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Experimental Investigation of Hydrogen Addition in the Intake Air of Compressed Engines Running on Biodiesel Blend

Hendrick Maxil Zárate Rocha, Ricardo da Silva Pereira, Manoel Fernandes Martins Nogueira, Carlos R. Pereira Belchior, Maria Emilia de Lima Tostes

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***Abstract*—**This study investigates experimentally the effects of hydrogen addition in the intake manifold of a diesel generator operating with a 7% biodiesel-diesel oil blend (B7). An experimental apparatus setup was used to conduct performance and emissions tests in a single cylinder, air cooled diesel engine. This setup consisted of a generator set connected to a wirewound resistor load bank that was used to vary engine load. In addition, a flowmeter was used to determine hydrogen volumetric flowrate and a digital anemometer coupled with an air box to measure air flowrate. Furthermore, a digital precision electronic scale was used to measure engine fuel consumption and a gas analyzer was used to determine exhaust gas composition and exhaust gas temperature. A thermopar was installed near the exhaust collection to measure cylinder temperature. In-cylinder pressure was measured using an AVL Indumicro data acquisition system with a piezoelectric pressure sensor. An AVL optical encoder was installed in the crankshaft and synchronized with in-cylinder pressure in real time. The experimental procedure consisted of injecting hydrogen into the engine intake manifold at different mass concentrations of 2,6,8 and 10% of total fuel mass (B7 + hydrogen), which represented energy fractions of 5,15, 20 and 24% of total fuel energy respectively. Due to hydrogen addition, the total amount of fuel energy introduced increased and the generators fuel injection governor prevented any increases of engine speed. Several conclusions can be stated from the test results. A reduction in specific fuel consumption as a function of hydrogen concentration increase was noted. Likewise, carbon dioxide emissions (CO_2), carbon monoxide (CO) and unburned hydrocarbons (HC) decreased as hydrogen concentration increased. On the other hand, nitrogen oxides emissions (NO_x) increased due to average temperatures inside the cylinder being higher. There was also an increase in peak cylinder pressure and heat release rate inside the cylinder, since the fuel ignition delay was smaller due to hydrogen content increase. All this indicates that hydrogen promotes faster combustion and higher heat release rates and can be an important additive to all kind of fuels used in diesel generators.

***Keywords*—**Diesel engine, hydrogen, dual fuel, combustion analysis, performance, emissions.

Hendrick Maxil Zárate Rocha is with the Department of Mechanical Engineering, Federal University of Rio de Janeiro, Cidade Universitária, 21941-970 Rio de Janeiro, Brazil.

Ricardo da Silva Pereira and Maria Emilia de Lima Tostes are with the Department of Electrical Engineering, Federal University of Pará, 66075-110 Belém, Pará, Brazil.

Manoel Fernandes Martins Nogueira is with the Department of Mechanical Engineering, Federal University of Pará, 66075-110 Belém, Pará, Brazil.

Carlos R. Pereira Belchior is with the Department of Mechanical Engineering, Federal University of Rio de Janeiro, Cidade Universitária, 21941-970 Rio de Janeiro, Brazil (e-mail: belchior@oceanica.ufrj.br).

I. INTRODUCTION

As the world's energy demand increases to propel economic and technical growth, so does the environmental impact associated with this demand. Fossil fuels, in particular, are responsible for the majority of noxious gas emissions, greenhouse gas emissions and due to its key strategic value, also play an important role in geopolitical interactions between countries and increase energy security concerns worldwide. In this context, there has been an increased interest in finding alternative and renewable energy sources of energy that can replace or at least mitigate those concerns [1]. Some of these alternative fuels include renewable biofuels such as ethanol, biodiesel and vegetable oils [2]-[4]. Sandalci et al. successfully conducted experimental tests on unmodified diesel engines operating with ethanol-diesel mixtures and found that increased ethanol percentage by volume in the mixture results in an increase specific fuel consumption, while also reducing thermal efficiency, CO_2 and NO_x emissions [5].

As it pertains to Brazil, commercial diesel consists of a blend of diesel oil and 7% in volume of biodiesel, which is usually made up of a transesterified mixture of mono-alkyl esters of long chain fatty acids from either vegetable oils or animal fats [6]. Due to having similar properties to diesel oil, this fuel can be used in most diesel engines without requiring significant changes to the machine [7], [8] and presents benefits in comparison to pure diesel, such as reduced particulate matter (PM), hydrocarbons (HC) and carbon monoxide (CO) emissions [7]-[12]. Furthermore, due to its viscosity, biodiesel can improve an engine's lubricity and consequently extend its useful life [8], [13].

On the other hand, biodiesel has a smaller lower heating value, as well as higher viscosity and smaller cetane number when compared to diesel. The latter results in increased ignition delays, which in turn causes the engine's efficiency to decrease and results in higher fuel consumption [7]. However, additives can be blended with biodiesel in order to mitigate or even solve this problem by improving the engine's combustion.

One of the methods employed to mitigate the downsides of biodiesel use in internal combustion engines is hydrogen addition. Hydrogen is a renewable, odorless, non-toxic fuel and can improve combustion speed while also reducing carbon emissions due to the absence of carbon in its composition. However, it is also a secondary energy source, meaning it does not exist natively in nature and must be produced. Hydrogen addition in diesel engines can be done using three methods: continuous injection in the intake manifold, controlled injection in the intake manifold and direct injection in the combustion chamber [14], [15]. Although continuous H_2 injection in the intake manifold is the simplest method, it can present potential explosion hazards and requires additional safeguards such as a flame arrestor valve [16]-[18]. On the other hand, the controlled injection method allows higher precision in the H_2 injection in the intake manifold, although this requires a calibrated gas injector synchronized with the fuel injection pump. Furthermore, both methods cause reduction of volumetric efficiency due to air displacement in the intake manifold, which limits the maximum effective H_2 doping concentrations to avoid reducing the engine's thermal efficiency [19]-[22]. This decrease in volumetric efficiency, in turn, can be solved by direct H_2 injection in the combustion chamber. However, this method requires intrusive modifications in the cylinder head prior to engine installation and attention to the high pressure injector's design [22].

Controlled hydrogen injection into the intake manifold has been the subject of experimental tests and has produced conflicting results in the literature. Deb et al. noticed that hydrogen addition through controlled injection resulted in reduced CO_2, CO and HC emissions and decreases in specific fuel consumption. NO_x, however, increased due to higher gas temperatures in the cylinder [23]. On the other hand, Karagoz et al. reported that although emission trends were similar, specific fuel consumption increased and attributed these results to decreased volumetric efficiency [17]. The authors had previously noted that different injection points had been tested, which had direct influence in the mixture's uniformity and this could, in certain situations, result in inefficiencies in the combustion process.

Morsy et al. noted that continuous hydrogen addition resulted in increased specific fuel consumption for loads under 50% and reduced specific fuel consumption for loads higher than 50% of nominal power [18]. In addition to this trend, which was in agreement with the results by Batmaz [19], hydrogen content increases result in higher flame propagation speed, peak pressure and heat release ratio. This results in better combustion and was demonstrated by showing there was an advance in the start combustion [24]. An increase in injected hydrogen concentration in the intake air, for all load conditions and tested rotations, was also shown to result in decreased thermal efficiency and increased specific fuel consumption. Furthermore, it also caused decreases in CO_2 and CO emissions and increases in maximum values of in-cylinder pressure and heat release rate [17], [25].

In conclusion, hydrogen addition to pure diesel in compression ignition internal combustion engines and its impact on engine performance and exhaust gas emissions depends on the amount of hydrogen added and how it is injected into the engine. However, there have been few studies that examined hydrogen addition and its influence on compression ignition engines operating with biodiesel. The present work investigated the effects of continuous hydrogen addition into the intake manifold on performance and emissions of a diesel genset operating on a biodiesel blend (B7). These results provide a more comprehensive view of the influence of hydrogen addition in the operation of thermal power plants fueled with diesel-biodiesel blends.

II. MATERIALS AND METHODS

A. Experimental Setup

A single-cylinder, four-stroke, air-cooled and direct injection genset was procured for this research. The engines technical specifications are given in Table I. Table II presents the measurement devices, their parameters and accuracy, while Fig. 1 shows a schematic diagram of the experimental apparatus. The genset was connected to a wirewound resistive load bank, which was used to control the electrical load. A SAGA 4500 electrical quantities analyzer measured the generated electric power (P_{el})while an Omega FLDH3303G flowmeter and an AKROM KR835, turbine type anemometer were used to quantify the hydrogen and air volumetric flowrates. An air box with 200 L internal volume was installed prior to the anemometer to minimize air fluctuations due to valves opening and closing.

A digital precision scale was used to determine the mass flow of fuel (B7) consumed by the engine, while a gas analyzer and a thermocouple were used to measure CO_2, CO, NO_x and HC emissions and exhaust gas temperature, respectively, at the exhaust manifold output. A piezoelectric sensor was installed in the combustion chamber to obtain in-cylinder pressure data of up to 250 bar. A crank angle encoder was coupled to the engine and can synchronize engine speed with the in-cylinder pressure in real time.

Hydrogen addition was done using the continuous method and was initially at 165 bar before passing through a two-stage pressure regulator and being supplied to the gas line at 1.5 bar. A firebreak valve was installed just upstream of the air intake manifold to prevent flashback phenomenon.

TABLE I
TECHNICAL SPECIFICATION FOR DIESEL QENSET

Engine	Engine manufacturer	Branco
	Aspiration	Natural
	Fuel injection	Direct
	Start of diesel injection	16^o BTD
	Fuel injection pressure	196 bar
	Cooling	Air cooled
	Number of cylinders	1
	Bore stroke	86 70
	Cylinder volume [cm^3]	406
	Compression ratio	19:01
	Speed [rpm]	3600
Generator	Frequency [Hz]	60
	Voltage	220 V
	Max. electric power [kW]	4.5 kW

B. Experimental Procedure

Hydrogen enrichment mass fraction was set to five different values (0, 2, 4, 6 8, 10 % of fuel mass) and and compared. For every operating point, the engine speed was fixed at 3600 RPM and the load was constant at 2.43 kW (approximately 60 % of nominal power. Before beginning the measurements,

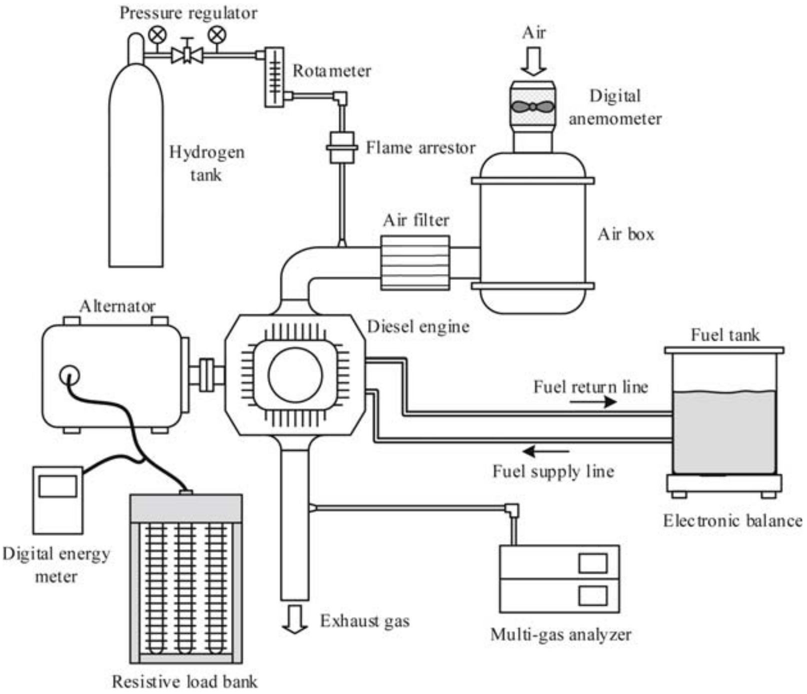

Fig. 1 Schematic view of the experimental setup

TABLE II
MEASUREMENT DEVICES, THEIR MEASURED PARAMETERS AND THEIR ACCURACY

Parameter	Device	Accuracy
Electric power	SAGA 4500	±1 W
Fuel mass	DIGIMED DG-15W	±0.2 g
H_2 flow rate	OMEGA FLDH3303G	±0.2 l/min
Air flow rate	AKROM KR835	±0.9 g/s
CO_2 (NDIR)	GREENLINE 8000	±0.1%
CO (NDIR)	GREENLINE 8000	±10 ppm
NO_x (NDIR)	GREENLINE 8000	±5 ppm
HC (NDIR)	GREENLINE 8000	±4 ppm
Cylinder pressure	AVL GU21D	±0.4 bar
Crank angle	AVL 365C	±0.05 ^{o}CA
Gas temperature	K-type thermocouple	±2 ^{o}C

TABLE III
CALCULATED AND MEASURED PARAMETERS AND THEIR UNCERTAINTIES

Parameter	Uncertainty
Electric power	±1.0%
Variation of fuel mass	±1.3%
H_2 flow rate	±0.9%
Air flow rate	±0.7%
CO_2	±0.18%
CO	±0.32%
NO_x	±1.08%
HC	±1.12%
Cylinder pressure	±0.11%
Crank angle	±0.21%
Gas temperature	±0.4%
B7 Mass flow rate	±1.39%
H_2 Mass flow	±1.64%
Specific fuel consumption	±1.92%

TABLE IV
PHYSICAL AND CHEMICAL PROPERTIES OF B7 AND HYDROGEN

Properties	B7
Chemical formula	$C_{6.95}H_{14.79}O_{0.05}S_{0.03}$
Density at 20 ^{o}C [kg/m^3]	872.7
Viscosity at 40 ^{o}C [cP]	2.9
Higher heating value [MJ/kg]	44
Lower heating value [MJ/kg]	41.7
Ultimate analysis	
C [%]	83.43
H [%]	14.91
O [%]	0.79
N [%]	0
S [%]	0.84

the exhaust gas temperature T_{gas}) was monitored to verify steady state operation and every parameter was measured three times and the results averaged. Table III shows the average uncertainties of measured and calculated parameters [23]. The physical and chemical properties of B7 were determined experimentally in laboratory and the hydrogen used in all tests had a purity of 99.99%. The physical and chemical properties of both fuels are shown in Table IV.

Hydrogen mass flow rate was calculated by converting the volumetric flow rate measured experimentally at the intake manifold and used to determine the hydrogen mass fraction according to (1).

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

Using the lower heating values (LHV) (see Table IV) and mass fractions, it was possible to calculate the energy fraction added by the addition of hydrogen using (2). With this data, the mass fractions of 2, 6, 8 and 10% respectively mean 5.1, 14.8, 19.6 and 24.0% of the total available energy in the blended fuels.

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

The volumetric efficiency was calculated using (3) as a function of the mass flow of admitted air ($\dot{m}_{air}$), engine speed (N), displaced volume (V_d) and air density (ρ_{air}), where ρ_{air} is calculated with air temperature and pressure measured in the intake manifold.

$$\eta = \frac{2\dot{m}_{air}}{\rho_{air} V_d N} \tag{3}$$

The specific fuel consumption ($BSFC$) was determined according to the fuel mass of both B7 and hydrogen to generate an electrical power (P_{el}), that is converted into break power (P_e) using generator efficiency, as shown in (4). The specific fuel consumption for B7 ($BSFC_{B7}$) only, was also determined using (4) but ignoring the mass flow of H_2.

$$BSFC = \frac{\dot{m}_{B7} + \dot{m}_{H_2}}{P_e} \tag{4}$$

The indicated mean effective pressure ($imep$) was calculated according to the pressure inside the cylinder (p) and the displaced volume according to (5).

$$imep = \frac{\int pdV}{V_d} \tag{5}$$

The rate of heat release ($ROHR$) was calculated using (6) after applying the first law of thermodynamics considering a closed volume of control and despising heat transfer losses.

$$\frac{dQ}{df} = \frac{k}{k-1} p \frac{dV}{df} + \frac{1}{k-1} V \frac{dp}{df} \tag{6}$$

where k is the ratio of specific heats c_p and c_v and ϕ is the crankshaft angle.

III. RESULTS AND DISCUSSION

A. Fuel Consumption

Table V shows the fuel mass flow rates used and lower heating value of the blended B7 and hydrogen. Hydrogen addition was shown to result in reduction of admitted B7 flow rate since electric power and rotation were kept constant. Furthermore, hydrogen addition also increased the lower heating value of blended fuels.

TABLE V
EXPERIMENT ADOPTED FUEL CONSUMPTION, MIXTURE LOWER HEATING VALUE IN MJ/KG AND HYDROGEN ENERGY FRACTION

y_{H_2}[%]	$\dot{m}_{B7}$[g/h]	$\dot{m}_{H_2}$[g/h]	LHV	E_{H_2}[%]
0	1107.2	0	41.7	0
2	1039.4	19.4	43.2	5
6	989.6	60.7	46.2	15
8	959	81.4	47.9	20
10	931.8	102.1	49.5	24

B. Volumetric Efficiency

Fig. 2 shows the variation of engine volumetric efficiency with injected hydrogen percentage. For each increase in the mass fraction of hydrogen there is a decrease in volumetric efficiency, which is caused due to air displacement in the intake manifold. The calculated volumetric efficiencies were 79.9% for pure B7 and 79.5, 78.7, 77.0 and 75.4% for each addition of hydrogen of 2, 6, 8 and 10% of the fuel mass, respectively, and the results showed similar trends to those in the literature [18], [19], [22], [26].

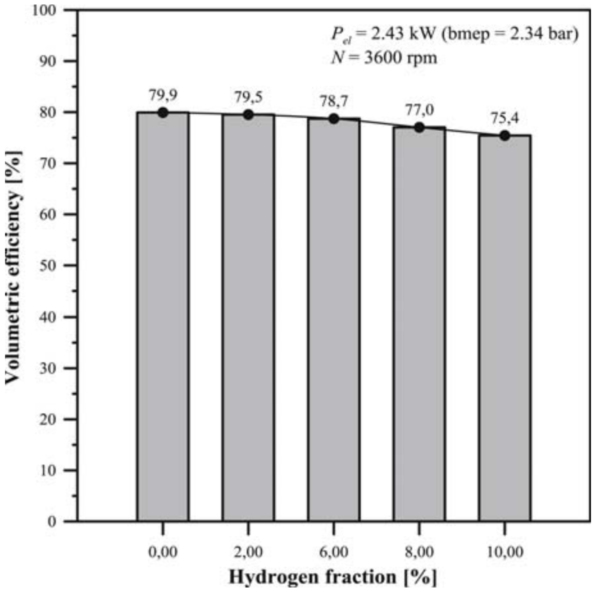

Fig. 2 Effect of hydrogen enrichment on the volumetric efficiency

C. Specific Fuel Consumption

Break specific fuel consumption ($BSFC$) is shown in Fig. 3. As hydrogen mass fraction is increased, $BSFC$ is lowered. The values of $BSFC$ were 387.1 g/kW-h when only B7 was used and 370.2, 367.2, 363.7 and 361.5 g/kW-h respectively for the four percentages of hydrogen. These results show that $BSFC$ was positively affected with hydrogen addition for all cases and showed reductions of 4.4, 5.1, 6.0 and 6.6% for each of the four hydrogen percentages in comparison to the B7 only case. Due to LHV increase in the blended fuels, the average gas temperature, peak pressure and peak temperature in the cylinder were also increased and as a result, the combustion process was accelerated. This, in turn, results in an increase of the mean indicated pressure and, consequently, in a decrease of the break specific fuel consumption. Similar results regarding $BSFC$ were reported by Jhang et al. [16], Hamdan et al. [20], Deb et al. [23], Yadav et al. [27].

On the other hand, Fig. 4 shows the specific fuel consumption by considering only the consumed mass of B7 ($BSFC_B7$). It is observed that hydrogen addition in all four injected percentages significantly affected the reduction of the specific consumption of B7, yielding reductions of 6.1, 10.6, 13.4 and 15.8% respectively.

D. Exhaust Gas Temperature

The temperature of the exhaust gases in relation to the increase of hydrogen content is shown in Fig. 5. As expected, higher hydrogen content in the blended fuels resulted in higher mean gas temperatures in the cylinder and exhaust gas temperatures. The temperature increased progressively at 10.4, 13.7, 16.3 and 18.9% due to the addition of hydrogen and was in agreement with the trends identified in the literature [18], [20], [22].

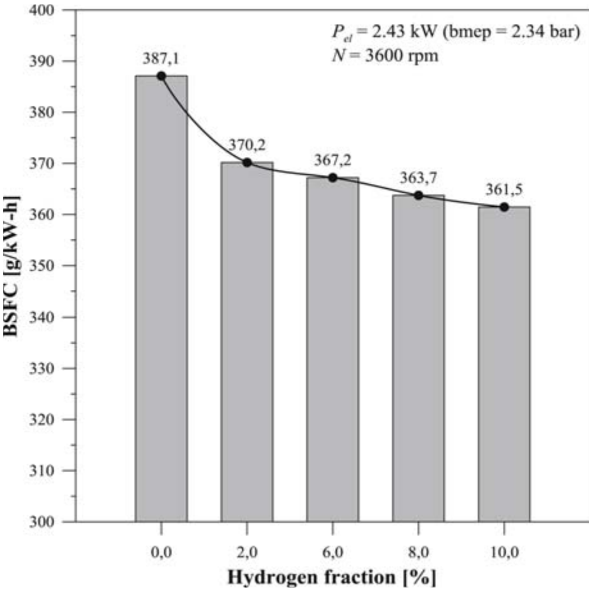

Fig. 3 Effect of hydrogen enrichment on the break specific fuel consumption

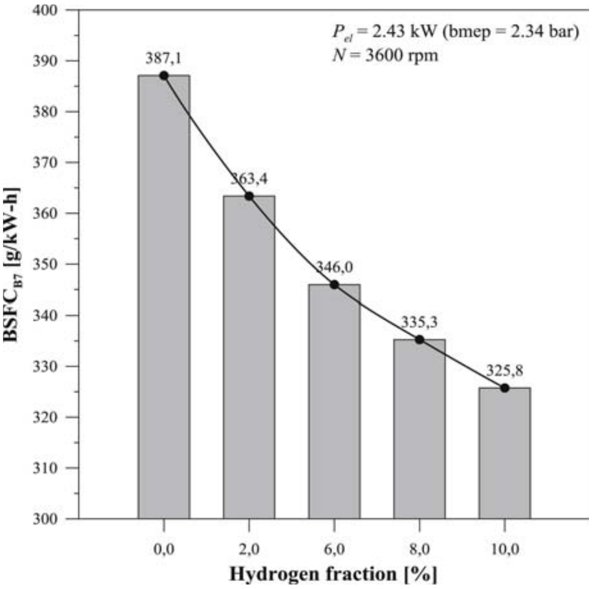

Fig. 4 Effect of hydrogen enrichment on the break specific fuel consumption of B7

E. Nitrogen Oxides

Fig. 6 shows the effect of hydrogen addition on NO_x emissions. For hydrogen additions of 2, 6 and 8%, emissions increased by 21.3, 23.0 and 29.9% respectively, while the addition of 10% of hydrogen resulted in a greater increase of 48.3%. NO_x emissions depend on reaction duration, in-cylinder gas temperature and nitrogen and oxygen availability. Compression ignition engines operate at excess air ratios, which leads to high oxygen and nitrogen levels. In addition, hydrogen addition leads to higher temperatures, as shown previously, which lead to increased NO_x emissions. The results obtained are in agreement with those reported in the literature [16], [23], [28].

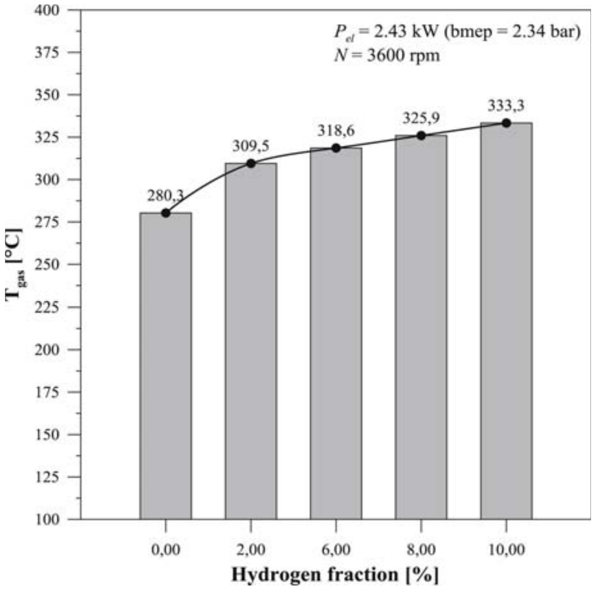

Fig. 5 Effect of hydrogen enrichment on exhaust gas temperature

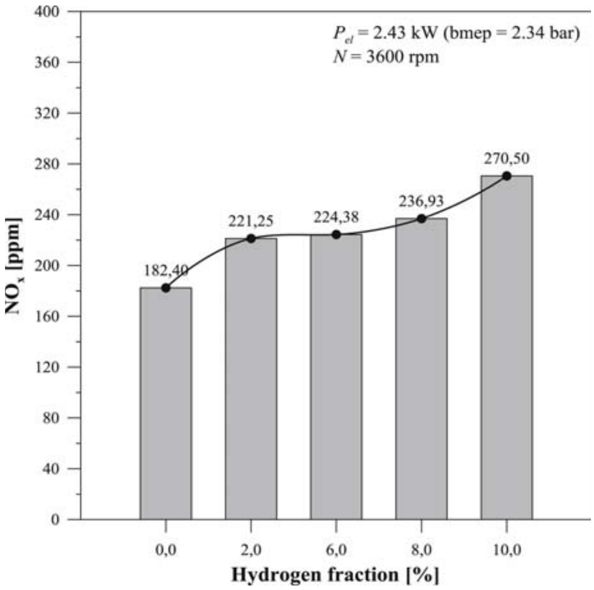

Fig. 6 Effect of hydrogen enrichment on oxides of nitrogen emission

F. Unburned Hydrocarbons

Fig. 7 shows the effect of hydrogen enrichment on HC emissions and it can be seen that for each addition of hydrogen of 2, 6, 8 and 10%, HC emissions were significantly reduced by 40.7, 67.3, 86.2 and 97.9% respectively. Since Hydrocarbon emissions (HC) are formed due to incomplete combustion of the B7 fuel, these trends in HC emissions can be expected as hydrogen enrichment reduces carbon supply through B7 by 6.1, 10.6, 13.4 and 15.8%, respectively(see Tables IV and V). Similar results were found in the literature [22], [29].

G. Carbon Monoxide

Fig. 8 presents CO emissions versus hydrogen addition. As can be seen, CO emissions decrease as hydrogen content

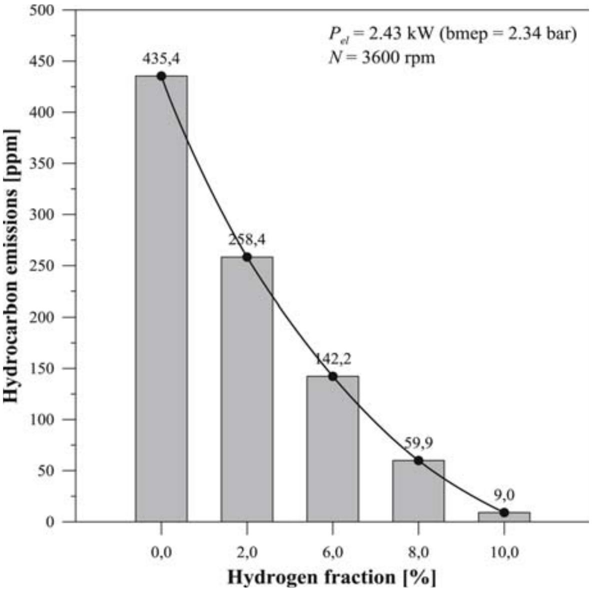

Fig. 7 Effect of hydrogen enrichment on hydrocarbon emission

increases, with percentage reductions of 38.5, 56.7, 59.4 and 63.4% in comparison to pure B7 operation. This trend was expected due to better combustion efficiency and decreased carbon content in the injected fuel caused by hydrogen addition. Similar trends were observed in the works of Karagz et al. [17], Kse et al. [22], Sandalci and Karagz [24].

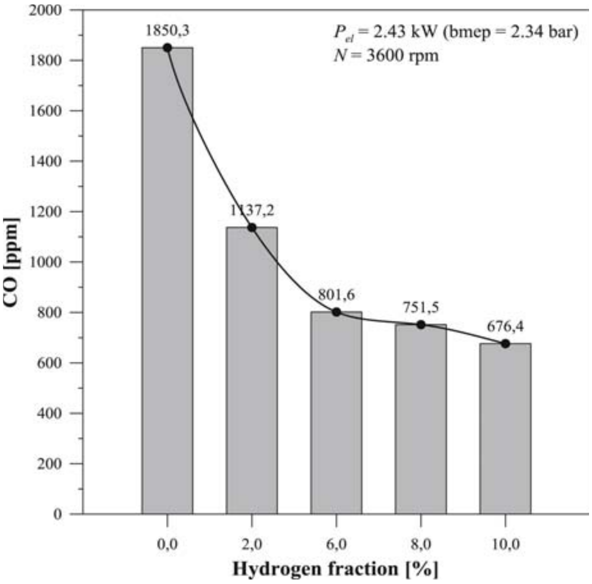

Fig. 8 Effect of hydrogen enrichment on carbon monoxide emission

H. Carbon Dioxide

Carbon dioxide emissions are shown in Fig. 9. The results showed reductions of 4.7, 13.3, 16.1 and 19.9% for each of the four hydrogen percentage injected into the engine, due to lower carbon supply to the engine caused by hydrogen addition. These results were in agreement with those by Pan et al. [15], Karagz et al. [17], Sandalci and Karagz [24].

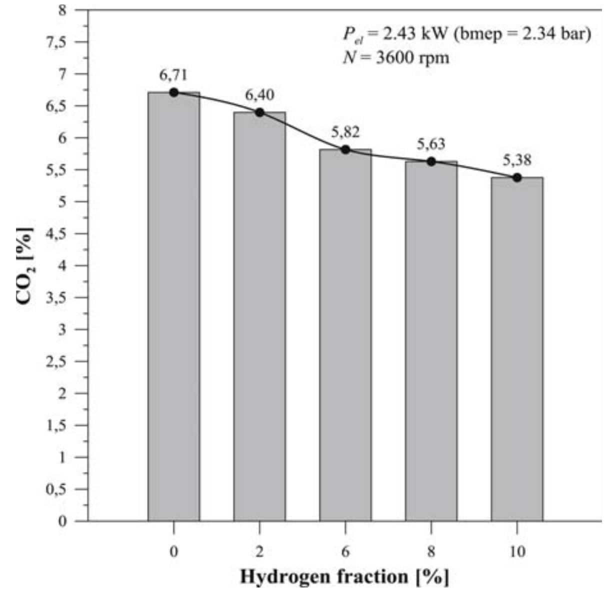

Fig. 9 Effect of hydrogen enrichment on carbon dioxide emission

I. Cylinder Gas Pressure

The effects of hydrogen addition on the pressure curve is shown in Fig. 10. In-cylinder peak pressure increase and combustion delay reduction are propoertional to the amount of hydrogen injected. Pressure peak rises from 56.1 bar for pure B7 to 57.4, 58.1, 59.1 and 61.2 bar for 2, 6, 8 and 10% hydrogen addition, respectively, or increases of 2.2, 3.5, 5.3 and 9.1%. This increase is caused by better combustion efficiency due to the high flame speed of hydrogen as well as its higher LHV. These experimental results were in agreement with the numerical results reported by Karagz et al. [17], Deb et al. [23].

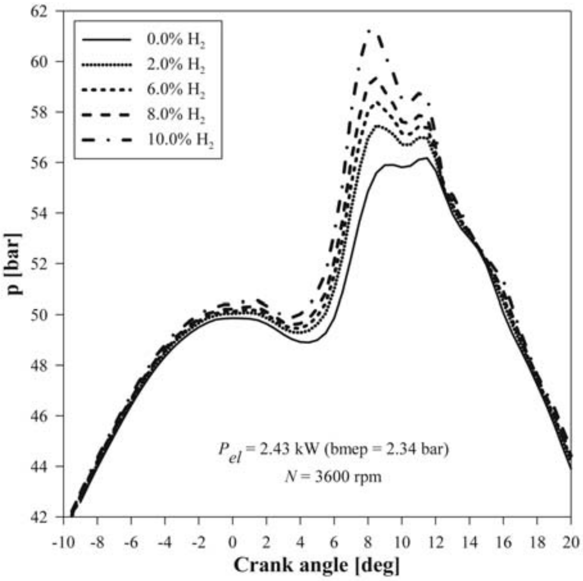

Fig. 10 Effect of hydrogen enrichment on cylinder gas pressure related to crank angle

J. Rate of Heat Release

Fig. 11 shows the effect of adding hydrogen on the rate of heat release. It is noted that the peak rate rises proportionally to the hydrogen mass fraction due to increases in the blended fuel's LHV and flame speed. On the other hand, these properties also incur in a reduction in pre-mixed combustion phase's duration and increase in the diffusion combustion stage's duration.

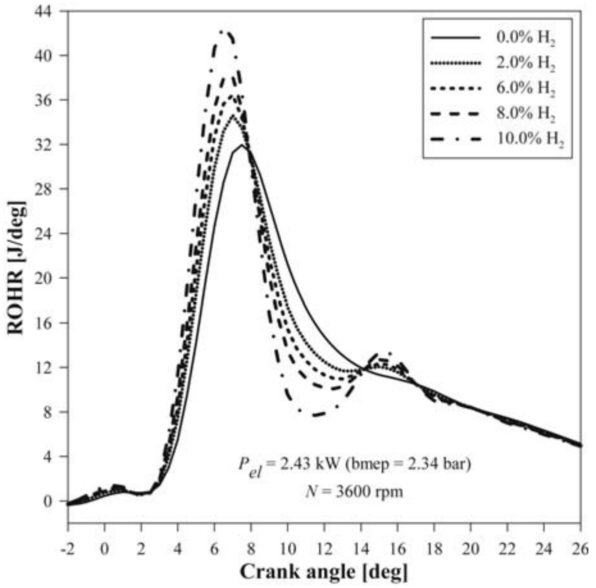

Fig. 11 Effect of hydrogen enrichment on rate of heat released

K. Start of Combustion

Fig. 12 shows the effects of hydrogen enrichment on start of combustion. In this work, SOC was considered as the moment when the rate of heat released changes from a negative value to zero, after its initial decrease due to fuel vaporization. Start of combustion due to the increased concentration of hydrogen is anticipated from 0.32^o, for pure B7, to 0.66, 0.76, 0.85 and 0.97^o for 2, 6, 8 and 10% of hydrogen addition, respectively. This behavior is due to faster combustion caused by hydrogen addition. Similar trends were reported by Karagz, Gler [17].

IV. CONCLUSIONS

In the present work, the effects of hydrogen addition to B7, using continuous injection into the intake manifold, on the performance and emissions of a diesel genset are reported. It was shown that engine performance and emissions can be significantly modified even with small amounts of hydrogen addition. Hydrogen addition was shown to reduce specific fuel consumption and PM, CO, CO_2 and HC emissions. Higher hydrogen content also anticipated and increased in-cylinder peak pressure and average temperature of the gas inside the cylinder. The latter, on the other hand, reflected in increases in NO_x emissions, which could be aggravated with higher engine loads. These trends indicated that hydrogen promoted a faster combustion process as well as higher rates of heat release.

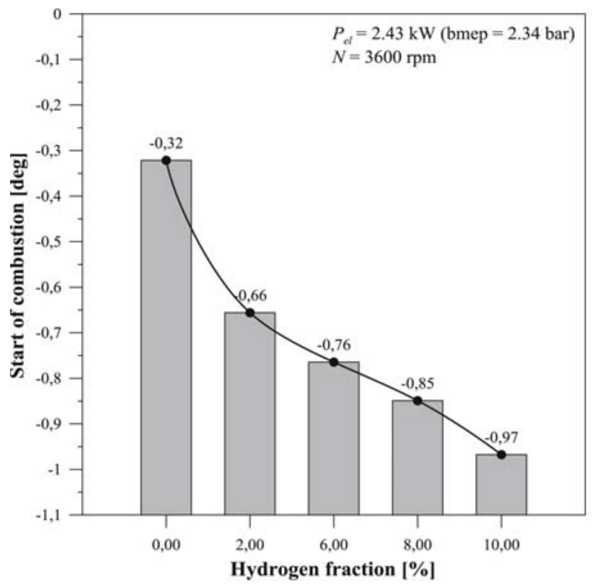

Fig. 12 Effect of hydrogen enrichment on start of combustion

The continuous injection method used in this work was done without significant modifications to the engine or use of complex equipment, thus, enabling its commercial utilization for power generation. However, the continuous method also results in air displacement in the intake manifold and results in lower volumetric efficiency. Therefore, high percentages of hydrogen addition could also result in decrease in engine performance due to less oxygen being present in the cylinder.

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