Considering the higher-octane number for CNG and hydrogen compared with gasoline, the engine's thermal efficiency was improved by increasing the compression ratio, from 9.5 to 11.5, for both heat release laws.

Keywords: Compressed Natural Gas; Hydrogen; Emissions; Spark-ignition Engine; Fractal; Wiebe 2-Zone; Compression ratio

1. Introduction

With the tightened limits demanded by actual pollution regulations, new technical solutions are being sought to reduce emissions and increase the efficiency of thermal engines. An effective solution for increasing the efficiency of thermal engines is to increase their compression ratio. This can only be achieved by using fuels with a higher octane number to avoid the unwanted phenomenon of detonation. Two of the most studied fuels with a higher octane number than gasoline are natural gas and hydrogen. Several studies have been carried out through simulation and experimental investigations to highlight the advantages and disadvantages of these changes [1].

Lim G. et al obtained an improvement in thermal efficiency by up to 2% using natural gas-hydrogen mixtures when increasing the compression ratio and by optimizing the spark advance for the rising of the air-fuel ratio [2]. Nguyen Q. T. et al studied the hydrogen impact on the combustion process for several compression ratios. They obtained a rise in NOx emissions and a decrease in

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carbon dioxide (CO_2) emissions with an increase in the amount of hydrogen [3]. Kriaučiūnas D. et al studied, through simulations using AVL Boost, the influence of different biogas-hydrogen mixtures on performance and emissions for several compression ratios. The results showed an increase in in-cylinder temperature and NOx emissions due to a better homogeneity that led to a better combustion process [4]. Lin J. et al obtained a decrease of brake specific fuel consumption (BSFC) by 6%–8% using a variable compression ratio system [5].

2. Simulation Setup

The authors 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% H_2. 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. Increasing the compression ratio over the standard value of 9.5 used for gasoline can be done without knocking when using higher octane fuels such as natural gas and hydrogen. This study did not aim to identify a maximum compression ratio but to highlight the influence of a higher compression ratio.

For this study, a Renault turbocharged gasoline engine was considered. Table 1 is presenting the engine specifications:

Table 1.

Engine specifications [6]

Name	HR09DET
Displacement	898 cm^3
Position of cylinders	In line
Index	411
Number of cylinders	3
Compression ratio	9.5
Bore x Stroke	72.2 x 73.1 mm
Fuel	CNG
Fuel System	Multi-point indirect injection
Power	66 kW at 5500 rpm
Torque	140 N·m at 2250 rpm
Number of valves	12 valves

The engine operation was simulated using the AVL Boost v2019.1 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 (Fig.1.)

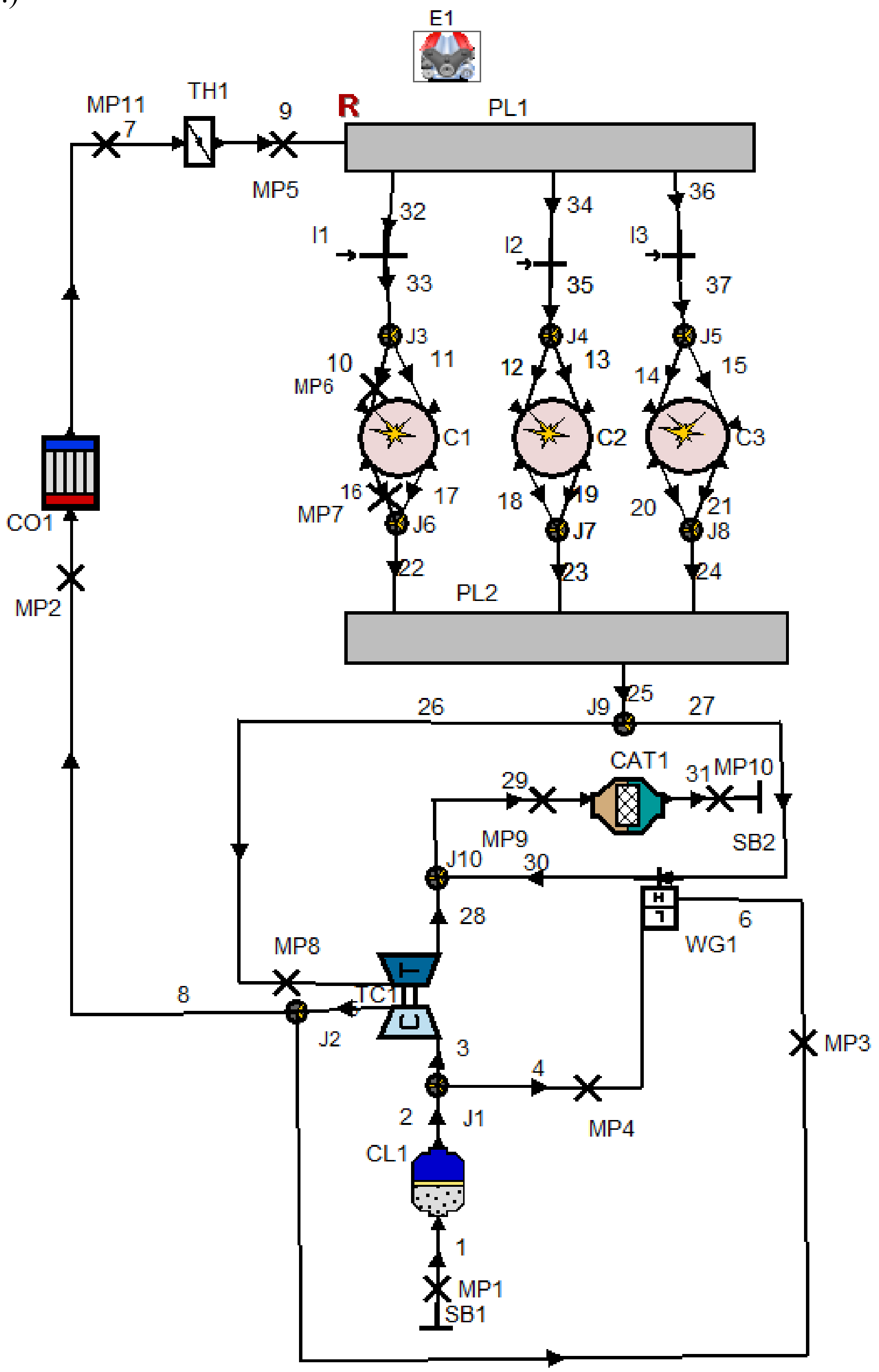


Fig.1. The engine symbolic layout in AVL Boost [7]

Wiebe 2 Zone is a thermodynamic combustion model that divides the combustion chamber into two parts and two types of components. The first one is the initial unburned mixture (reactants) and the second one is the burnt gases (products of reaction). The Fractal heat release combustion model is a quasi-dimensional model, which considers, the cylinder charge composition, the architecture of the combustion chamber, the spark discharge timing, and the spark plug position, in which the rate of heat release is dependent on the level of turbulence in the combustion chamber [7], [8], [9], [10].

The mathematical models used in this simulation program for the two heat release models Wiebe 2 Zone and Fractal are explained in detail in the AVL Boost Theory [7].

In this study, 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.

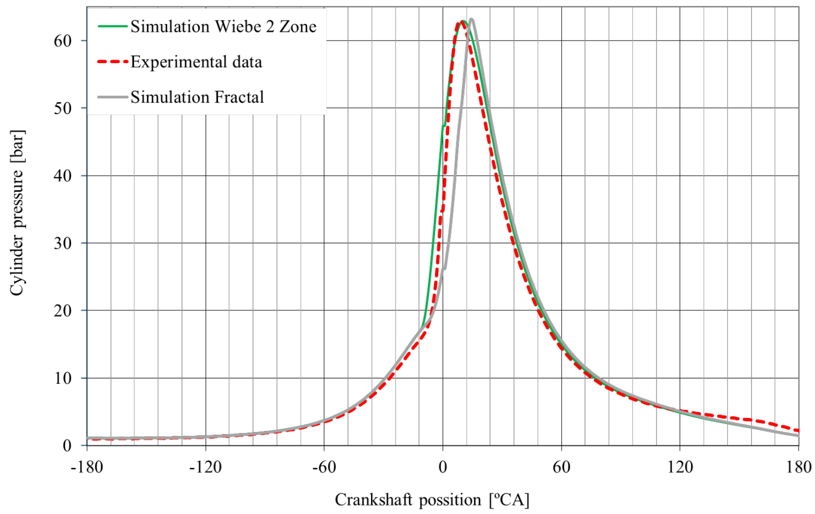


Fig.2. Cylinder pressures calibration (2000 rpm, BMEP of 9.52 bar)

In Fig.2 a comparison was made for 2000 rpm engine speed and a load of 9.52 bar brake mean effective pressure (BMEP) for gasoline fuel between in-cylinder pressure traces of simulation results (Fractal and Wiebe 2 Zone) and experimental data. The calibration of the model is very accurate and it was done within the limit of 0.5% for the peak cylinder pressure, 4% for the BMEP and 4 crank angle (CA) degrees for the peak cylinder pressure angle. Due to a less accurate overlay of the pressure diagram in the case of Fractal, the obtained results must be considered with caution.

Table 2 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.

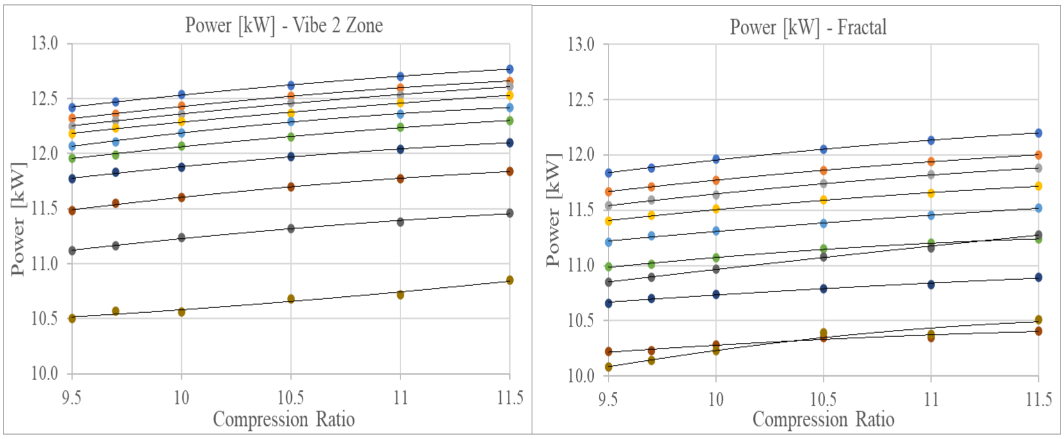
Table 2.

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%

3. Results and discussion

This section presents the results obtained for each heat release model, namely Wiebe 2 Zone and Fractal. Following the comparison in Fig.3 a and b between the Wiebe 2 Zone and Fractal heat release characteristics for effective power, a difference of 5.3% was obtained for the fuel 80% CH_4+20% H_2, at the compression ratio of 9.5.



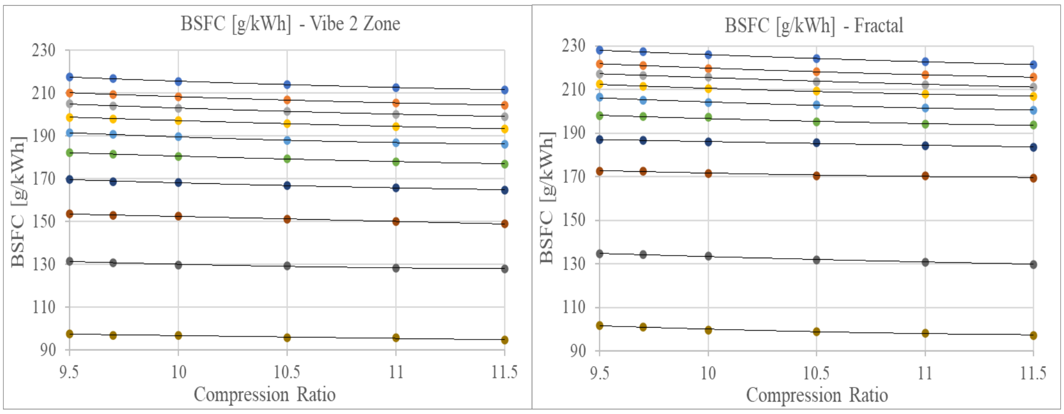
(a) Heat release Wiebe 2 Zone (b) Heat release Fractal

Fig.3. Evolution of the effective power with the fuel used for the 10 operating conditions with different compression ratios

The legend for figures 3, 4, 5, 6, 7, and 8:

• 100% CH4 • 80% CH4 + 20% H2 • 70% CH4 + 30% H2 • 60% CH4 + 40% H2 • 50% CH4 + 50% H2
• 40% CH4 + 60% H2 • 30% CH4 + 70% H2 • 20% CH4 + 80% H2 • 10% CH4 + 90% H2 • 100% H2

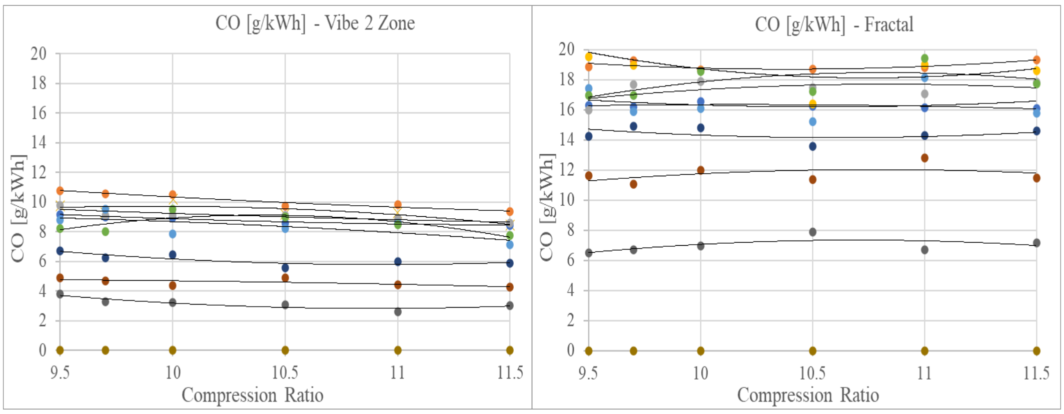
A deviation of 5.6% for BSFC was obtained between the Wiebe 2 Zone and the Fractal heat release characteristics for the fuel 80% CH_4 + 20% H_2, at the compression ratio of 9.5 (Fig.4 a and b). The lower values obtained for effective power and the higher valuer of BSFC in the Fractal case can be attributed to the higher maximum pressure angle obtained during calibration, which has a direct influence on the indicated mean effective pressure (IMEP).



(a) Heat release Wiebe 2 Zone (b) Heat release Fractal

Fig.4. Evolution of BSFC with the fuel used for the 10 operating conditions with different compression ratios

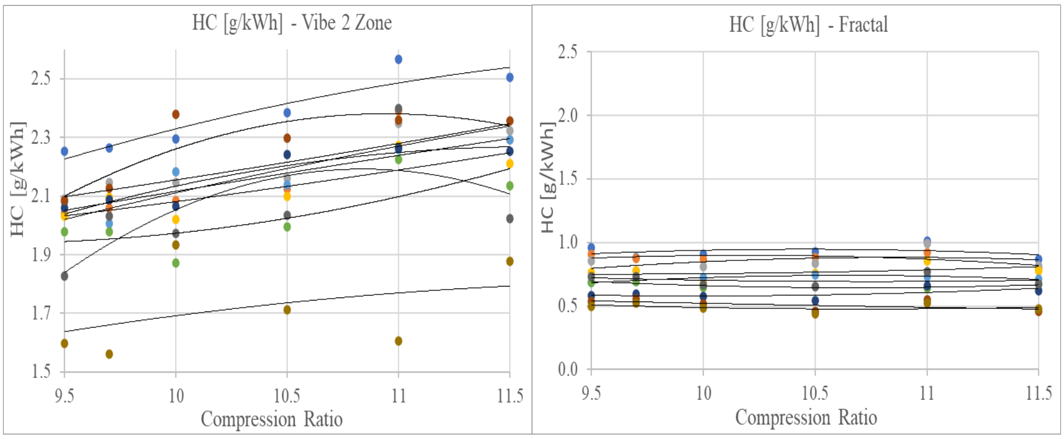
Fig.5 a and b show the evolution of CO emissions. Lower values for Wiebe 2 Zone are due to weaker oxidation existing in the case of the more realistic Fractal model compared to the Wiebe 2 Zone.



(a) Heat release Wiebe 2 Zone (b) Heat release Fractal

Fig.5. Evolution of CO with the fuel used for the 10 operating conditions with different compression ratios

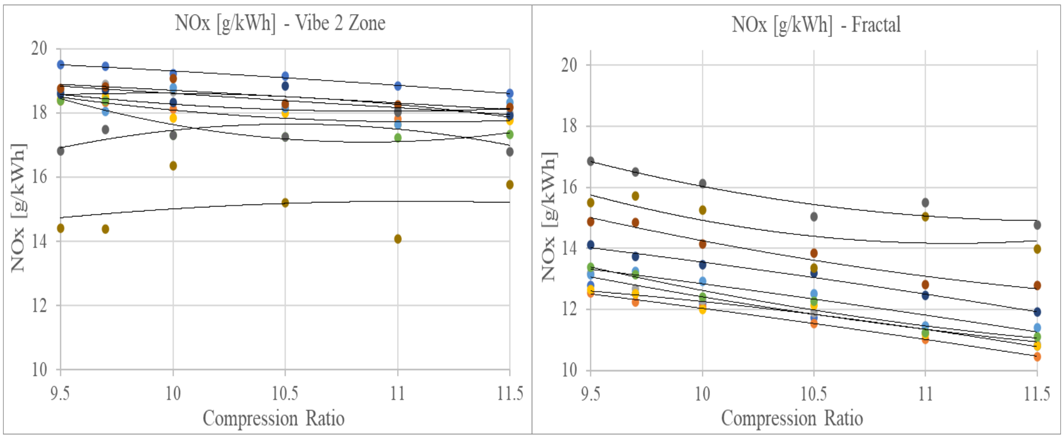
The lower emissions of HC can be due to more complete combustion in the flame extinguishing zone near cylinder walls in the case of the Fractal. In the Wiebe 2 Zone model, the spherical flame does not completely cover the volume of the combustion chamber, this leads to higher HC emissions (Fig.6 a and b)



(a) Heat release Wiebe 2 Zone (b) Heat release Fractal

Fig.6. Evolution of HC with the fuel used for the 10 operating conditions with different compression ratios

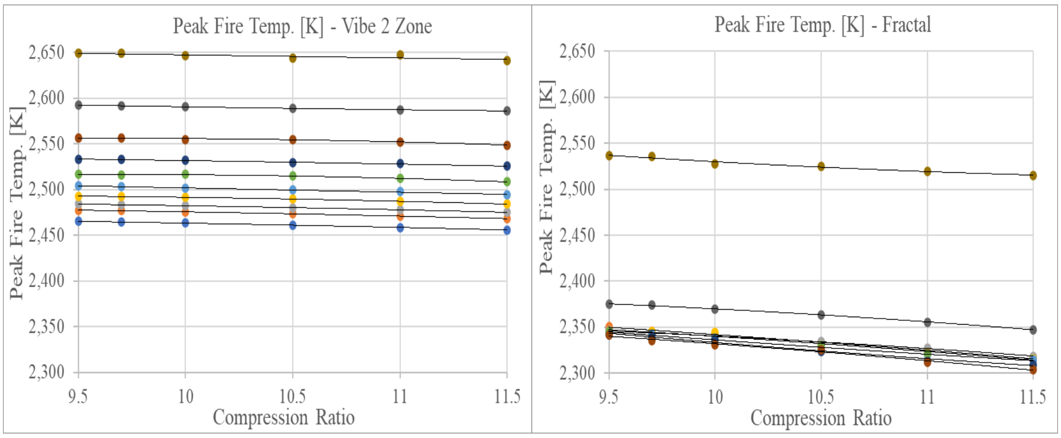
Fig.7 a and b display the evolution of the NOx between the 2 heat release characteristics. A decrease of 23.3% was obtained for Fractal compared with Wiebe 2 Zone heat release for the fuel 20% CH_4+80% H_2 with a compression ratio of 9.5.



(a) Heat release Wiebe 2 Zone (b) Heat release Fractal

Fig.7. Evolution of NOx with the fuel used for the 10 operating conditions with different compression ratios

The decrease in NOx emissions is attributed to lower values of the peak fire temperature. The drop in temperature between Wiebe 2 zones and Fractal is due to a higher heat transfer to the walls in the case of Fractal; the flame reaches a smaller distance from the cylinder walls than in the case of Wiebe 2 zones. The decrease of the peak fire temperature with the increase in the compression ratio is due to a higher heat transfer to the walls in the case of higher compression ratios (Fig.8 a and b).



(a) Heat release Wiebe 2 Zone (b) Heat release Fractal

Fig.8. Evolution of Peak Fire Temperature with the fuel used for the 10 operating conditions with different compression ratios

4. Conclusions

The study revealed the results obtained by simulation with the AVL Boost v2019.1 software when using 2 heat release characteristics, "Wiebe 2-Zone" and "Fractal", which can accurately simulate the behavior of a spark ignition engine at various operating conditions. The engine operating conditions have been considered as a constant speed of 2000 rpm, a constant load of 9.52 bar brake mean effective pressure, and a stoichiometric mixture $\lambda=1$. The authors studied the influence of engine fuelling with compressed natural gas mixed with hydrogen in different mass fractions: 0%, 20%, 30%, 40%, 50%, 60%, 70, 80%, 90%, and 100% H_2. For each fuel mixture, a parametric study for compression ratio was conducted using the following values: 9.5, 9.7, 10, 10.5, 11, and 11.5. Among the results obtained between the 2 heat release characteristics the authors can list some conclusions:

- a decrease in the effective power of 5.3% and an increase in BSFC of 5.6% was obtained for the fuel 80% CH_4+20% H_2, at the compression ratio of 9.5; this can be attributed to the higher maximum pressure angle obtained during calibration;

- lower CO values for Wiebe 2 Zone are due to weaker oxidation in the case of the more realistic Fractal model;
- the lower emissions of HC occur due to more complete combustion in the flame extinguishing zone near cylinder walls in the case of the Fractal model;
- a decrease in NOx of 23.3% was obtained for Fractal compared with Wiebe 2 Zone for the fuel 20% CH_4+80% H_2 with a compression ratio of 9.5. The decrease in NOx emissions is attributed to lower values of the peak fire temperature.

Comparing the two heat release models considered in this study, Wiebe 2 Zone and Fractal, the results show that similar trends are related to H_2 addition, meaning the decreasing of the maximum engine output, the BSFC, and CO and HC emissions. The NOx emission seems to increase for the Fractal heat release model by hydrogen addition due to the increase of the peak fire temperature, while for the Wiebe 2 Zone model, the trend is not so apparent.

A more thorough study of the Fractal heat release characteristic would be welcomed in terms of combustion chamber geometry.

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