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AVALIATION OF THE ADDITION OF HYDROGEN IN THE DIESEL ENGINE ADMISSION AIR CONSUMING FUEL B7 - NUMERICAL AND EXPERIMENTAL ANALYSIS

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Abstract. *This work analyzes the performance effects of a diesel generator set operating with a mixture of B7 (7% biodiesel in mineral diesel) and hydrogen gas (99.98% purity) injected into the engine intake air. Hydrogen was injected continuously at various mass concentrations (6, 8 and 10%). The results of the tests showed a reduction in the specific fuel consumption as a function of the increase in the hydrogen mass fraction, in the same way the CO2 and O emissions decreased proportionally as the hydrogen concentration was increased. On the other hand, the levels of nitrogen oxides (NOx) increased due to the increase of the average temperature inside the cylinder. In addition, the numerical results using the AVL-BOOST program showed that there was an increase in the peaks of the maximum pressure and the rate of heat release inside the cylinder as a function of the increase of hydrogen addition. It was also identified that there was reduction of the volumetric efficiency as the percentage of hydrogen concentration increased.*

Keywords: *Hydrogen, diesel b7, AVL-BOOST, generator set*

1. INTRODUCTION

The growing increase in consumption of fossil fuels, a special highlight for conventional diesel (DO), motivates different researchers to find more suitable alternatives for their possible replacement or reduction in consumption. This fossil fuel is widely used in compression ignition engines mainly in transportation, power generation and agricultural machinery. In the course of time, different fuels have been tested, such as ethanol, biodiesel, vegetable oils and hydrogen, among others due to the gradual increase in their price and the incentive of various government agencies in different countries. Currently, one of the most used to reduce the consumption of diesel fuel is biodiesel, as is the case in Brazil, where the National Program for the Production and Use of Biodiesel (PNPB) introduced the use of this fuel in the national energy matrix (ANP, 2014).

Biodiesel is composed of alkyl esters of long chain fatty acids, usually produced from vegetable oils or animal fats by the transesterification process (Leung, 2010). Its reported advantages include generally lower emissions of carbon monoxide (CO), hydrocarbons (HC) and particulate matter (PM) compared to conventional diesel oil (Datta and Mandal, 2016). On the other hand, its viscosity improves the lubrication capacity of the engine and can extend the engine life (Hoekman, 2012). The limitations of biodiesel are the low calorific value and higher viscosity, which lead to less favorable conditions for complete combustion, reducing the engine efficiency reflecting the increased fuel consumption (Datta and Mandal, 2016). To improve this condition, it is necessary to introduce a new blended fuel that improves the combustion process in the engine.

Hydrogen is a non-toxic, odorless, renewable and recyclable alternative fuel, making it a promising candidate as a source of clean energy. The use of this fuel would significantly improve the ambient air quality, since it does not contain carbon in its composition, but one of the problems in which hydrogen cannot be used as a single fuel directly in diesel engines is its high autoignition temperature of 585 ° C compared to that of 257 ° C diesel (Deb, M. et al., 2015).

Analyzing several studies were found three methods to add hydrogen to the diesel engine, two of them directly injecting the H2 in the air intake manifold, either continuously or controlled and the third method with an injection directly controlled inside the combustion chamber the engine. Continuous injection of H2 into the inlet manifold is the simplest method but requires the use of fire-cut valves because of the high risk of explosion, since the controlled injection method allows to define the exact amount and moment of H2 injection in the inlet manifold. In addition, both methods of hydrogen injection may lead to a decrease in the volumetric efficiency of the engine since the hydrogen would displace part of the intake air that is in the manifold (Batmaz, 2015; Köse and Ciniviz, 2013). The third method consists in the use of a gas injector in the combustion chamber of the engine, with which it is possible to overcome the problem of decreasing the volumetric efficiency. This method presents advantages with respect to the injection of hydrogen, but presents great difficulties, such as the design of the injector and necessary modification of the head for its installation in the engine (Köse and Ciniviz, 2013).

Numerous researches have been conducted to examine the effects of hydrogen addition on the performance and emissions characteristics of diesel engines. Deb. (2015) have shown that the addition of hydrogen to a diesel engine can reduce CO2, CO and HC emissions, but increase NOx emissions due to the increase in the temperature of the gases, which at the same time produces an increase in thermal efficiency. Moreover, Morsy El-Leathy (2015) found that the addition form of hydrogen continues decreases the engine's thermal efficiency at low load but increases above 50% of nominal power loads even with a reduction in volumetric efficiency of motor, this phenomenon was also evidenced in the work of Batmaz (2013), Sandalcı and Karagöz (2014) showed that there is an improvement in the combustion process due to the increase of flame propagation velocity, where the peak pressure and heat release rate also increase in the engine cylinder with the increased hydrogen content injected, showing that there is an advance at the start of combustion.

With respect to Zhou and Cheung (2015) particulate emissions, found that particle mass and particle numbers are reduced with increased hydrogen addition when the engine operates at low and medium loads. At high loads (above 50% of rated power), lack of oxygen from hydrogen injection tends to affect the oxidation of soot particles, resulting in larger primary particles. Most of the work shows that CO_2, CO and particulate matter emissions are reduced, as opposed to NOx emissions that increase as a result of increased hydrogen addition (Deb., 2013; Köse, 2013; Karagöz, 2016). This increase in NOx can be controlled by recirculating small amounts of exhaust gas (EGR), this process causes the ignition of the fuel mixture to slow down, also reducing the maximum cylinder pressure and temperature resulting in a decrease in NOx emissions (Yadav, 2015).

The literature review above shows that the addition of hydrogen in diesel engines using diesel as the main fuel can influence their performance and emissions, either positively or negatively depending on the form and quantity of the hydrogen injection. However, there is little research of its influence on the consequences of using hydrogen in diesel generator sets for electric power production, especially when biodiesel is used as the main fuel. In this study, the influence of the addition of hydrogen on the performance and emissions of a diesel generator set operating with a biodiesel blend (B7) currently marketed at the fuel distribution stations in Brazil will be analyzed. These results may provide a more comprehensive view on the influence of hydrogen addition and its possible application in diesel thermoelectric plants.

2. EXPERIMENTAL PROCEDURE

The generator set used for this research was the BRANCO BD-6500 CF3E single-cylinder, four-stroke, with aspiration natural, air-cooled and direct fuel injection engine. The general specifications of the generator set are shown in Table 1. The generator is connected to a resistor bank that is used to vary the electric load, the electric power generated was measured using the SAGA 4500 electrical quantity analyzer, volumetric flow rate of hydrogen was obtained using the OMEGA FLDH3303G rotor and for the volumetric flow of air consumed by the engine the AKROM KR835 turbine-type anemometer was installed after an air-box designed to avoid air fluctuations due to the opening and closing of the valves.

Table 1. Technical specifications of the diesel generator set.

Parameters	
Diameter [mm] × Stroke [mm]	86 × 70
Cylinder volume [cm3]	406
Compression ratio [-]	19:1
Rotation [rpm]	3600
Electrical Frequency [Hz]	60
Maximum electrical power [kW]	4,5

A precision digital scale was used to measure the mass flow of fuel (B7) consumed by the engine. The exhaust emissions (CO2, CO and NOx) and their temperature at the point of collection were measured with the MADUR CMS-07 gas analyzer. At the same time, a K type thermocouple was used to measure the temperature of the gases at the start of the exhaust manifold outlet as close as possible to the cylinder. The accuracy of each equipment used is shown in Table 2.

Table 2. Technical specifications of the diesel generator set

Measured Parameters	Measuring device	Precision
Electric power	SAGA 4500 – Electric power meter	±1 W
Fuel Mass	DIGIMED DG-15W – Digital scale	±0.2 g
Flow rate of H_2	OMEGA FLDH3303G – Rotator	±0.2 l/min
CO	MADUR CMS-7 – Gas analyzer	±5 ppm
CO_2	MADUR CMS-7 – Gas analyzer	±0.1 %
NO_x	MADUR CMS-7 – Gas analyzer	±5 ppm
Gas Temp.	K- thermocouple type K	±2 °C

In this work the hydrogen was introduced into the air intake manifold continuously, without performing any modification or installation of complex equipment in the engine. For this, a high pressure hydrogen cylinder of 165 bar was used, where this pressure was reduced to 1,5 bar, using a double stage pressure regulator. At the same time a fire shut-off valve was installed before the air intake manifold to prevent a possible explosion. The schematic view of the test stand is shown in Figure 1.

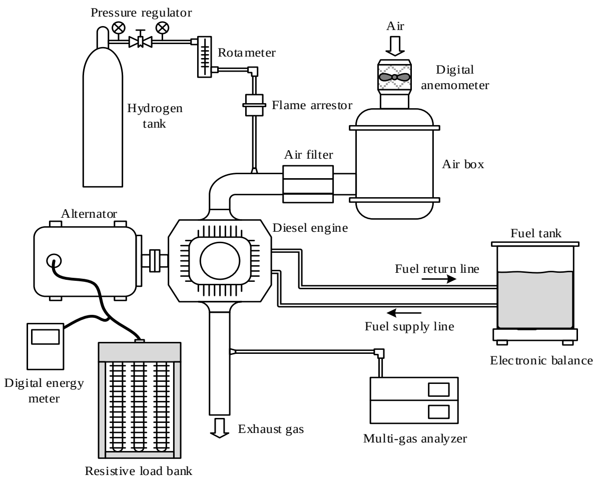

Figure 1. Schematic of the experimental apparatus.

2.1 Experimental procedure

Initially, tests were carried out in the generator set running panes with B7, which served as baseline for the comparative analysis. Three different hydrogen mass fractions of 6, 8 and 10% of the total fuel were applied and compared. For all tests the generator set operated until reaching the stability in the exhaust gas temperature measurement (Tgas), theoretically reaching the steady state, taking approximately one hour for this process. The load applied to the generator set was produced by a bank of electrical resistors, maintaining a constant power of 2.43 kW (approximately 60% of the maximum rated power) and rotation at 3600 rpm. To guarantee the reliability of the results, three tests were repeated for each hydrogen mass fraction tested, where the final result represents the mean of these tests. The uncertainty was calculated applying the same method used by Deb, Sastry (2013), and the results are presented in Table 3.

Table 3. Mean of the uncertainties of the measured and calculated parameters

Parameters	Uncertainties
Electric power	±1.0 %
Mass of fuel	±1.3 %
Flow rate of H_2	±0.9 %
Air flow	±0.7 %
CO	±1,14 %
CO_2	±1,51 %
NOx	±1,08 %
Gas temperature	±0.4 %
Mass fuel flow	±1.39 %
Mass flow of H_2	±1.64 %
Specific fuel consumption	±1.92 %

Hydrogen was introduced by induction into the air intake manifold at volumetric flow rates controlled by the rotameter, and then with the help of the pressure and temperature of the injected hydrogen, determine the mass fraction of hydrogen in the fuel mixture that was 6, 8 and 10 %, as shown in Equation (1).

$$y_{H_2} = \frac{\dot{m}_{H_2}}{\dot{m}_{B7} + \dot{m}_{H_2}} \tag{1}$$

This mass fraction can be represented in terms of the available energy by Equation (2), where the lower calorific value of B7 determined in this work was 39.8 MJ / kg, while that of hydrogen was 119.93 MJ / kg extracted from the work by Deb, Sastry (2015). With these data the mass fractions of 6, 8 and 10% can be represented by the values of 15.4; 20.3 and 24.8% of the total energy available in the fuel mixture.

$$E_{H_2} = \frac{\dot{m}_{H_2} \cdot PCI_{H_2}}{\dot{m}_{B7} \cdot PCI_{B7} + \dot{m}_{H_2} \cdot PCI_{H_2}} \tag{2}$$

The volumetric efficiency was calculated as a function of the admitted air mass flow rate, engine speed and displaced volume for each specific mass of the air as a function of the temperature and pressure measured in each test, as shown in Equation (3).

$$\eta_V = \frac{2 \cdot \dot{m}_{H_2}}{\rho_{ar} \cdot V_d \cdot N} \tag{3}$$

The specific fuel consumption was determined as a function of the mass of fuel consumed (both B7 and hydrogen) to generate a given electric power as shown in Equation (4).

$$C_{esp} = \frac{\dot{m}_{B7} + \dot{m}_{H_2}}{P_{el}} \tag{4}$$

2.2 Simulation methodology

The simulation software used in this study was the AVL-Boost that uses a one-dimensional mathematical model based on the first law of thermodynamics simulating the entire motor cycle including combustion (AVL,2014).

$$\frac{dx}{d\varphi} = \frac{a}{\Delta\varphi_c} \cdot (m+1) \cdot y^m \cdot e^{-a \cdot y \cdot (m+1)} \tag{5}$$

$$y = \frac{\varphi - \varphi_0}{\Delta\varphi_c} \tag{6}$$

$$\frac{dQ}{d\varphi} = Q_{comb} \cdot \frac{dx}{d\varphi} \tag{7}$$

Within the program there are several models for the simulation of combustion in the cylinder, one of the most used combustion models is the Vibe described in equations (5) and (6). It expresses the fraction of fuel mass burned by angle degree of the crankshaft as an exponential function of some coefficients and parameters. It is possible to calculate the rate of combustion heat release (ROHR) as a function of four parameters given to the model as shown in Equation (7); start of combustion, duration of combustion, shape parameter and parameter. The shape parameter determines the shape of the curve representing the mass of fuel burned, ie for low parameter values, the heat is released very fast at the beginning and then slower, or vice versa for high values. The parameter is related to the combustion efficiency, if the value is less than 6,9 the combustion will be incomplete, for higher values the combustion would happen more quickly . Figure 2 presents the model created to simulate the motor enriched with different percentages of hydrogen. The model consists of a cylinder (C1), air-box (PL1), silencer (PL2), air filter (CL1), a hydrogen injector (I1) and the tubes through which fluid is transferred between designated system components with the numeration from 1 to 6 with their respective measuring points (MP).

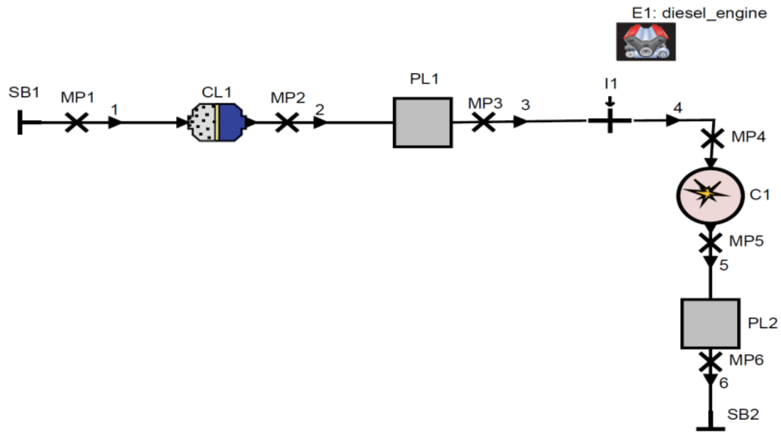

Figure 2. Schematic of the symbolic model of the motor.

The hydrogen injector (I1) was placed in the line of air flow, in order to simulate the enrichment of the intake air with small amounts of hydrogen. For the validation of the numerical model the experimental results and the Design Explorer program (DE) were used. The DE is a computational tool used for the analysis and optimization of simulation models, it can be implemented in conjunction with the AVL-Boost program because it is developed by the same manufacturer (AVL, 2014). For this reason, the DE program was used to identify the unknown parameters of the Vibe combustion model as a function of experimentally measured parameters (specific fuel consumption, generated electric power and gas temperature) using the genetic algorithm method in DE.

$$min\lfloor \Delta C_{esp} \rfloor = min\lfloor Abs(C_{esp,exp} - C_{esp,sim}) \rfloor \tag{8}$$

$$min\lfloor \Delta P_{ele} \rfloor = min\lfloor Abs(P_{ele,exp} - P_{ele,sim}) \rfloor \tag{9}$$

$$min\lfloor \Delta T_{gas} \rfloor = min\lfloor Abs(T_{gas,exp} - T_{gas,sim}) \rfloor \tag{10}$$

There are several optimization techniques whose main task is to find a set of ideal parameters that allow to minimize or maximize certain variables of a function. In this work, the objective of the optimization was to find the condition of the smallest absolute error between the experimental and numerical variables as shown in equations (8), (9) and (10), for this the algorithm method was applied genetic variability by varying the unknown parameters of the Vibe combustion model until it reaches the lowest absolute error of the parameters measured experimentally with respect to specific fuel consumption, generated electric power and gas temperature. The detailed description of the genetic algorithm method and its application in internal combustion engines can be found in the work of Deb, Banerjee (2013).

3. RESULTS

3.1 Volumetric Efficiency

The volumetric efficiency can be influenced by several factors such as the rate of compression of the engine, rotation and design of the air intake system, among others. Figure 3 shows the variation of the volumetric efficiency of the engine for each of the percentages of hydrogen injected. For each increase of the injected hydrogen mass fraction there is a decrease in the volumetric efficiency, this decrease is caused during the continuous injection of hydrogen in the intake manifold, since the hydrogen displaces the volume of the air admitted by the engine, thus reducing the amount of oxygen inside the cylinder (Jhang, 2016). The calculated volumetric efficiencies were 78.2% for pure B7 and 77.4; 75.7 and 74.1% for each hydrogen mass addition of 6, 8 and 10% respectively. The results presented similar trends with those obtained in the works of Batmaz (2013), Köse and Ciniviz (2013), and Bose, Banerjee (2013).

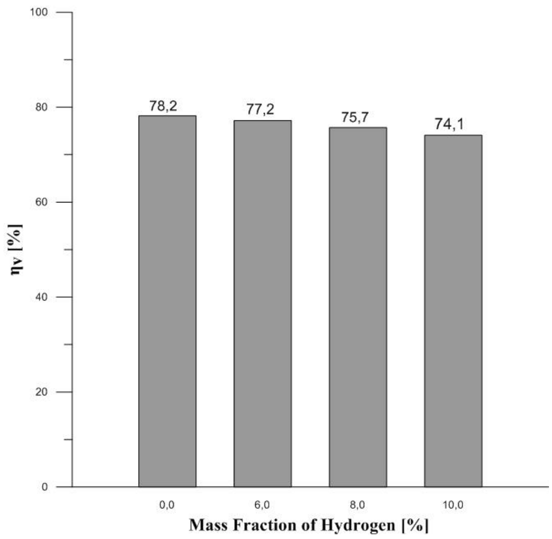

Figure 3. Effects of H_2 enrichment on the volumetric efficiency.

3.2 Specific fuel consumption

The variation of the specific fuel consumption is represented in Figure 4, it is possible to verify that the value of was reduced as a function of the addition of hydrogen, three injected percentages of 6, 8 and 10% of the total fuel. The obtained values were 451.1 g/kW-h when used only B7 and 443.5; 426.8 and 415.8 g / kWh respectively for the three hydrogen percentages. In this study, it was positively affected by the increase in the percentage of hydrogen, showing a reduction of 1.7%; 5.4% and 7.8% for each of the three percentages of hydrogen compared to the result obtained with pure B7. This demonstrates that adding hydrogen to B7 results in faster and more complete combustion which causes a general improvement in combustion quality. Similar results were found in the studies of Deb (2015), Jhang, Chen (2016), Yadav, Sharma (2015).

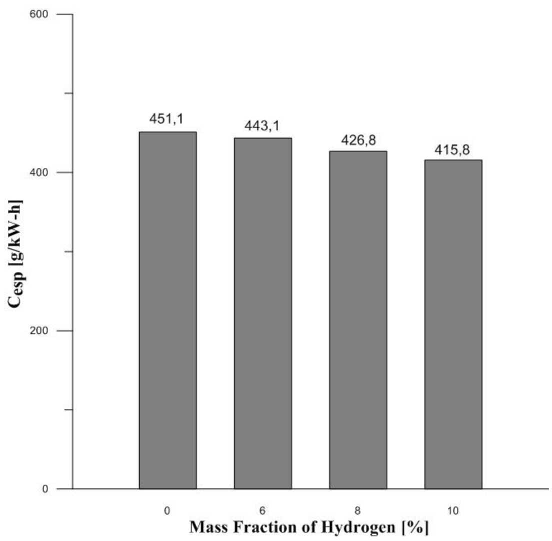

Figure 4. Effects of H_2 enrichment on specific fuel consumption.

3.3 Exhaust Gas Temperature

The temperature of the exhaust gases in relation to the increase of the hydrogen flow is shown in Figure 5. As expected, the increase of the addition of hydrogen caused an increase of the temperature of the flame, reflecting in the increase of the temperature of the exhaust gases. The temperatures progressively increased by 3.0; 3.4 and 3.7% as a function of the addition of hydrogen. These results are compatible with those identified in the works of Hamdan, Selim [16], Köse and Ciniviz [18], Morsy, El-Leathy [20].

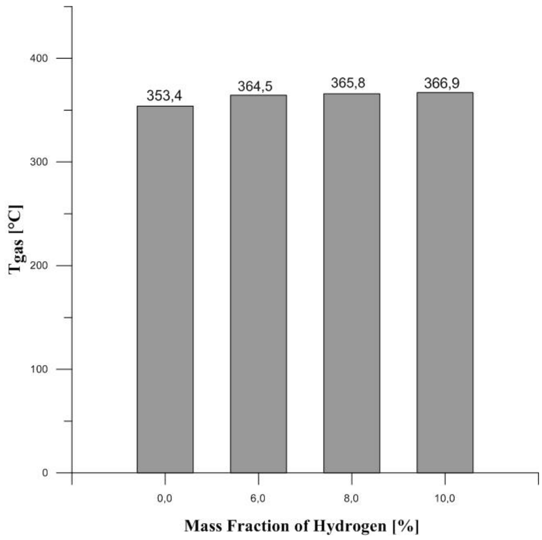

Figure 5. Effects of H_2 enrichment on exhaust gas temperature.

3.4 Nitrogen oxides

NOx emissions are basically dependent on reaction duration, gas temperature, and availability of oxygen and nitrogen [29]. Normally, the addition of hydrogen causes an increase in the combustion temperature tending to increase NOx emissions, as shown in Figure 6. For hydrogen additions of 6 and 8% emissions increased by 1.4 and 7.1% respectively, already for the addition of 10% of hydrogen had a greater increase of 22.2%. The results are similar to those reported by Deb, Sastry (2015), Jhang and Chen (2016).

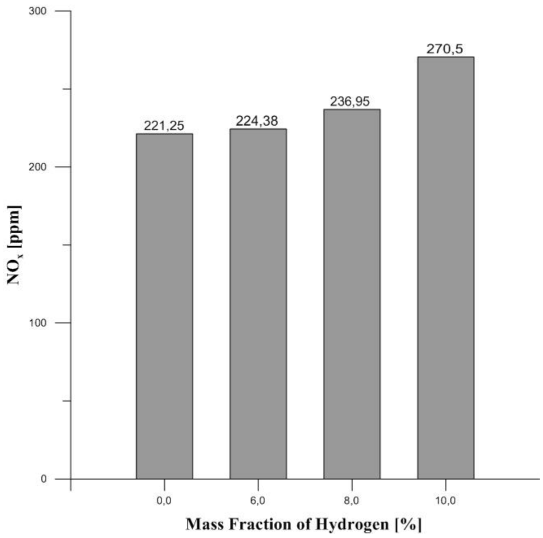

Figure 6. Effects of H2 enrichment on the emissions of nitrogen oxides.

3.5 Carbon Monoxide

Carbon monoxide (CO) is formed by the incomplete combustion of any fuel containing carbon in its composition. During the combustion process, the carbon in the fuel in the presence of oxygen is converted to CO and subsequently, due to its oxidation, converted into CO2. As the diffusion coefficient of hydrogen in the air is higher than other conventional fuels, the use of the same results in a more uniform mixture of the fuels in the cylinder, which added to the greater flame propagation speed of the hydrogen, promote an improvement in the combustion process, resulting in a reduction of CO emissions (Deb et al., 2015). B7 mixed with hydrogen reduced carbon monoxide emissions, as shown in Figure 7, where the average percentage reductions in carbon monoxide emissions were 29.5; 33.9 and 40.5%. Similar trends were observed in the works of Köse and Ciniviz (2013), Karagöz, Güler (2016), Sandalcı and Karagöz (2016).

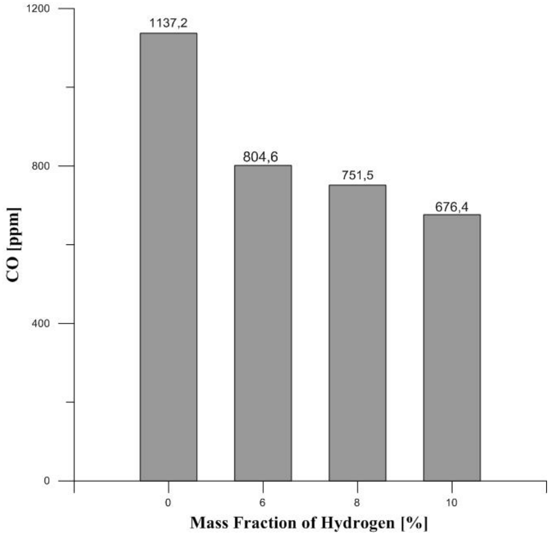

Figure 7. Effects of H_2 enrichment on carbon monoxide emissions.

3.6 Carbon Dioxide

The carbon dioxide emissions are shown in Figure 8, the results showed small reductions of 9.1; 9.4 and 9.8% for each of the three percentages of hydrogen injected into the engine. Since CO2 and CO emissions are interrelated, CO reductions are expected to produce an increase in CO2 emissions, but due to the lack of carbon in the hydrogen composition, the total amount of carbon the formation of CO and its subsequent oxidation in CO2 is decreased. Similar results are found in the works of Karagöz, Güler (2015), Sandalcı and Karagöz (2016).

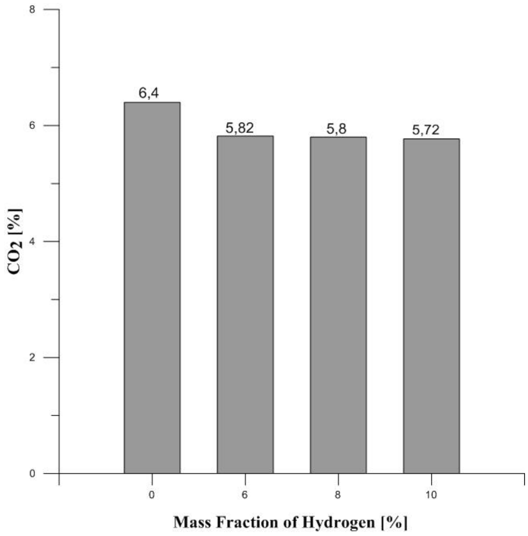

Figure 8. Effects of H_2 enrichment on carbon dioxide emissions.

3.7 Results of numerical simulation

The results obtained in the validation of the numerical model as a function of the experimental results are shown in Table 4, it is possible to verify small variations comparing with the experimental results regarding electric power and specific fuel consumption, since the temperature of the gases presented higher variations.

Table 4. Validation of the results obtained in the combustion simulation of B7 with and without H2 enrichment.

Parameters	Pel [kW]	Cesp [g/kW-h]	Tgas [°C]
0.0%H_2 (Exp.)	2,38	451,13	582,6
0.0%H_2 (Sim.)	2,37	451,9	544,9
6.0%H_2 (Exp.)	2,41	443,5	591,8
6.0%H_2 (Sim.)	2,41	443,06	555,6
8.0%H_2 (Exp.)	2,44	426,8	599,1
8.0%H_2 (Sim.)	2,44	426,57	556,2
10.0%H_2 (Exp.)	2,48	415,81	606,5
10.0%H_2 (Sim.)	2,48	416,23	560,4

The largest relative error found between the experimental and numerically determined variables was 7.6% at the gas temperature for a 10% hydrogen mixture, as shown in Table 5.

Table 5. Relative error of the simulated results compared to the experimental ones.

	Pe [%]	Cesp [%]	Tgas [%]
0.0%H_2	0,24	0,17	6,5
6.0% H_2	0,07	0,10	6,1
8.0%H_2	0,10	0,05	7,2
10.0% H_2	0,14	0,10	7,6

With the validation of the model it was possible to determine the unknown parameters of the Vibe combustion model as a function of the parameters measured experimentally as shown in Table 6.

Table 6. Parameters of the Vibe model determined using optimization methods.

Parâmetros	0.0%H_2	6.0% H_2	8.0%H_2	10.0% H_2
Início da combustão [deg]	-17,49	-19,9	-19,92	-19,98
Duração da combustão [deg]	58,8	38,37	37,12	31,98
Parâmetro a [-]	6,9	6,9	6,9	6,9
Parâmetro m [-]	0,442	0,448	0,475	0,532

3.8 Pressure curve in cylinder

The result of the simulated pressure curve shown in Figure 9 shows that the maximum pressure peak in the cylinder increases proportionally with the amount of hydrogen injected. This peak peak rises from 103.4 bar for pure B7 and 119.1, 119.9 and 122.8 bar for each hydrogen addition of 6, 8 and 10%, representing increases of 15.1; 15.9 and 18.7% based on the result obtained with pure B7. This increase is a result of the high flame speed of the hydrogen, which provides a rapid combustion of the fuel mixture, thus improving the combustion process. Experimental results similar to those obtained numerically in this study were found by Deb et al. (2015); Yasin Karagöz et al. (2016).

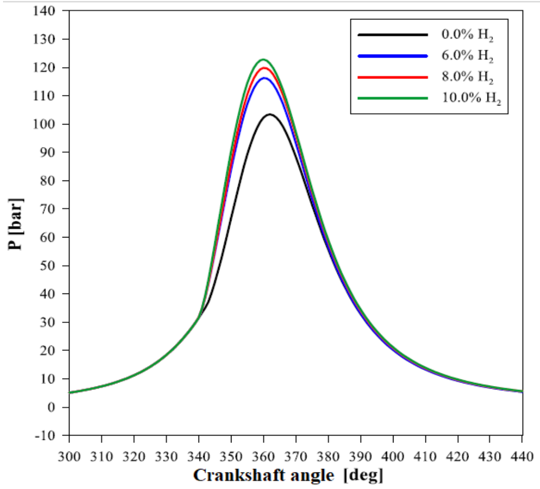

Figure 9. Effects of hydrogen enrichment on cylinder internal pressure as a function of crankshaft angle.

3.9 Heat release rate

The high flame velocity and the high calorific value of hydrogen allow the lower calorific power of the fuel mixture to be increased, resulting in a higher rate of heat release. Figure 10 shows the effect of the addition of hydrogen on the rate of simulated heat release, it is possible to verify that the maximum peak of this rate increases proportionally with the increase of the injected hydrogen mass fraction. However, during the simulation of the engine the Vibe combustion model was used, and it does not describe which phase of combustion dominated the process. But the experimental work of Deb et al. (2015); Yasin Karagöz et al. (2016) show that the premixed combustion phase is dominant, releasing more energy, unlike the diffusive phase that is reduced with the increase of the injected hydrogen.

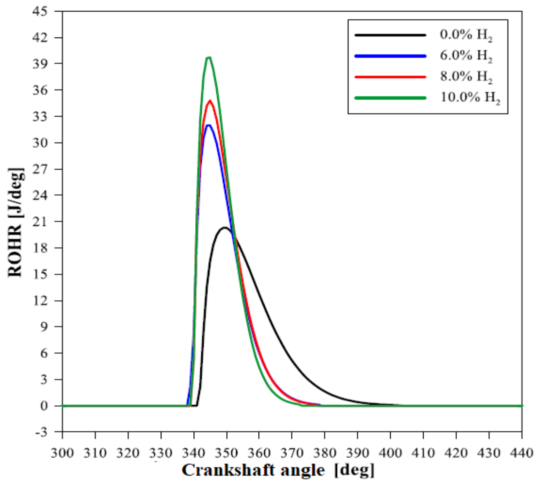

Figure 10. Effects of hydrogen enrichment on heat release rate as a function of crankshaft angle.

4. CONCLUSION

In this work small amounts of hydrogen were added to the B7 to verify their effects on the performance and emissions of a diesel generator set. This study showed that even a small amount of hydrogen can change engine behavior from the perspective of performance and emissions. Adding hydrogen tends to improve engine performance by reducing your specific fuel consumption and your CO and CO2 emissions. However, increasing the hydrogen content raises the temperature of the gases, which reflects in the increase of the NOx emissions, where this condition can be aggravated for high engine loads. Hydrogen was introduced into the air intake manifold continuously, without making any modification or installation of complex equipment in the engine, thus making possible its direct use in diesel thermal plants. At most, the addition of 10% hydrogen by mass of the total fuel mixture was tested, but as hydrogen is continuously admitted with the intake air, this addition tends to reduce the air admitted by the engine, thus decreasing its efficiency volumetric. Because of this, high concentrations of hydrogen could impair engine performance due to lack of oxygen in the cylinder, in addition, high concentrations of hydrogen may also produce early detonations of the fuel mixture.

5. REFERENCES

ANP, Oil, Natural Gas and Biofuels Statistical Yearbook 2014. 2014, Agency of Petroleum, Natural Gas and Biofuels: Rio de Janeiro.

AVL-BOOST, Users Guide version 2014.1, in AVL LIST GmbH. 2014: Graz, Austria.

Bose, P.K., R. Banerjee, and M. Deb, Effect of hydrogen-diesel combustion on the performance and combustion parameters of a dual fuelled diesel engine. International Journal of Energy & Environment, 2013. **4**(3): p. 497-510.

Batmaz, I., The Impact of Using Hydrogen as Fuel on Engine Performance and Exhaust Emissions in Diesel Engines. Energy Sources, Part A: Recovery, Utilization, and Environmental Effects, 2013. **35**(6): p. 556-563.

Datta, A. and B.K. Mandal, A comprehensive review of biodiesel as an alternative fuel for compression ignition engine. Renewable and Sustainable Energy Reviews, 2016. **57**: p. 799-821.

Deb, M., et al., An experimental study on combustion, performance and emission analysis of a single cylinder, 4-stroke DI-diesel engine using hydrogen in dual fuel mode of operation. International Journal of Hydrogen Energy, 2015. **40**(27): p. 8586-8598.

Dincer, I. and C. Acar, Review and evaluation of hydrogen production methods for better sustainability. International Journal of Hydrogen Energy, 2015. **40**(34): p. 11094-11111.

Hoekman, S.K., et al., Review of biodiesel composition, properties, and specifications. Renewable and Sustainable Energy Reviews, 2012. **16**(1): p. 143-169.

Hamdan, M.O., et al., Hydrogen supplement co-combustion with diesel in compression ignition engine. Renewable Energy, 2015. **82**: p. 54-60.

Jhang, S.-R., et al., Reducing pollutant emissions from a heavy-duty diesel engine by using hydrogen additions. Fuel, 2016. **172**: p. 89-95.

Karagöz, Y., et al., Engine performance and emission effects of diesel burns enriched by hydrogen on different engine loads. International Journal of Hydrogen Energy, 2015. **40**(20): p. 6702-6713.

Köse, H. and M. Ciniviz, An experimental investigation of effect on diesel engine performance and exhaust emissions of addition at dual fuel mode of hydrogen. Fuel Processing Technology, 2013. **114**: p. 26-34.

Leung, D.Y.C., X. Wu, and M.K.H. Leung, A review on biodiesel production using catalyzed transesterification. Applied Energy, 2010. **87**(4): p. 1083-1095.

Sandalcı, T. and Y. Karagöz, Experimental investigation of the combustion characteristics, emissions and performance of hydrogen port fuel injection in a diesel engine. International Journal of Hydrogen Energy, 2014. **39**(32): p. 18480-18489.

Prashant, G.K., D.B. Lata, and P.C. Joshi, Investigations on the effect of ethanol blend on the combustion parameters of dual fuel diesel engine. Applied Thermal Engineering, 2016. **96**: p. 623-631.

Yadav, V.S., D. Sharma, and S.L. Soni, Performance and combustion analysis of hydrogen-fuelled C.I. engine with EGR. International Journal of Hydrogen Energy, 2015. **40**(12): p. 4382-4391.