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INFLUENCE OF WATER ELECTROLYSIS PRODUCTS ON DIESEL ENGINE PERFORMANCE IN COLOMBIA

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Abstract

Restrictions imposed by regulatory frameworks, the high cost of fuels, environmental impacts and the efficiency of internal combustion engines encourage research into reducing the consumption of fossil fuels. Additionally, to think about the alternative energy sources. In compression ignition engines, researchers around the world have been working for years on the use of biodiesel fuel, in order to reduce emissions and the consumption of diesel fuel. In other investigations, water electrolysis products obtained in an HHO gas generator and supplied to an internal combustion engine allow for improving performance, reducing fuel consumption and emissions. HHO gas is a mixture of hydrogen and oxygen resulting from the electrolysis process of water, with energy supplied by an electric source or accumulator. The main objective of this work is to evaluate the influence of an HHO generator products in a diesel engine that operates with diesel fuel produced in Colombia with 10 % biodiesel. The objective of this study is evaluated the influence of gas HHO on mechanical performance, fuel consumption, and polluting emissions in a single-cylinder diesel engine, performing a comparative analysis when the HHO generator operates with different amperages. The results showed a 25 % average reduction in fuel consumption between 1500 by 2500 engine revolutions when the HHO cell operated with 8 amperes. The breaking power maximum value increased a 10 %, and CO and PM10 emissions were reduced by 14 % and 53 %, respectively, at 1000 rpm. It is possible to conclude that supplying water electrolysis products in the fuel-air mixture increases the mechanical performance of a diesel engine and reduces polluting gas emissions. Additionally, research areas are opened in the development of HHO generators and standards for the application of this technology.

Keywords: diesel, engine, electrolysis, performance, emissions, water, power brake, torque, fuel consumption, dynamometer, biodiesel.

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1. Introduction

The global energy sector is seeking to reduce the use of non-renewable and polluting sources; in this sense, the use of hydraulic, solar, and wind energy, among others, in electric power generation systems has increased. On the other hand, the automotive sector is one of the largest energy consumers. As a result, significant efforts have been made over the years to improve the performance of internal combustion engines and reduce fuel consumption and emissions of polluting gases [1]. Consequently, the use of biofuels has been promoted for alternative internal combustion engines with partial or total substitution of fossil fuels. In the case of CI engines, several types of biodiesels have been developed from vegetable oils, animal fats, and waste oils. In these cases, the engine does not require significant changes in its structure, only calibration of the injection system for high biodiesel replacements [2, 3].

Hybrid vehicles combine more than one onboard energy source that can directly or indirectly provide the power needed to operate and have evolved significantly. The most developed hybrid vehicles use an internal combustion engine and electric motors that alternate operation and some of them charge the batteries using the braking system [4]. Hydrogen hybrid vehicles are another option, which uses fuel cells that can significantly increase autonomy [5]. In addition, hydrogen is a non-polluting fuel with advantages such as high flame speed, low ignition energy, high self-ignition temperatures, and a high flammability range [6]. The above characteristics have led several automotive companies to work on the development of hydrogen propulsion systems. However, systems that use hydrogen fuel have some problems to solve. For example, gaseous hydrogen is considered hazardous due to its high volatility, which makes it difficult to store and transport [7].

One way to supply hydrogen to an internal combustion engine is to generate the hydrogen-oxygen mixture (HHO gas) produced by water electrolysis. The process of water electrolysis occurs when power flows between the terminals of a stainless-steel plate cell in which the water molecules are separated as HHO gas. In the case of vehicles, the HHO gas generator is connected to the electrical system [8, 9]. The HHO gas is then injected into the engine's intake manifold to mix with the air and fuel in the combustion chamber. The use of HHO gas generators aims to exploit the good properties of hydrogen as a fuel due to its high calorific value and high flame propagation speed in the engine [10]. Furthermore, some vehicle performance evaluations using these technologies indicate their operation is technically feasible [11]. In laboratory tests with spark-ignited internal combustion engines, the use of HHO gas results in a nearly 5 % increase in thermal efficiency and a similar decrease in fuel consumption, as well as reductions in HC and CO emissions of 5 % and 13.5 %, respectively [12].

In Colombia, heavy freight and passenger transportation use diesel fuel, which still has low sulfur content concentrations, and the percentage of biodiesel is 10 %. Diesel and biodiesel quality conditions are regulated by resolution 40103 of 2021 in Colombia [13]. Regarding the technology of HHO gas generators, there are commercially distributed devices with different characteristics and capacities for which there is no regulation for their installation or use. Considering the above, this research presents the results of the environmental performance tests of a single-cylinder diesel engine fueled with diesel that meets Colombian technical standards. The engine is coupled to a hydraulic dynamometer and an electrolysis cell. As part of the environmental assessment, we conducted tests for emissions of particulate matter, carbon dioxide, carbon monoxide, and unburned hydrocarbons at several engine revolutions (rpm) and operating amperages of the HHO gas generator. The results are presented comparatively over the range of engine revolutions tested.

2. Materials and Methods

2. 1. Equipment and materials

In this project an HHO gas generator installed on a dynamometer bench in the Thermal Machines Laboratory of the Universidad Francisco de Paula Santander (**Fig. 1**). In the actual system, the HHO gas generator is installed in the vehicle's electrical system. In the laboratory, we installed it to a power source that allowed multiple electrical operating conditions, such as the amps of each test. **Fig. 1** also shows the single-cylinder diesel engine, the hydraulic dynamometer, and the gas analyzer.

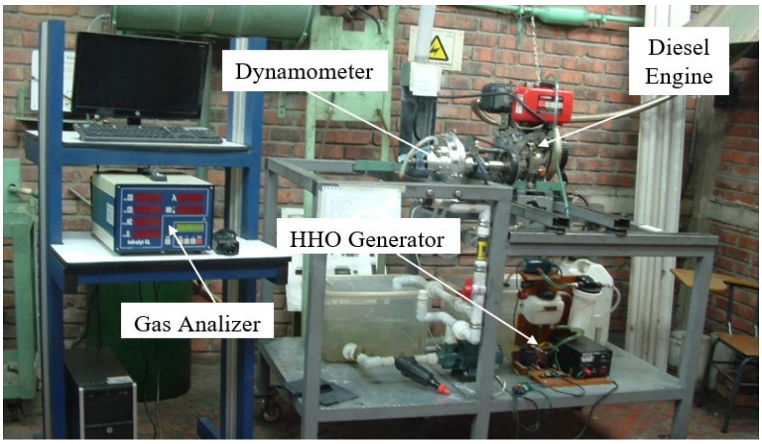

Fig. 1. Bench with the hydraulic dynamometer

Fig. 1 shows the following equipment: a single-cylinder Kama engine, the HHO gas generator consisting of a tank, a bubbler, a cell, and an electrical source. It also shows a hydraulic dynamometer with a load cell and an encoder to measure torque, power, and engine speed. This information is processed by a data acquisition card programmed in LabView. In **Table 1** details the characteristics of these systems.

Table 1
Test Bench Equipment features

HHO generator	
Reference	HydroClubUSA
Cells Number	9
Capacity	2.25 (l/min)
Peak Current	20 (A)
Voltage	12 (V)
Dynamometer	
Capacity	37.2 (kW)
Rotor Diameter	0.203 (m)
Water flow	29.4 (l/min)
Load Cell	Utilcell 300
Encoder	Leni Selkin (CB H100HC)
Engine	
Diesel engine	Kama (KM178F)
Peak power	4.47 kW
Fuel	Diesel (Direct Injection)
Volume	296 (cm^3)
Compression Ratio	20:1

In addition, **Table 2** shows the technical characteristics of the gas analyzer used to measure the pollutant emissions of the engine.

Table 2
Characteristics of the gas analyzer

Item	Reference		
Brand	Infralyt CL		
O_2 Meter	Electrochemical Dispersion		
Item	**Measuring range**		
	Min	**Max**	**Units**
O_2	0	25	% Vol.
HC	0	2500	% Vol.
CO_2	0	20	% Vol.
CO	0	10	% Vol.

For the performance tests, we used commercial diesel fuel with a 10 % biofuel blend following current regulations [13]. The characteristics of diesel and biodiesel purchased and distributed in Colombia are in **Table 3**.

Table 3
Characteristics of diesel and biodiesel fuels

Diesel fuel specifications in Colombia [13]				
Parameter	**Unit**	**Limits**		**Test**
		Min	**Max**	
Sulfur content (As of 5-2021)	Mg/kg	N/A	50	ASTM D5453-19 ISO 20846-19
Total aromatic hydrocarbons	% (m/m)	N/A		ASTM D5186-20
Polycyclic aromatic hydrocarbons	% (m/m)	N/A	8.0	ASTM 12916-19
Cetane number	N/A	48	N/A	ASTM D613-18 ISO 5165-17
Flash point	°C	52	N/A	ASTM D 93-20 ISO 2719-16
Density (a 15°C)	Kg/m^3	860	900	ASTM D1298-12 ASTM D4052-18
Cetane number	mm^2/s	3.5	5	ASTM D613-18 ISO 5156-17
Flash Point	°C	52	N/A	ASTM D 93-20 ISO 2719-16

2. 2. Description of the tests

Considering the operating conditions of the hydraulic dynamometer and its instrumentation, the recommendations of the HHO cell manufacturer, the diesel engine's characteristics, and the literature review [14, 15], the following tests were applied.

Fuel consumption test were developed with the engine operating on diesel and diesel + HHO. Then, with the engine running at maximum speed, the load is applied with the dynamometer to brake it and keep it at the desired rpm. The testing started at 1000 rpm until to 3500 rpm. **Fig. 1** shows a calibrated test tube containing fuel and allowing its variation to be measured. For each test, we measured the volume of fuel consumed in the test tube at the end of one minute for each defined engine revolution. The mass of fuel consumed is obtained by dividing the volume by its density of 853 kg/m^3 [16].

The torque and power test are performed simultaneously with the fuel consumption test. According to the recommendations, the estimated torque and power data are reported from the information provided by the load cell and the rpm meter [17], the calculations are performed in LabView. The CO, HC, and CO_2 emissions values are measured in the performance tests at the engine speeds evaluated and registered by the gas analyzer equipment. We use the method described by the literature [18] to measure the particulate matter, with samples taken in a filter using a vacuum pump and, after drying, weighed to determine the amount emitted.

3. Results and Discussion

3. 1. Mechanical and energy performance

The most characteristic parameters of the mechanical performance of an internal combustion engine are braking power and torque. In this sense, we established a baseline and evaluated these two parameters with the engine operating in its original conditions and without the addition of hydrolysis products.

Fig. 2 presents the braking power in kilowatts (kW) as a function of engine rpm. This figure displays that as the engine load increases and the engine speed increases, the braking power W_b starts to increase continuously up to a maximum value where the high speed limits the combustion duration and the adequate filling of the cylinder with the air-fuel mixture and W_b starts to decrease.

Fig. 2 also shows the evolution of engine torque (*T*) in Newton-meters (*N-m*). Unlike power, **Fig. 2** shows that torque reaches its maximum values at low engine speeds and decreases continuously. The above is because as the engine speed increases, the time the expansion obtained in the combustion process drives the piston reduces [19].

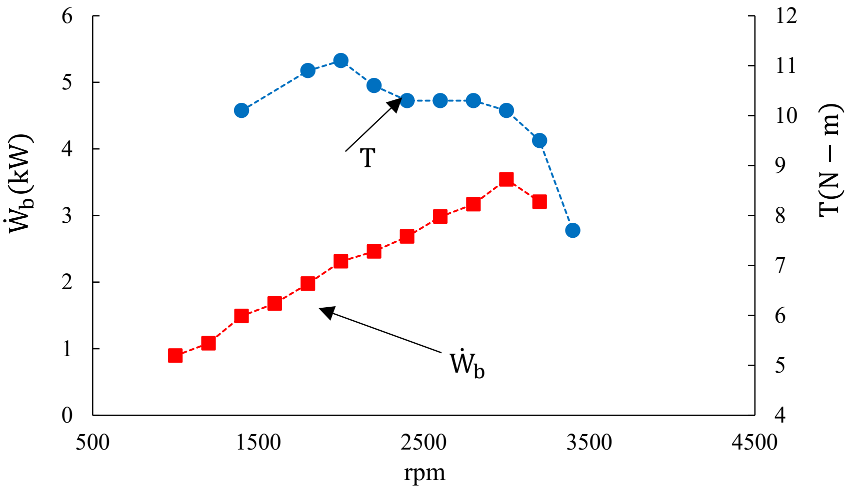

Fig. 2. Diesel engine torque and power base curves

Once we drew the baseline of **Fig. 2**, we tested the engine by introducing the electrohydrolysis products into the intake manifold. According to literature [19], the HHO gas production is higher as the amperage in the cell increases. Therefore, this paper evaluated the influence of HHO gas when the cell operated at 4, 6, and 8 amps. In addition, the HHO cell tank contains distilled water and a catalyst that promotes the formation of HHO gases, in this case, 5 grams of sodium hydroxide per liter of water. Sodium dioxide not only increases water temperature but can also help to improve engine performance [20].

Hydrogen has a higher calorific value and a faster flame speed than traditional liquid fuels, allowing for a more efficient combustion process. Furthermore, adding oxygen to the intake improves the combustion process inside the engine and reduces the quantity of unburned fuel [21]. The high flame speed results in a shorter ignition delay and combustion period, which reduces heat losses, and raises the pressure and temperature in the combustion chamber more rapidly. In addition, this reduces knock, vibration, and noise in the engine. Finally, the hydrolysis products extend the flammability range and allow a higher power to be delivered over a wider rpm range, as shown in **Fig. 3**.

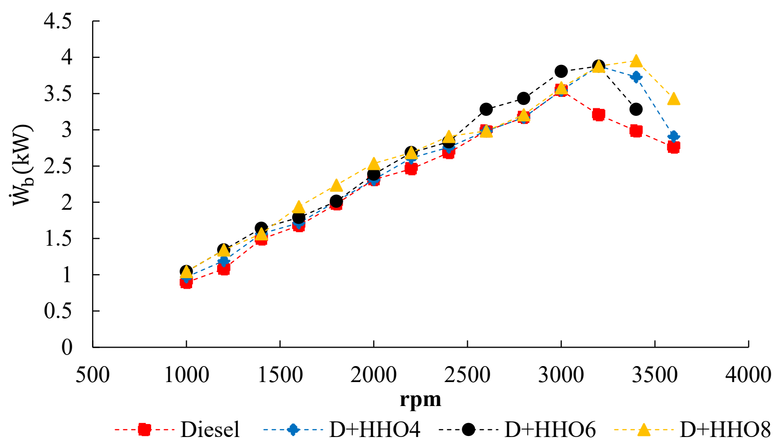

Fig. 3. Influence of HHO cell on engine braking power

Fig. 3 shows the evolution of the engine braking power, comparing the initial condition with the use of the HHO cell. Most of the configurations increased the engine performance. For example, the D+HHO8 configuration (HHO generator operating at eight amps) achieved higher powers in 13.1 % on average between 1500 and 2500 rpm, after 3000 rpm reported a difference of 11.58 % in the maximum values concerning the original configuration. The D+HHO6 configuration (HHO generator operating at six amps) outperforms the diesel configuration over the entire range, especially after 2000 rpm, where the differences are 10 %. However, the peak of the power curve is at a lower rpm than the D+HHO8. The D+HHO4 configuration (generator operating at four amps) barely outperforms the original configuration after 3000 rpm.

The components of HHO gas have low ignition energy and high flame speed. Therefore, the HHO-diesel mixture ignited and burned faster than pure diesel fuel, improving torque, especially at high engine rpm.

Fig. 4 shows the engine torque versus speed for the different configurations evaluated. The D+HHO8 configuration presents the best torque values in the speed range below 200 and above 3000 rpm. The D+HHO4 and D+HHO6 configurations show intermediate torque values, although generally above the diesel configuration, with average increases of 7.1 % and 6.2 %, respectively.

The products of electro-hydrolysis provide an energy contribution that, due to its high calorific value and other advantages described, improves the combustion process, making it easier to burn as much fuel as possible [21] and reducing the initial fuel consumption of the engine.

Fig. 5 illustrates the evolution of the fuel consumption $\dot{m}_f$ of the engine in the tested configurations. The D+HHO8 configuration has the lower fuel consumption in the evaluated speed range; this decrease was 25 % on average. The D+HHO4 and D+HHO6 configurations have intermediate values but are always lower than the original engine configuration.

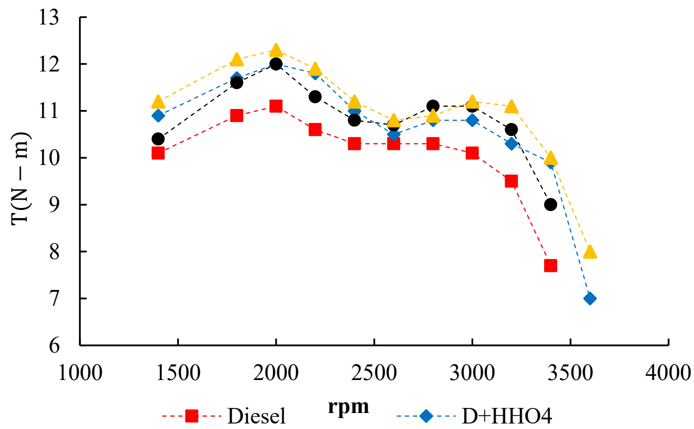

Fig. 4. Influence of HHO cell on engine torque

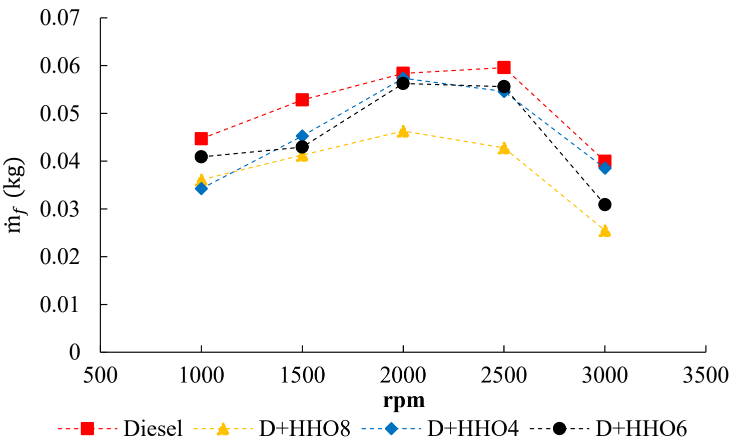

Fig. 5. Influence of HHO cell on fuel consumption

3. 1. Environmental performance

As a complement to the mechanical performance of the engine, we collected data to analyze the environmental performance under the influence of the HHO generator.

Fig. 6 shows the results of the carbon monoxide (CO) emissions at different engine speeds, where emissions decrease by enriching the intake with products from the HHO generator. For example, at 1000 rpm, the most significant decrease in CO occurs at the maximum amperage used (D+HHO8) with a difference of 11.5 %. At 2000 rpm, the carbon monoxide emissions decrease in all configurations with HHO gas supply emissions, and at 3000 rpm, the differences are minimal. The decrease in CO is due to the decrease in the concentration of carbon in the mixture formed inside the engine with fuel, air, and the products of the HHO generator. In addition, the increase in available oxygen also helps the reduction of carbon monoxide emissions.

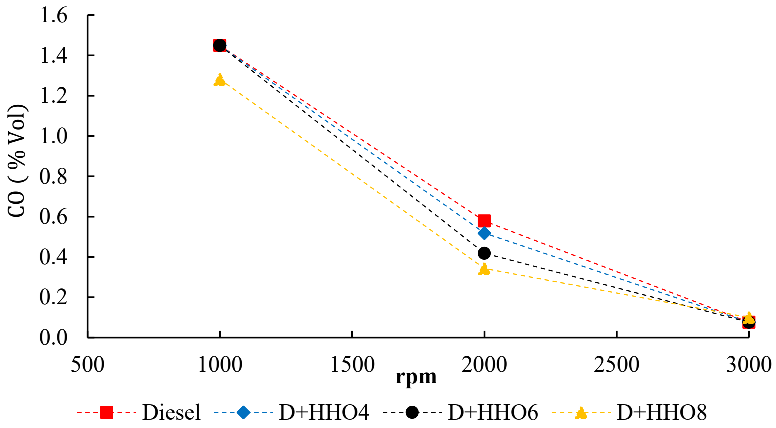

Fig. 6. Influence of HHO cell on carbon monoxide emissions

The absence of carbon in the hydrolysis products, besides reducing CO emissions, also facilitates the reduction of carbon dioxide (CO_2), as seen in **Fig. 7**. Especially at low and medium engine speeds, the reduction in CO_2 emissions are between 7 % and 22 %. At high speeds and due to the higher flame speed, that the HHO gas can generate, the conversion of CO to CO_2 is made easier when the temperature increases [22]. In this sense, at 3000 rpm the CO_2 emission increases between 28 % and 44 % when using the HHO generator gases.

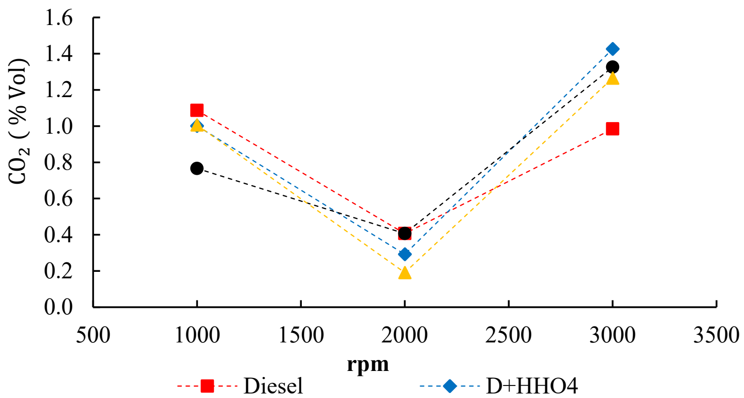

Fig. 7. Influence of HHO cell on carbon dioxide emissions

Fig. 8 presents the hydrocarbon emission results for the single-cylinder engine. The figure shows that as the amperage in the HHO generator increases and more products are generated, HC emissions are reduced, especially at low engine speeds. In addition, complete combustion is due to the longer time available for fuel oxidation and the presence of hydrogen and oxygen in the air-fuel mixture. Therefore, the condition with the lowest HC emissions occur in the D+HHO4 configuration at 1000 rpm with a decrease of about 76 %. As the engine speed increases, the influence of the HHO generator products on the HC emissions decreases; this can be observed at 3000 rpm, where the differences do not exceed 3 %.

Finally, the rate of particle formation and particle oxidation rival each other in determining the amount of particulate matter emitted in a diesel engine. Although these processes are not known in detail, the increase in oxygen in the mixture due to the presence of HHO gases helps to reduce particulate matter emissions.

Fig. 9 shows the emissions of particulate matter (PM10), where at low engine speeds, reductions of approximately 47 % can be achieved when the engine operates the D+HHO8 configuration. At mid-range engine speeds, the maximum PM10 emission reduction is approximately 28 %. When the motor runs at 3000 rpm, emissions are low, and the maximum decrease in particulate matter emissions is about 82 % when working in the D+HHO4 configuration.

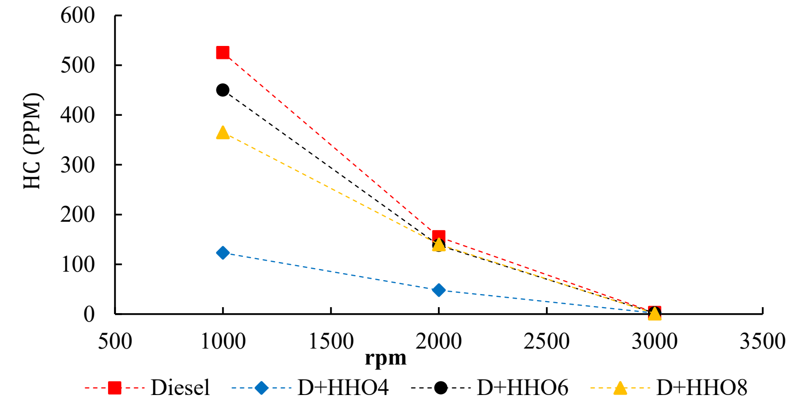

Fig. 8. Influence of HHO cell on unburned hydrocarbon emissions

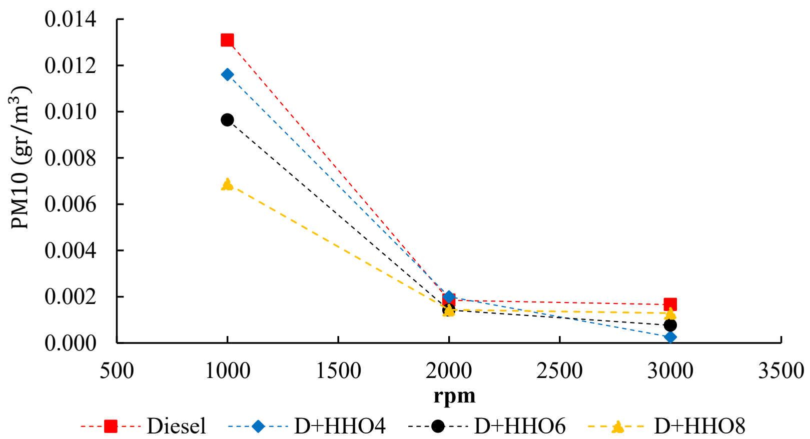

Fig. 9. Influence of HHO cell on particulated matter emissions

This research was developed in a laboratory, similar results could be expected in operating a stationary Diesel engine, considering that its functioning does not vary. However, it should be noted that an industrial engine represents higher power, torque, and fuel consumption.

Future work can focus on applying these systems in mobile engines for transportation. In these applications, it is required to evaluate the HHO gas supply according to the motor load parameters and evaluate a control unit that allows regulating the voltage and electrolysis current as a function of engine speed.

Although this paper shows the environmental and energetic benefits of applying HHO generators commercialized in Colombia, evaluating aspects related to safety and their adequate assembly would be convenient. Moreover, future research should study the generator's influence on the engine's electrical system.

4. Conclusions

This research evaluated the influence of the products of an HHO gas generator on the performance of a single-cylinder diesel engine, finding improvements in mechanical performance. We observed an increase in torque and power in all speed ranges, even in the maximum power range, which also increases with hydrolysis products. In addition, the increase in the amperage of the HHO generator generated more products that improved the mechanical performance of the engine.

According to the energetic properties of hydrogen and oxygen supplied by the HHO generator and in the proposed mixtures, a reduction of fuel consumption is achieved, which is possible in a wide range of engine revolutions. Therefore, this can become a source of savings in operating internal combustion engines and reducing pollutant emissions.

Including the products of the HHO generator in the air-fuel mixture reduces the emissions of pollutant gases from the diesel engine. The greatest reductions in emissions resulted in around 1000 rpm; after 2000 rpm, the differences are minimal or even increased, as in the case of carbon dioxide. While increasing the operating amperage in the HHO generator reduces fuel consumption and mechanical performance, not always achieved with pollutant emissions.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

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Data availability

Manuscript has no associated data.

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