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AN ASSESSMENT OF A TRACTOR DIESEL ENGINE OPERATING IN RCCI MODE FUELED WITH DIESEL-BIODIESEL-GASOLINE

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Simulation and experimental research should always connect in order to emphasize the basic aspects of thermal engines operation. More than ever diesel engines are subjected to a worldwide analysis regarding their efficiency, performance and emissions. This is why modern concepts of combining high-reactive with low-reactive fuel components in rigorously controlling the air-fuel dosage, the combustion, the heat release and the formation of the pollutant becomes a key part of a more elaborate strategy versus classic diesel configuration and operating modes. The proposed work refers to a simulation study on performance, efficiency and emissions involving an agricultural tractor propulsion engine, fueled with 100% diesel-gasoline and biodiesel (B20)-gasoline blends, applying AVL-Boost platform numerical codes with integrated Wiebe-2-Zone combustion model and calibrated on experimental data when testing the engine at maximum load and rated speed. The findings highlight that compared to diesel classic configuration, the increase of the gasoline fueling ratio improves the engine operation in terms of efficiency and mechanical performance, while emissions are slightly dropping under the limit of 50% gasoline usage.

Keywords: Biodiesel B20, reactivity controlled compression ignition, Wiebe-2-Zone combustion model, simulation and experiment.

1. Introduction

An overwhelming number of studies has proved the existence of a constant trade-off between the performance, the efficiency and the exhaust emissions' levels of the operating engines in order to meet the core specifications required by the user and therefore, engine designers must balance a large number of engine parameters [1].

Modern numerical codes allow an accurate prediction of engine performance without the need to build a physical model. One-dimensional engine

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and gas dynamics simulation software products, such as Ricardo Wave or AVL Boost are appropriate tools for processes simulation and design of modern engines [2].

Used as high accuracy simulation programs, AVL Boost and AVL FIRE usually offer a comprehensive image of parameters variation at the boundaries between the containing elements of the analyzed configuration. This allows to include 3D geometry effects in a 1D Model and to follow the influence of design adjustments on the assembly of the system performance. Predicting 1D/3D tools refer to the intake and the exhaust manifold design, efficient exhaust gas recirculation (EGR) and in-cylinder mixture preparation, combustion, heat exchange and emissions formation [3].

AVL Boost platform simulations were carried out on two distinct engine types: an opposed-one cylinder piston, two-stroke engine (OP2S) and a conventional 2-cylinder, four-stroke engine (4S) to emphasize the in-cylinder operating processes comparative improvement. It was found that as an advanced virtual engine simulation tool, the AVL Boost platform can deliver a satisfactory forecast of engine efficiency, performance and fuel consumption in terms of emissions optimization. To simulate the two different engines operation, a one-dimensional (1D) thermodynamic model was linked to the AVL Boost platform. As general considerations, the engines with opposing pistons have a greater combustion volume than four-stroke conventional engines. The two-stroke combustion mechanism performs under a leaner mixture compared to a four-stroke engine, leading to an increased combustion rate and an intensified heat release, because of the absence of the cylinder head and of the valve train as well [4].

An initial multi-dimensional study by Kokjohn et al. [5] managed to compare results obtained by testing conventional diesel combustion (CDC) and reactivity control compression ignition (RCCI) strategies. In particular, it was discovered that the RCCI strategy is preferable to apply over a large domain of engine loads, leading to acceptable NOx and soot emissions, to satisfactory pressure rise rate and noise intensity and too high levels of indicated efficiency.

Another numerical study [6] was performed assisted by AVL Boost software to evaluate the influence of biodiesel (B20) on the main combustion parameters, expressed by the ignition delay, the combustion duration, the peak fire pressure and the peak fire temperature, when testing a 4-cylinder, 4-stroke, naturally aspirated direct injection diesel engine. The results were related to the engine operation with pure diesel and biodiesel (B20) at 100% load and different speeds, within 1000 and 2400 rpm. Findings suggested that ignition delay and combustion phase for B20 were shorter compared to pure diesel fueling at low engine speeds.

Furthermore, another numerical study [7] based on the AVL Boost simulation model was conducted on the same tractor propulsion engine fueled with conventional diesel and diesel-hydrogen blends. The results found that CO and NO_x emissions, together with the thermal engine efficiency decrease by adding hydrogen to pure diesel fuel for different injection timings.

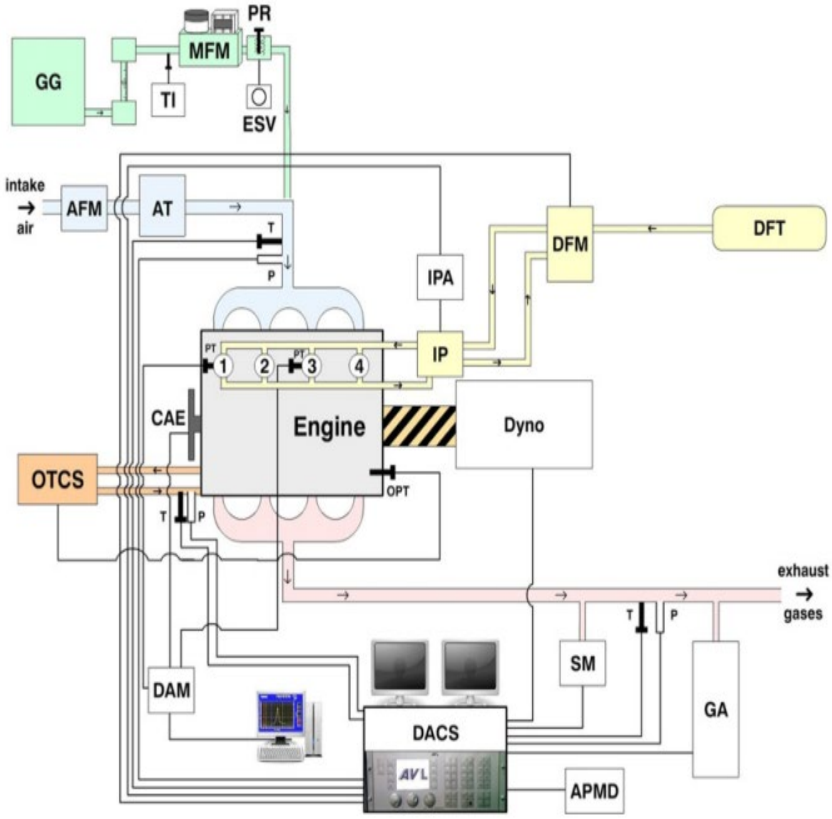
Mohsin et al. [8] highlighted that biodiesel could be subjected to a dual-fueling system under no further engine required modification. Hanson et al. [9] analyzed the situation of RCCI configured engine when fueled with gasoline-ULSD (ultra-low sulfur diesel) and gasoline-biodiesel blends, with the tested biodiesel obtained by mixing 100% vol. soy methyl ester with 20% vol. ULSD. The research revealed a drop in NOx and HC emissions when using gasoline-biodiesel combination compared to gasoline-ULSD.

The first aim of this paper is to establish the applicability level of a Wiebe-2-Zone (V2Z) combustion model, integrated into the AVL-Boost 2019 software while analyzing the operating behavior of 4-strokes, 4-cylinders, and naturally aspirated tractor diesel engine. The calibration of the model using experimental data obtained at maximum load and speed (2400 rpm) when fueling the engine with classic diesel and B20 implied the identification of the best suitable V2Z parameters' values, considering the maximum relative errors related to the combustion, efficiency, performance and emissions' indicators.

A successive goal of the study is to investigate and to suggest the necessary improvements for the engine operation when using different diesel-gasoline and biodiesel-gasoline percentages at maximum load and speed as a base to further extend the range of other analyzed engine regimes.

2. Testbed configuration

The instrumented engine was a 4-strokes, 4-cylinders, naturally aspirated, tractor diesel engine, featuring: bore × stroke (102 mm × 115mm), the compression ratio of 17.5, maximum rated torque of 228 Nm at 1400 rpm and maximum rated power of 50 kW at 2400 rpm. The fuel injection system is a Delphi-type, consisting of a DP210 rotary pump, high-pressure lines and four Delphi injectors with five holes, commended to open at 330 bar injection pressure. Additionally, it is equipped with a Perkins-Lucas injector, including a position hall-effect sensor to record the needle lift. The assembly of the laboratory setup is schematized in figure 1.



AFM - air flow meter

AT - air tank

SM - smoke meter

GA - gas analyzer

PT - pressure transducer

CAE - crank angle encoder

DAM - data acquisition module

DFT - diesel fuel tank

DFM - dynamic fuel meter

IP - injection pump

IPA - injection pump actuator

GG - gas generator

TI - temperature indicator

MFM - mass flow meter

PR - pressure regulator

ESV - emergency stop valve

T - temperature sensor

P - pressure sensor

OPT - oil pan temperature sensor

DACS - data aquisition control system

APMD - ambient parameters measurement device

OTCS - oil temperature control system

Fig. 1- Schematization of the testbed [12]

The test engine is loaded using an AVL eddy-current dynamometer, as shown in figure 2. The AVL digital display meter is controlling the engine speed and the engine output is connected to the AVL 620 INDISET data acquisition system.

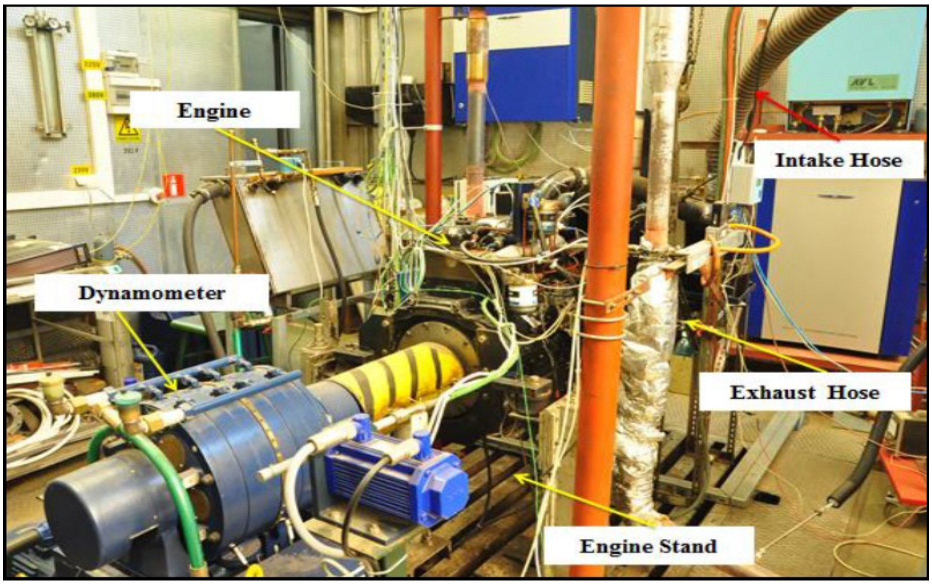


Fig. 2-Operating testbed assembly view.

The in-cylinder pressure measuring system uses two pressure transducers (AVL GN 12D), installed inside the cylinder head, corresponding to cylinders one and three. A wide range of temperature values was obtained by using K-type thermocouples. All the emissions data were recorded and linked to a computer by using a Horiba Mexa 7140 D Multi-Component gas analyzer.

Experimentally data acquisition and calculation refer to the in-cylinder combustion performance, efficiency and emissions numbers, as following: peak fire pressure, peak pressure rise, peak fire temperature, brake specific fuel consumption (BSFC), rating power, NO_x, CO and soot emissions' levels, corresponding to maximum load and speed (2400 rpm) operating conditions, when fueling the engine with classic diesel and biodiesel B20 fuels [10,11].

3. Simulation procedure and results

3.1 Engine operation modelling

In this study, the simulation related to the combustion process involved a particular Wiebe-2-Zone model, created and operating under AVL-Boost software 2019, fully capable to project combustion features, output, performance, and exhaust emissions for the tested engine.

Figures 3 and 4 are shown the schematic of the engine and Wiebe-2-Zone parameters screen. The model consists of several pipes (1-17), manifolds (Plenum, PL1-PL4), injection points of gasoline (I1-I4), air filter CL1, cylinders (C1-C4) and measuring points (MP1-MP3). The atmospheric conditions are often considered by environmental parameters (System Boundary SB1-SB2). Together, all the other AVL-Boost required specifications were incorporated in the software, such as fuel properties, engine load, engine speed and other parameters.

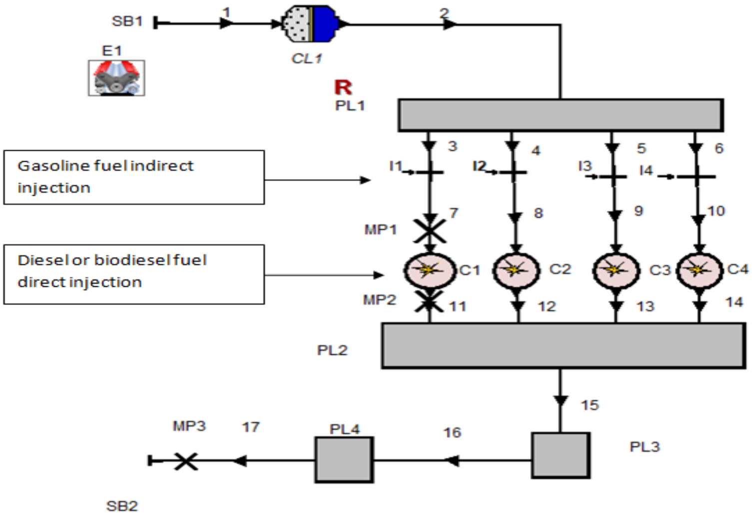


Fig. 3-The schematic model of the engine configuration for RCCI operation

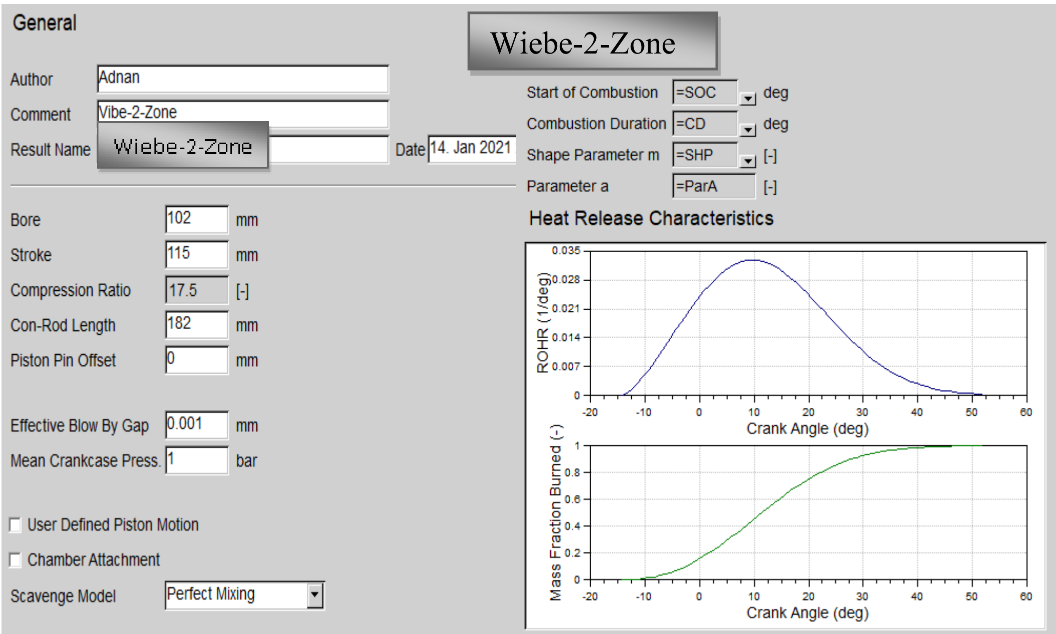


Fig. 4-The model of the Wiebe-2-Zone parameters screen

In this model, mathematical equations describe the flow processes through the pipes or manifolds using a one-dimensional model and allow to calculate of the in-cylinder thermodynamic status together with the mass and energy exchange, based on the first principle of thermodynamics [1].

The induced air stream enrichment in the cylinder is simulated by the continuous flow of gasoline through the I1 to I4 injectors (figure 3). The fuel mixing ratio is determined by the weight percentages of diesel or biodiesel fuels combined with the gasoline inside the cylinder [13].

3.2 Model calibration and validation

A series of parameters were adjusted in order to get the numerical results obtained with the Wiebe-2-Zone combustion model closer to the experimental data and the main aim of the calibration was to obtain a nearly similar or less than 5% values for the pressure diagram, effective power, BSFC, maximum temperature and exhaust concentrations for the AVL code compared to the experimental results. Thus, by repeated iterations, a good agreement could be reached for each of the used diesel fuels – classic and biodiesel (B20) [14].

Calibrating the model with diesel fuel and consequently with biodiesel (as high reactive fuels - HRF) through direct injection while no gasoline (as low reactive fuel - LRF) injected in the intake port fuel (PFI) consisted in assigning the following values to the parameters listed in Table 1.

Table 1

Calibration parameters for pure diesel and biodiesel (B20) fuels

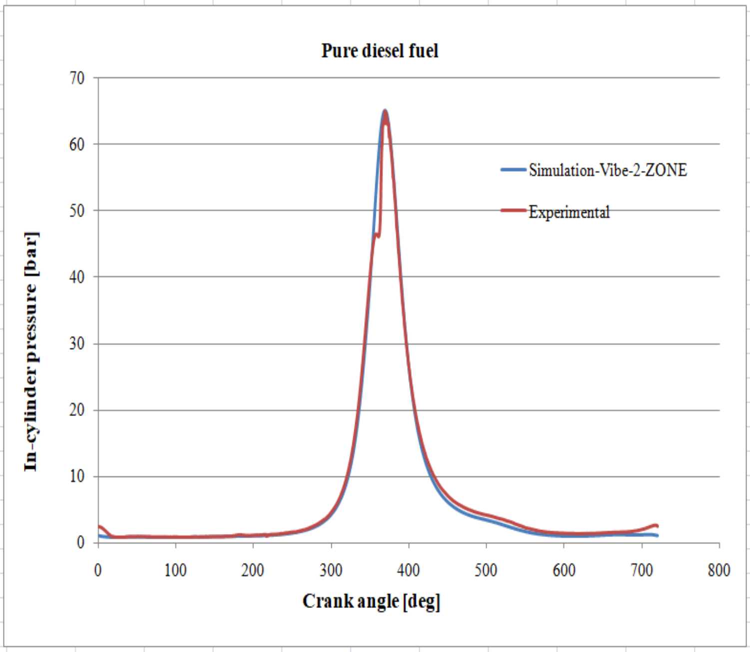
Calibration parameters	Calibration parameters values	
Fuel type	Pure diesel	Biodiesel (B20)
Start of combustion (SOC)	-14 [deg]	-14.3 [deg]
Wiebe parameter a	6.9 [-]	6.9 [-]
Combustion duration (CD)	66 [deg]	66.5 [deg]
SHP	1.5 [-]	1.42 [-]
Rail pressure	285 [bar]	285 [bar]
Combustion parameter	1 [-]	1 [-]
Turbulence parameter	2 [-]	2 [-]
Dissipation parameter	0.0001 [-]	0.0001[-]
Kinetic Multiplier NOx	2.4 [-]	1.8 [-]
Postprocessing Multiplier NOx	0.45 [-]	0.28 [-]
Kinetic Multiplier CO	0.0038 [-]	0.005 [-]
Soot Production Constant SPC	2200 [-]	2200 [-]
Soot Consumption Constant SCC	330 [-]	268 [-]

Simulation data were calibrated with experimental data and the results were satisfactory similar to those regarding the peak fire pressure, peak pressure rise, BSFC, effective power, and relative air-fuel ratio. Also, NO_x, CO and soot emissions provided a satisfactory approach to those acquired by the tests. This comparison could be followed in Table 2 and figures 5, a and b.

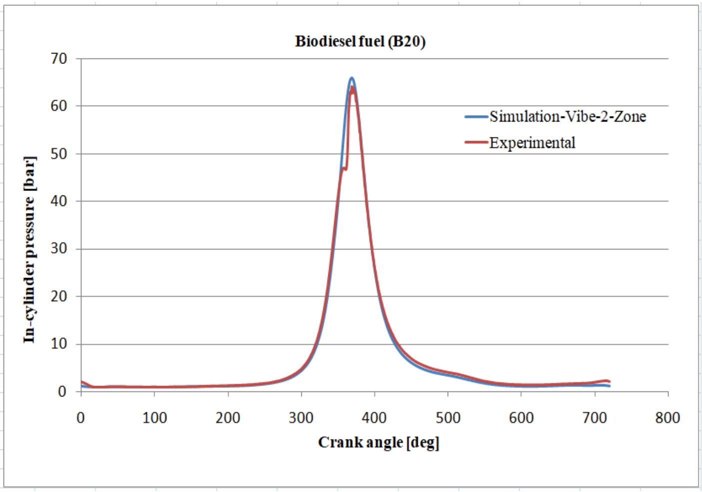
Table 2

Calibration errors between the simulation and experimental data

	P-max	PPR	BSFC	power	NOx	CO	Soot
	bar	bar/deg	g/(kW.h)	kW	ppm	ppm	g/(kW.h)
EXP.-D100	64.63	7.27	255	47.37	640	455.8	1.54
AVL-D100	64.94	1.84	257	46.93	646.4	457.4	1.52
Error %-D100	0.5	-295	0.8	-0.9	1	0.3	-1.5
EXP.-B20	64.05	7.12	265	46.33	727	465	1.44
AVL-B20	65.94	1.94	270	44.98	721.9	465	1.46
Error %-B20	2.86	-267	1.85	-3	0.7	0	1.3



(a)



(b)

Fig. 5, a and b-Comparison between experimental and simulation pressure traces for pure diesel and biodiesel (B20) fuels at full load and 2400 rpm speed.

3.3 Model simulation

Following the calibration of the model with the two fuels, the same list of engine performance, efficiency and emissions parameters came into the described numerical analysis when simulating the engine fueling with different gasoline rates (5, 10, 20, 50 and 80%) port-fuel injected (PFI), under the same operating conditions, at full load and 2400 rpm. Table 3 presents for each of the input gasoline rate the values of the low heating value (LHV) and air-fuel (A/F) stoichiometric ratio obtained for each corresponding fuel blend, with pure diesel and respectively with biodiesel as (HRF).

Table 3

Different diesel-gasoline and biodiesel-gasoline fuels properties

Gasoline percentages %	Pure diesel fuel		Biodiesel (B20) fuel	
	LHV (KJ/kg)	A/F stoich.	LHV (KJ/kg)	A/F stoich.
Calibration at 0	4.28E04	15.16	4.15E04	13.32
5	4.28E04	15.14	4.16E04	13.39
10	4.28E04	15.11	4.17E04	13.45
20	4.29E04	15.05	4.19E04	13.58
50	4.31E04	14.88	4.25E04	13.96
80	4.33E04	14.71	4.43E04	14.34

4. Results and comments

In this paper engine performance, efficiency and emissions values were theoretically and experimentally investigated involving normally aspirated diesel tractor engine, as a response to the fueling strategy with different percentages of gasoline mixed with diesel and biodiesel (B20), when operating at full load and a maximum speed of 2400 rpm. Simulation performed with the AVL-Boost-Wiebe-2-Zone combustion model allowed the evaluation of the peak fire pressure, peak pressure rise, peak fire temperature, BSFC, effective power, and exhaust engine emission for NO_x, CO and soot. Figures 6-13 highlight the results concerning all these parameters when using different gasoline percentage in addition to pure diesel or biodiesel (B20). Figure 6 reveals that experimental data related to peak fire pressures in the case of biodiesel (B20) was slightly decreasing because biodiesel has a higher viscosity and lower energy content compared to pure diesel fuel, while simulation results for biodiesel fuel tests showed an opposite trend compared to the reference ones. However, there is no significant effect on peak fire pressure by increasing the gasoline percentage in diesel-gasoline or biodiesel-gasoline fuels because of the weaker auto-ignition potential for gasoline compared to diesel-based-on fuels [15–17] led to loses of combustion energy. Nevertheless, the RCCI strategy helped the charge to gain enough energy to keep the peak fire pressure with approximately the same level values.

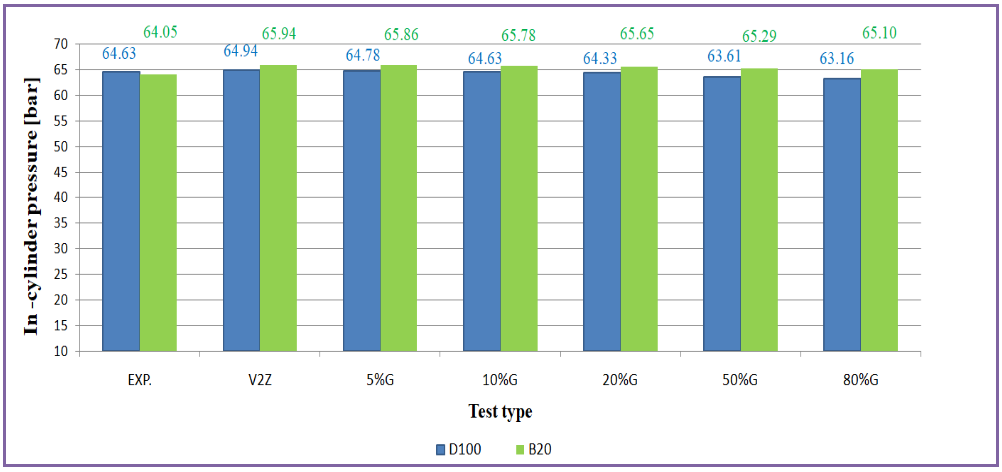


Fig. 6-Peak fire pressure results from experiment and simulation for different tested fuels

Figure 7 shows no significant effect on the peak pressure rise variation when using different percentages of diesel-gasoline and biodiesel-gasoline blends. This could be explained by compensation between the energy losses when replacing diesel fuel with biodiesel and the gain reached when using the RCCI strategy, in terms of combustion and efficiency improvement. Simulation results for the extreme peak pressure rise were about 1.98 bar/deg in the case of biodiesel-gasoline (80%) and 1.82 bar/deg in both cases of 80% and 50% diesel-gasoline blends. Experimental results were considerably higher (up to 4 times) than all the other simulation results.

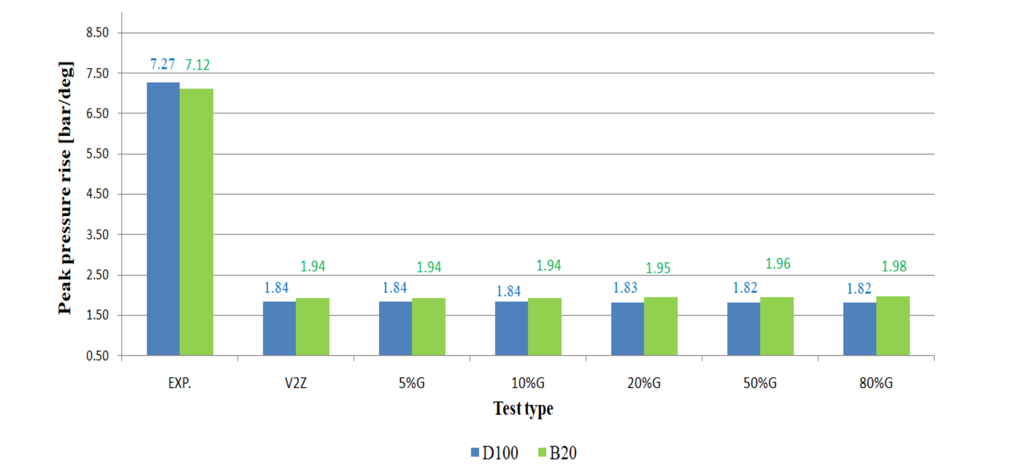


Fig. 7-Peak pressure rise values from experimental and simulation for different tested fuels

Fig. 8 reveals the dependence of peak fire temperature on the kind of fuel. Despite the difference regarding the oxygen content between biodiesel and diesel fuel, simulation results showed no significant effect by changing the gasoline rate in diesel-gasoline or biodiesel-gasoline blends. Thus, the highest peak of temperature reached with biodiesel-gasoline blend at 80% gasoline comparable to the smaller value in the case of the diesel-gasoline blend at 50% gasoline, both numbers slightly under 2000 K.

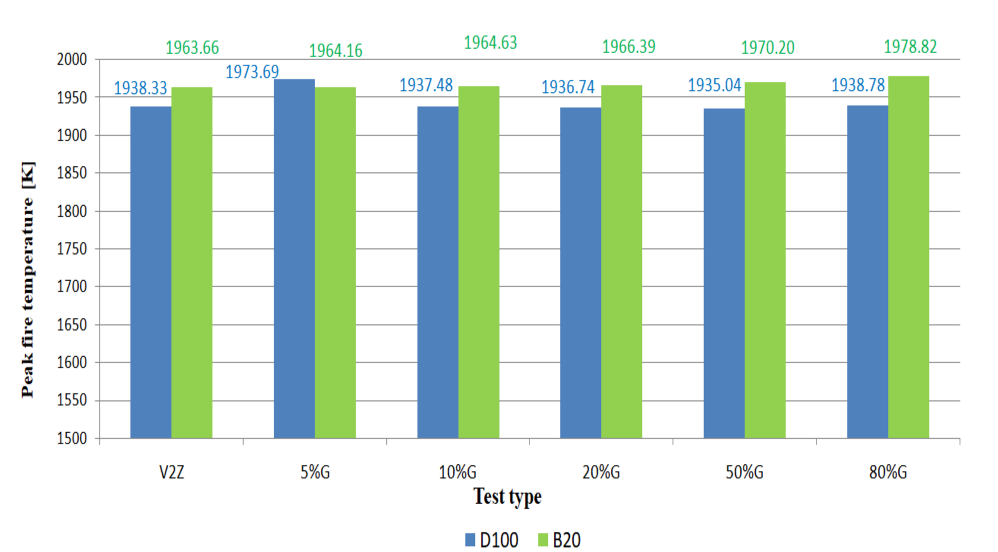


Fig. 8-Peak fire temperature results from experiment and simulation for different tested fuels

Fig. 9 emphasizes the dependence of BSFC on the rate of mixing gasoline in diesel and biodiesel fuels. The experimental value for BSFC with biodiesel (B20) was higher than the one characterizing the operation with pure diesel because of the higher density, viscosity and lower heating value of biofuel comparing to diesel fuel, leading to increased fuel consumption so that the engine could rate the same power as in the classic configuration [18].

Simulation BSFC values reached for all blends including 20% gasoline percentages were higher than those experimentally evaluated, meaning virtually that no significant effect occurred by blending diesel or biodiesel with small amounts of gasoline. BSFC is observed to decrease when increasing gasoline percentages for all blends due to the increase of the potential to form a more homogenous mixture for combustion, to ensure more oxygen content and better atomization with the RCCI strategy [19]. Meanwhile, BSFC values in the case of biodiesel-gasoline blends were higher than those corresponding to diesel-gasoline blends because of the higher viscosity and density values of biodiesel.

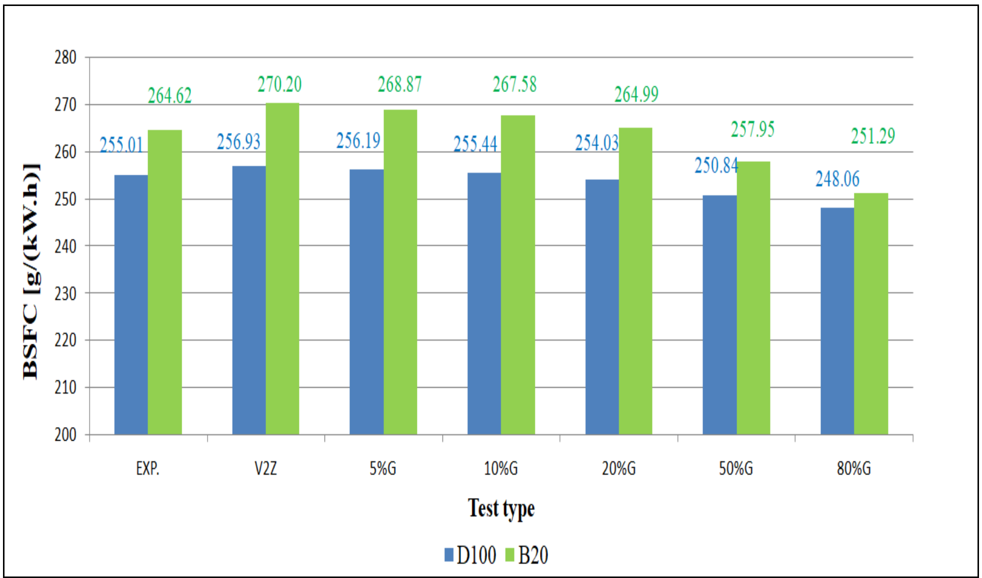


Fig. 9-BSFC results from experiment and simulation for different tested fuels

Fig. 10 shows higher effective power with pure diesel or diesel-gasoline blends than biodiesel or biodiesel-gasoline blends caused by the higher energy content of pure diesel fuel compared to biodiesel.

Findings show an improvement of the engine efficiency in terms of effective power by increasing percentages of gasoline fuel in biodiesel blends because of the higher gasoline volatility and the homogeneous status of the air-fuel mixture with the RCCI strategy [20]. Moreover, the addition of gasoline into diesel or biodiesel fuel can reduce fuel viscosity, provide more oxygen content and improve atomization, enabling the system to gain an increased rate of conversion from chemical energy to useful mechanical engine work [19].

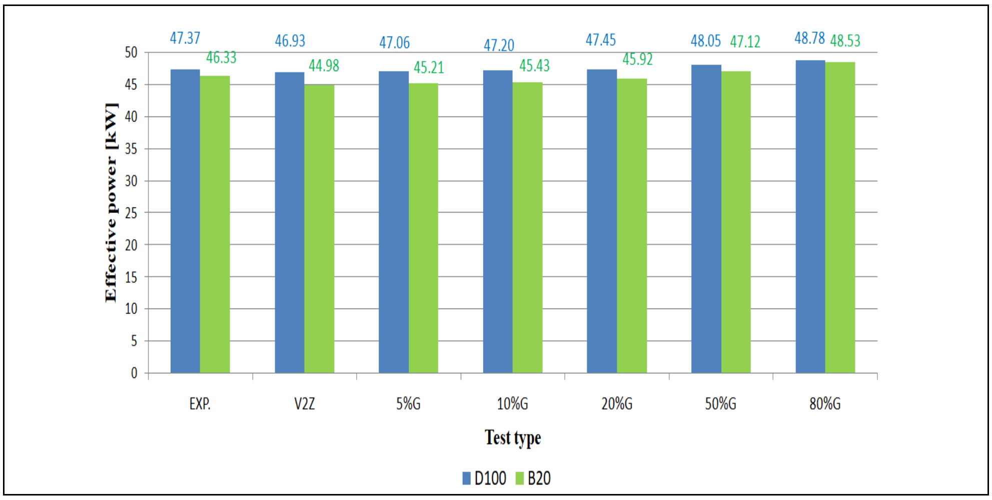


Fig. 10-Effective power results from experiment and simulation for different tested fuels

Fig. 11 highlights enhanced NO_x emissions with biodiesel fuel under experimental conditions compared to pure diesel fuel, explained again by the higher oxygen amount of biodiesel, similarly to other studies [21]. No significant change is noticed, except for a slight decrease of NO_x emissions by increasing the gasoline rate by less than 50% into blends fuel due to the lack of any important change in combustion pressure and temperature values. Meanwhile, increasing the gasoline rate by more than 50% into diesel-gasoline blends leads to NO_x emissions increase compare to biodiesel-gasoline caused by the fact that gasoline is forming more homogeneous mixtures according to RCCI strategy [22].

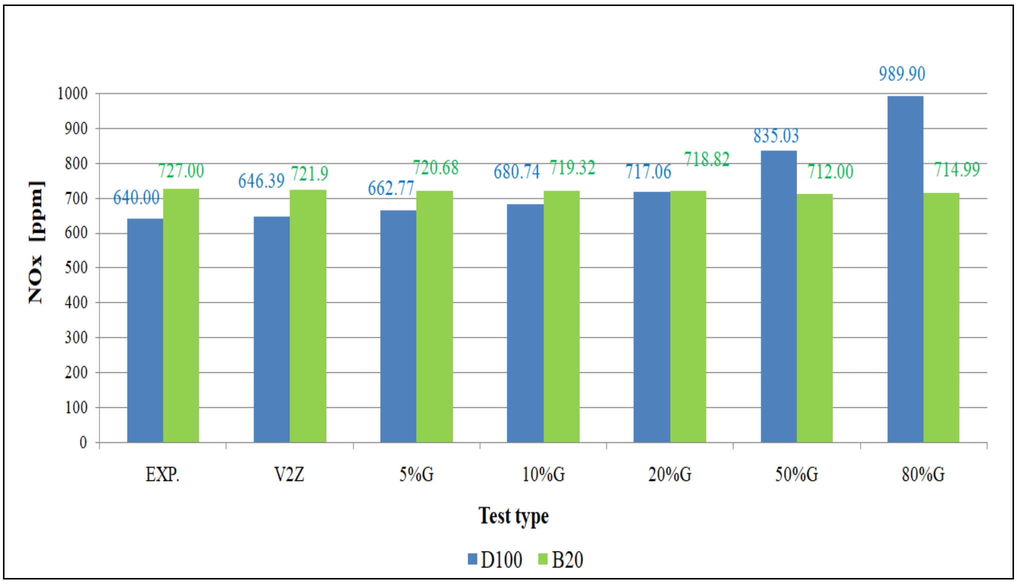


Fig. 11-NO_x emissions obtained from experiment and simulation for different tested fuels

Although biodiesel fuel has higher oxygen content than diesel fuel, it leads to higher carbon monoxide (CO) emissions, according to the tests. On another hand, the simulation showed that biodiesel-gasoline blends combustion caused higher CO emissions compared to those produced by diesel-gasoline blends below 20% gasoline used to rate, while increasing the gasoline above 20% the results were reversed, those aspects being in agreement with [9], respectively with [21]. At the same time, enhanced (CO) emissions were obtained by increasing gasoline percentages in all cases compared to data experimentally measured as shown in figure 12.

Therefore, this study is concluding that CO emissions increased by increasing the gasoline rate in both diesel-gasoline and biodiesel-gasoline analyzed blends [23].

Fig. 12-CO emissions obtained from experiment and simulation for different tested fuels

Fig. 13 shows that the experimentally measured soot emissions were augmented for pure diesel than those obtained for biodiesel, explained by the higher cetane number and higher oxygen content (10-12%) of biodiesel compared to the classic fuel. By increasing the gasoline amount in diesel or biodiesel blends a significant reduction of soot emissions occurred because of the higher volatility and the lower distillation point of gasoline [18].

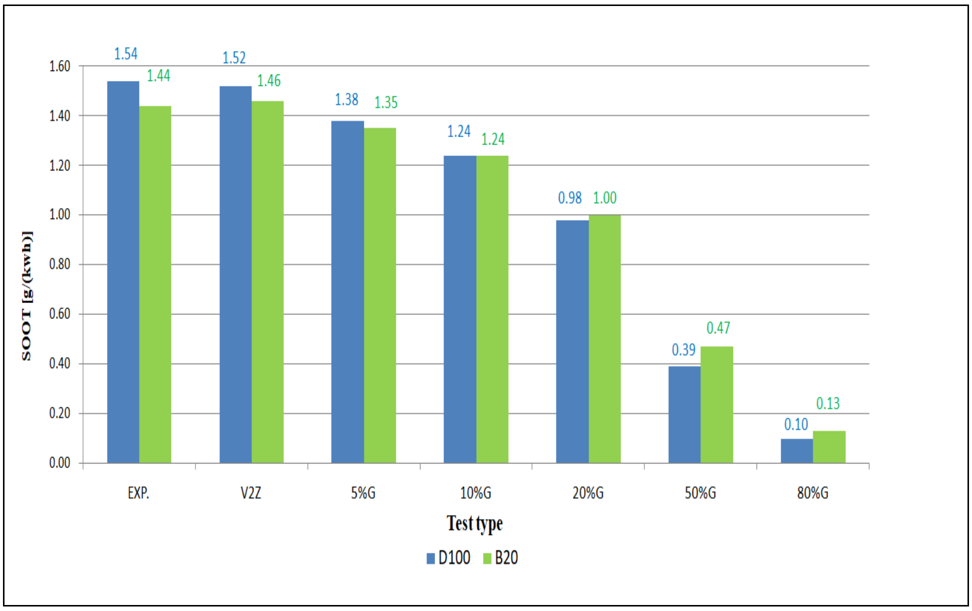


Fig.13-Soot emissions obtained from experiment and simulation for different tested fuels.

It is also described that from 0-10% gasoline percentage, diesel-gasoline blends produced higher soot emissions than biodiesel-gasoline blends. At higher gasoline rates the situation is reversed due to the reduced amount of biodiesel which reduces the consisting in-fuel oxygen concentration.

5. Conclusions

Performance, efficiency and emissions values were theoretically and experimentally investigated for a normally aspirated diesel tractor engine, as a response to the fueling strategy with different percentages of gasoline mixed with diesel and biodiesel (B20), when operating the engine at full load and a maximum speed of 2400 rpm. Simulation performed with the AVL-Boost-Wiebe-2-Zone combustion model allowed the evaluation of the peak fire pressure, peak pressure rise, peak fire temperature, BSFC, effective power and exhaust emissions. The performed analysis suggested a potential to improve diesel engine operation, noticing that:

1. By increasing the gasoline ratio when mixing with diesel fuel in RCCI strategy, compared to classic diesel configuration:
    - There is no significant effect on the level of peak fire pressure, peak pressure rise and peak fire temperature.
    - BSFC decreased and effective power increased.

- There is no significant change in NO_x and CO emissions below 50%. Above this threshold, NO_x and CO emissions increased while soot emissions decreased by increasing the gasoline rate.

2. By increasing the gasoline ratio when mixing with biodiesel in RCCI strategy, compared to B20 fuel.
    - There is either no significant effect on the level of peak fire pressure, peak pressure rise and peak fire temperature.
    - BSFC decreased and engine effective power increased.
    - NO_x emissions with biodiesel-gasoline blends were higher compared to diesel-gasoline blends for a gasoline ratio of less than 50% and lower for a gasoline ratio above 50%.
    - CO emissions increased and soot emissions reduced. On another hand, with biodiesel-gasoline blends, it was found that CO and soot emissions were higher and lower respectively, compared to diesel-gasoline blends when gasoline rate less than 50% while they proved an opposite behavior when the gasoline rate overpasses 50%.

RCCI strategy has proved clear benefits when using an increasing rate of gasoline in diesel-gasoline blends compared to biodiesel-gasoline blends speaking of engine performance and efficiency, while the emissions recorded values switch the trend between the categories of mixtures, based on the reference limit of 50%.

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