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PERFORMANCE ANALYSIS OF AN INTERNAL COMBUSTION ENGINE POWERED BY GASOLINE AND HYDROGEN

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Abstract. Fossil fuels are energy sources widely used in the transportation sector, but are also exhaustible sources and pollutants. Many studies have been carried out about alternative sources capable of ensuring efficiency in energy conversion and reduction of current pollution levels. The addition of hydrogen to the engine supply seems to have significant practical advantages due to the properties of that gas, although its production by electrolysis is costly. The main goal of this study is to investigate the engine performance using hydrogen as supplementary fuel in an internal combustion engines (ICE) powered by gasoline. Hydrogen was produced by an alkaline water electrolyser and injected into the air intake. Three different flow rates of hydrogen were used as supplementary fuel. The experiments were carried out in an inertial dynamometer. The performance curves of engine torque and power were built for a range of 1000 to 6500 rpm. The fuel consumption and hydrocarbons (HC), carbon monoxide (CO) and carbon dioxide (CO_2) emissions were evaluated for three different rotation speed and three different flow rates of hydrogen. The results showed some contribution of the hydrogen to the increase of torque and power and to the reduction of the specific consumption of gasoline. Furthermore, the experimental tests allowed making important analysis about the use of hydrogen in SI engines.

Keywords: *internal combustion engine, spark ignition engine, hydrogen, electrolysis process, pollutants emission*

1. INTRODUCTION

Due to the limited fossil fuel resources and severe energy safety issues, more and more researchers have focused on investigating non-petroleum based, clean and renewable alternative fuels. In this context, the use of hydrogen can be qualified as a good alternative, as one of its main benefits is to promote the reduction of carbon compounds in the combustion products (Almeida *et al*., 2015). Furthermore, hydrogen has unique physicochemical properties that can enhance combustion properties and engine performance (Wang *et al*., 2011a).

According to the literature, there exist a lot of research confirming the potential of the use of hydrogen as fuel. The diffusion coefficient of hydrogen is larger than gasoline. For that reason, it improves the homogeneity of combustible mixture. The enhanced mixture homogeneity benefits the fast and complete combustion (Wang *et al*., 2011b). As a consequence, there is an increase in engine efficiency and lower production of soot and unburned hydrocarbons. (Zhao *et al*., 2010). The flame speed of hydrogen (237 cm/s) is five times as large as that of gasoline (42 cm/s) and therefore it may improve thermal efficiency, because the combustion of hydrogen engines is much closer to ideal constant volume combustion (Karagoz *et al.*, 2015). This results in increased fuel burning rate, shortened combustion period and the possibility to operate with higher cylinder pressures. Consequently, the addition of hydrogen produces improved engine thermal efficiency, increased mean effective pressure and reduced fuel consumption (Almeida *et al*., 2015). In addition, hydrogen has a wider flammability range than other fuels, which allows the engine to run with a wide range of air-fuel ratios (Yilmaz *et al*., 2010). However, because of the narrow flammability of gasoline, the original engine suffers a slow burning or even incomplete combustion at high excess air ratios (Wang *et al*., 2014). The quenching gap of hydrogen is less than gasoline and thus hydrogen addition will allow the air-fuel mixture to travel closer to the cylinder wall and farther into the crevices before being extinguished, thereby promoting complete combustion (Ceviz *et al*., 2012).

Hydrogen in vehicles can be used in two modes, namely fuel cells and hydrogen fuelled internal combustion engines (ICEs). Although fuel cells have many advantages, their high cost and short life span have become the concerns of their wide application. The ICEs, in turn, are based on a well-known technology, so that the use of hydrogen in these engines can occur simply and quickly. In addition, the current costs for the addition of hydrogen to internal combustion engines are considerably lower than with fuel cells (Sopena *et. al*, 2012).

Hydrogen has very low density, so it can be stored by compression in tanks. In order to eliminate hydrogen storage problem, hydrogen can be produced on-board through the electrolysis of water. In this way, there is no need for a high pressure tank. In the on-board hydrogen production systems, hydrogen is only produced while the engine is being operated.

In this context, the main goal of this study was to investigate the effects of the use of the hydrogen, produced by alkaline water electrolysis, as additional fuel in an internal combustion engine. The engine performance was evaluated by means of the measurements of torque, power, specific fuel consumption and emissions of HC, CO and CO_2.

2. MATERIALS AND METHODS

The scheme of the projected electrolyser is shown in Figure 1. The reactor was constructed in cylindrical format with a volume of approximately 1805 cm^3. The upper end of the reactor is designed to receive the necessary electrical connections, as well as contain the fluid passageways. Two stainless steel 304 cylinders (diameter ¾ in) were used as electrodes.

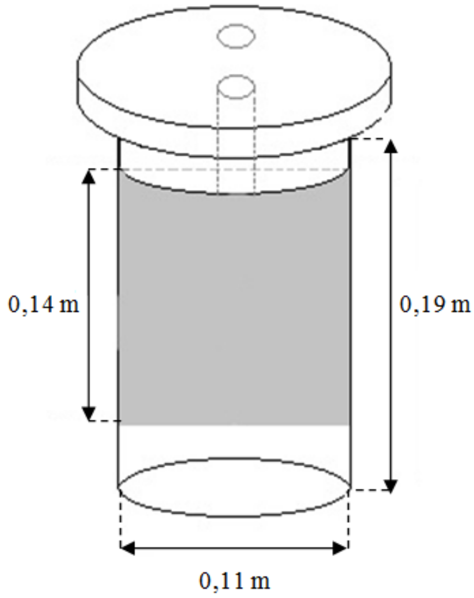

Figure 1. Scheme of the electrolyser

An acrylic plate was placed in the center of the electrolyser between the two electrodes, in order to prevent the mixing of the produced gases. However, since electrolysis occurs, there is a need for ionic transfer between the electrodes. The plate had a length shorter than the height of the reactor, allowing the ionic contact in the lower part of the cell and avoiding the mixing of the gases.

The hydrogen produced by the electrolyser was added to air inlet of an internal combustion engine. The experiments were performed in a spark ignition engine, four-stroke, powered by gasoline, which outfit a vehicle Fiat Palio ELX 1.6 16V, year 1990. The main engine specifications are summarized in Table 1.

Table 1. Technical specifications of the engine.

Definition	Value/Specification
Manufacturer e type	Palio ELX 1.6 16V, 1999
Fuel	Gasoline
Displacement volume (cm^3)	1581
Number of cylinders	4
Number of valves per cylinder	4
Bore x stroke (mm)	86.4 x 67.4
Compression ratio	10.15:1
Fuel system	Multi-point fuel injection
Maximum brake power (hp/rpm)	99.62/5500
Maximum torque (N.m/rpm)	140.24/4500

The engine performance was evaluated by means of characteristic curves of torque and power, which were constructed through tests carried out at an inertial dynamometer. These experimental tests were performed using three different flow rates of hydrogen (0, 150 e 300 mL/min), making possible to analyze the hydrogen effects over the engine performance. The specific fuel consumption and the hydrocarbons (HC), carbon monoxide (CO) and carbon dioxide (CO2) emissions were evaluated for three different rotation speeds and three different flow rates of hydrogen. Thus, an experimental design was created with three levels and two variables.

The rotational speeds were maintained by means an inertial dynamometer (operating range: 1000 to 6500 rpm). In continuous load mode, the dynamometer used the electromagnetic brake to keep the motor in a constant rotation that was specified for each experiment: 1573 ± 4, 2692 ± 11 e 3879 ± 7 rpm. The hydrogen flow rate was modified through the current applied to the electrolysis process. An electronic control circuit was used to change the electric current of the process according to the desired value. Hydrogen was produced through electrolysis with currents of 7.0 and 23.5 A. These currents were chosen in preliminary tests performed with the electrolyser.

A rotameter was used to measure the flow rate of hydrogen. However, due to the instability presented by the hydrogen production system, the rotameter showed high variations in the measurements. For an electric current of 7 A, the reading of the rotameter was of 150 mL / min, with a variation of ± 50 mL/mim. For an electric current of 23.5 A, the reading was of 300 mL/min, with a variation of ± 100 mL/min. Despite of the high level variations, experimental data were obtained when the stability of the measurement was observed.

The levels of the experimental design are presented in Table 2, where Q_V is the hydrogen flow rate and *v* is the rotational speed.

Table 2. Levels of the experimental design

Q_V (mL/min)	*v* (rpm)
0	1573 ± 4
150 ± 50	2692 ± 11
300 ± 100	3879 ± 7

It were performed nine experiments with replicates at all points, totaling 18 experiments. The averages were considered in the presentation of the results. The experimental design was made to evaluate as responses the specific fuel consumption (SFC) and the pollutant emissions.

The Figure 2 presents a scheme of the experimental unit prepared to carry out the experiments. The hydrogen produced by the electrolyser was sent to a bubbler. The bubbler prevents the electrolytic solution contained inside the electrolyser could be sucked directly into the engine. Subsequently, the hydrogen was routed directly to the engine air intake manifold.

The specific fuel consumption (SFC) was obtained by the ratio between the fuel consumption (variation of fuel mass per unit of time) and the power obtained by the dynamometer at the speed of the experiment, according to Eq. (1).

$$SFC = \frac{\dot{m}_f}{N} \quad (1)$$

where is the specific fuel consumption (g/kWh), (g/h) is the consumed gasoline mass flow rate and is the the power obtained by the dynamometer in kW.

The gravimetric method was used to obtain the consumed gasoline mass flow rate. For this, the injection of gasoline into the engine was performed through a reservoir placed under a digital scale. With the variation of mass of fuel during the time of the experiment, it was possible to obtain the mass flow rate of gasoline.

The exhaust emissions (HC, CO and CO2) were measured by the equipment PC Multigas, with infrared gas sensor (NDIR).

A statistic treatment was carried out for the SFC and the pollutant emission, providing models and response surfaces to represent these parameters in function of the studied variable.

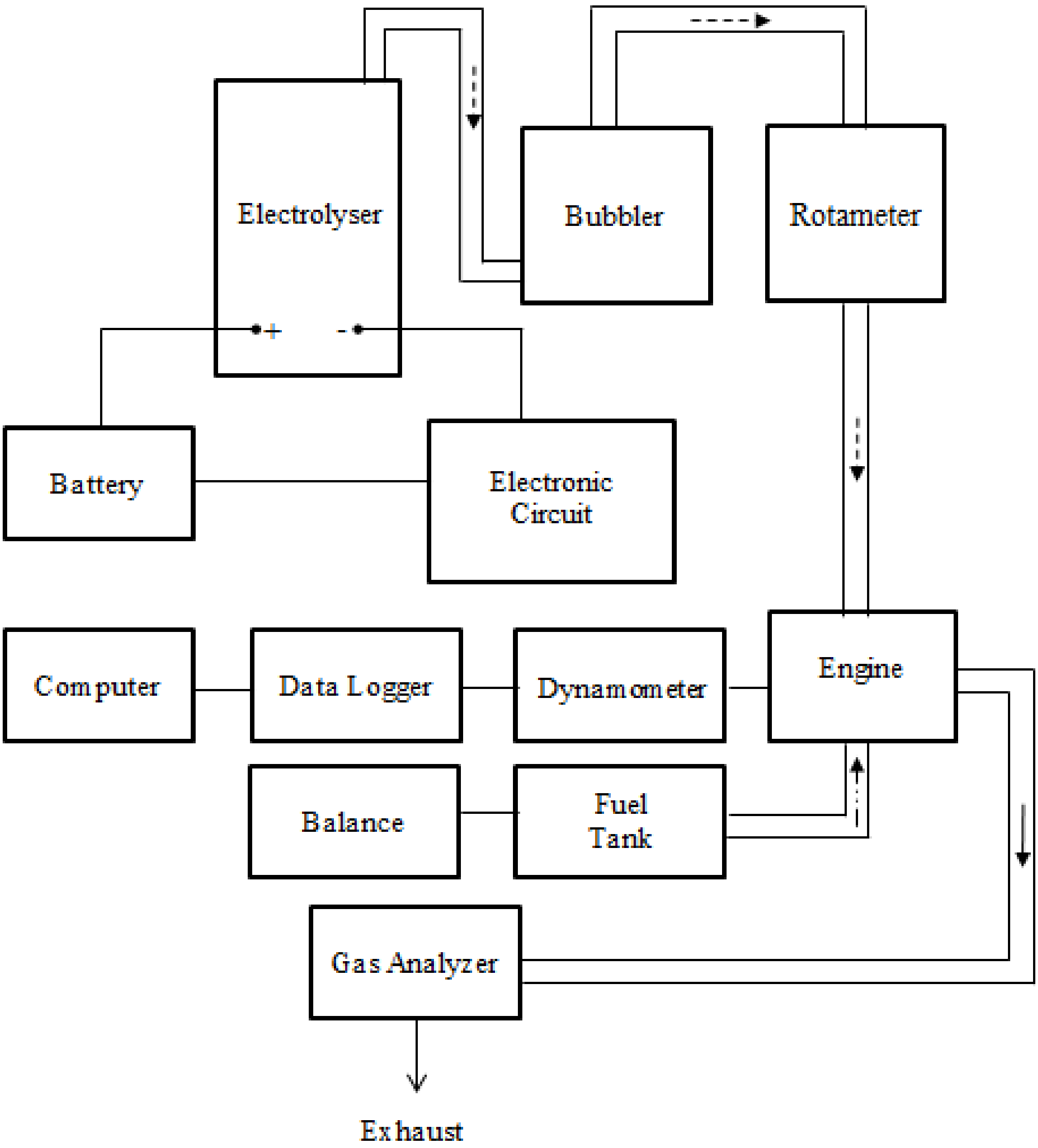

Figure 2. Scheme of the experimental unit in which (- - ▶) represents the direction of flow of hydrogen by the system, (— · · ▶) represents the direction of flow of gasoline and (——▶) represents the direction of combustion products.

3. RESULTS AND DISCUSSION

The influence of the hydrogen flow rate added as supplementary fuel on the torque (T) and the power (N) is presented in Figures 3 and 4, respectively. The results show some contribution of the hydrogen to the increase of torque and power. However, this effect was observed only at the highest hydrogen flow rate (300 ± 100 mL/min), while at the intermediate flow rate (150 ± 50 mL/min) no significant differences were found.

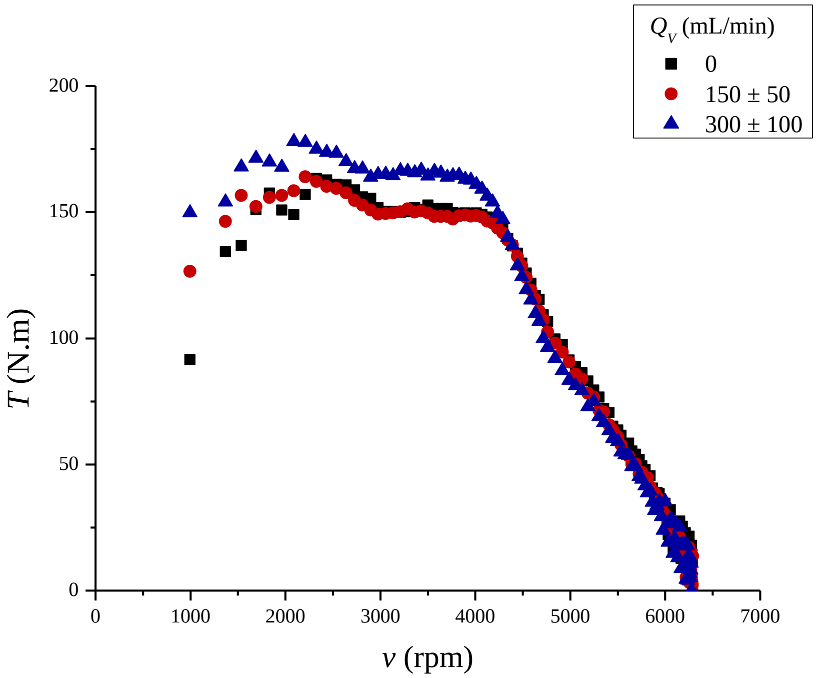

Figure 3. Influence of hydrogen flow rate on the engine torque (*T*) characteristic curve

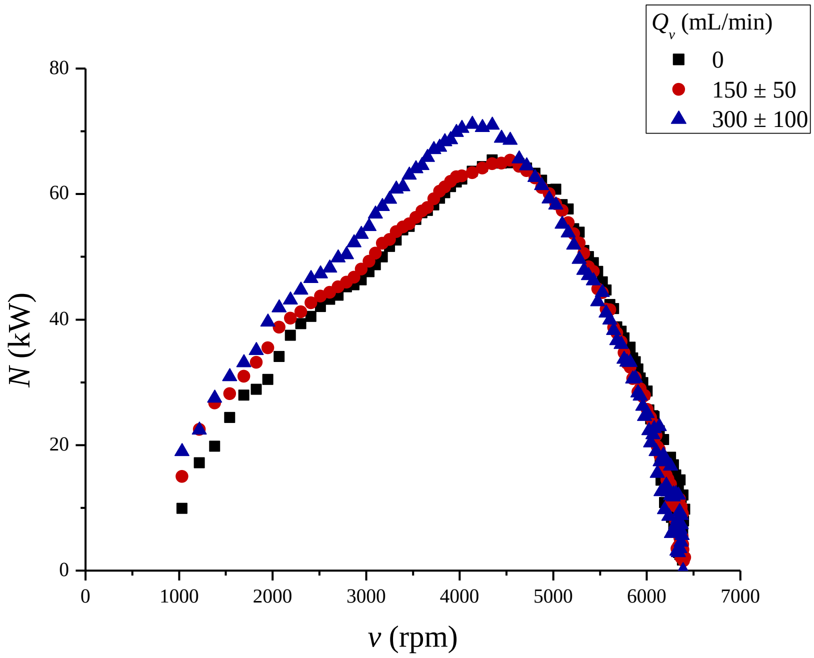

Figura 4. Influence of hydrogen flow rate on the engine power (*N*) characteristic curve

In addition, it was possible to notice that at rotations above approximately 4500 rpm, the addition of hydrogen in the two analyzed flows did not result in changes in the torque and power. This fact could have occurred due to the lack of adequate time for hydrogen production by the electrolyser at higher speeds of rotation, since in these conditions the engine performs more cycles, drawing air, and consequently, hydrogen, faster.

The maximum brake torque (MBT) had an increase of 5.8%, while the maximum power (MBP) had an increase of 7.6%. It is believed that the increasing of torque and power had been occurred due to the rising of overall efficiency, including combustion and thermodynamic efficiency, as mentioned by Karagoz et al. (2015). This fact could be explained because the hydrogen's heating power per kg is higher than gasoline. In addition, the temperature and pressure is higher in-cylinder with hydrogen added to gasoline combustion thanks to high flame speed of hydrogen.

Figure 5 shows the curves of SFC, as a function of the engine speed, for the three different flow rates of hydrogen.

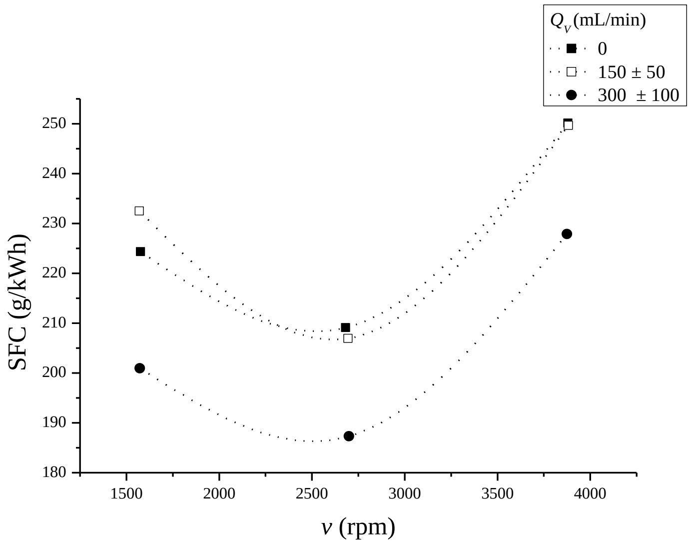

Figure 5. Specific Fuel Consumption (SFC) in function of the engine speed for three different hydrogen flow rates.

The behavior of the SFC curves is in agreement with the literature. The specific fuel consumption pass through a minimum point at intermediary speeds. There were no significant differences in the specific fuel consumption with the addition of hydrogen at the flow rate of 150 mL/min. However, there were reductions between 0.20 to 10.43% in the SFC with the addition of 300mL/min of hydrogen when compared to the operation without hydrogen. A statistical treatment was performed considering a significance level of 15%. This value is a little higher than that often used, but it is acceptable due to the many factors that affect the engine operation, such as ignition and injection system. The statistical analysis allowed to obtain the response surface presented in the Figure 6 and the Equation (2).

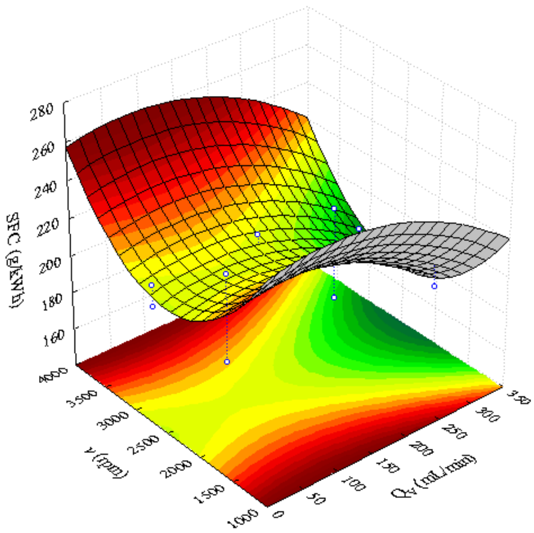

Figure 6. Response surface for the specific fuel consumption (SFC).

$$U(X_1, X_2) = 209.83 -11.25X_1 -13.07X_1^2 +11.65X_2+29,79X_2^2 \qquad R^2= 0.72 \qquad (2)$$

where U is the specific fuel consumption, X_1 is the flow rate of hydrogen, X_2 is the engine speed, in coded variables in coded variable. The R^2 is the determination coefficient

The determination coefficient of 0.722 for the model presented in Eq (20) shows the difficulty in the adjustment of the data, probably due to the high deviations at low speed experiments. The linear coefficients of the hydrogen flow rate (-11.25) and the speed (+11.65) presented in Eq (2) were similar in magnitude, but with opposite effects. Thus, the negative effect for hydrogen flow rate proofed its contribution as supplementary fuel to reduce the specific consumption of gasoline. Since flame speed of hydrogen is five times as large as that of gasoline, higher flame speed of the mixture has a positive contribution on thermal efficiency. Moreover, the shorter burning duration and the wider flammability range of the hydrogen result in a more efficient combustion when blended to gasoline.

The Figure 7 shows the average emissions of unburned hydrocarbons, as a function of engine speed for the three different flow rates of hydrogen.

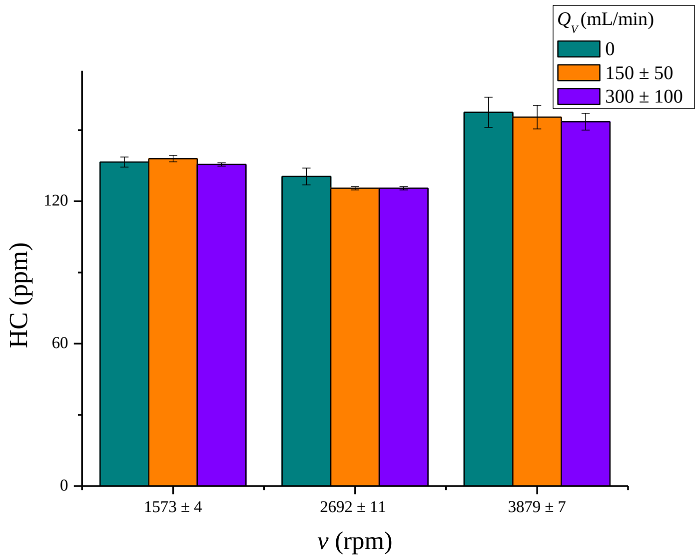

Figure 7. Emissions of unburned hydrocarbons, as a function of engine speed for three different flow rates of hydrogen.

It is possible to notice that the addition of hydrogen caused a slight decrease in the emission of these pollutants at all speeds of rotation. An average reduction of 0.20 to 3.83% was obtained in relation to the operation without hydrogen.

The flame quenching distance of hydrogen is shorter than gasoline, which can reduce the hydrocarbon emissions caused by the loss of heat. In addition, the diffusion coefficient of hydrogen is larger than gasoline, for that reason, hydrogen improves the homogeneity of combustible mixture, making combustion more complete, decreasing the HC formation.

The statistical treatment of the data was performed, obtaining the response surface presented in the Figure 8 and the non linear equation (3).

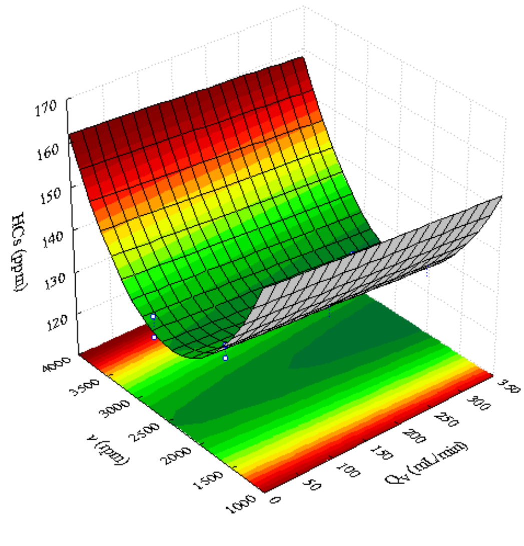

Figure 8. Response surface for the emission of unburned hydrocarbons (HC).

$$W(X1, X2)=127.17-1.67X_1 +9.42X_2+18.92X_2^2 \qquad R^2= 0,95 \qquad (3)$$

where W is the for the emission of unburned hydrocarbons, X_1 is the flow rate of hydrogen and X_2 is the engine speed, in coded variables.

There was a well adjustment of the experimental data to the model, which can be observed by the determination coefficient. The linear effect of the velocity (+9.42) was about six times greater than the effect of the hydrogen flow (-1.67), evidencing the greater influence of the velocity in the emission of unburned hydrocarbons, which may be justified by the small amount of hydrogen added to the engine. At the same time, although small, the negative effect obtained for the flow rate of hydrogen proves the positive result of the addition of the gas in the reduction of hydrocarbons.

The average emissions of carbon monoxide, as a function of engine speed, in the different flow rates of hydrogen are presented in the Figure 9.

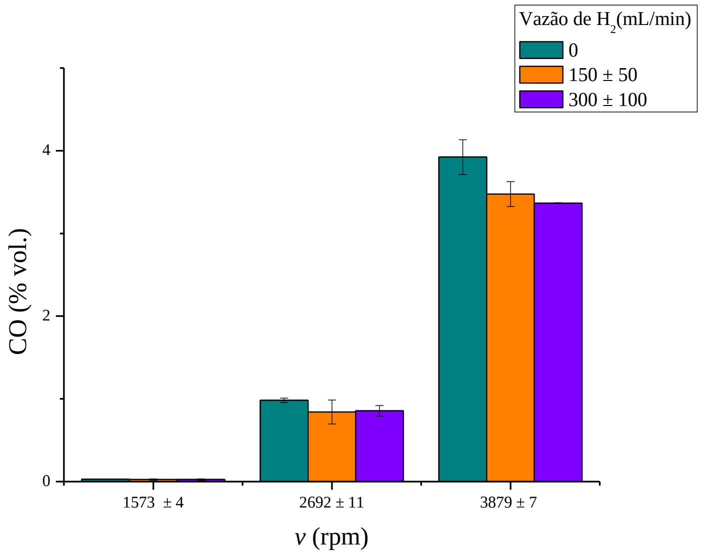

Figure 9. Emissions of carbon monoxide, as a function of engine speed, for three different flow rates of hydrogen.

According to the Figure 9, the addition of hydrogen reduced the CO emissions in the two analyzed flow rates. The decreases varied between 11.40 and 14.24%, when compared to the operation without hydrogen. The combustion of a blended of hydrogen and gasoline emits less CO, since H_2 fuel does not include any carbon element. Furthermore, hydrogen has unique combustion properties, as already cited, increasing the engine performance.

The Figure 10 shows the response surface obtained from the regression equation for carbon monoxide emission and represented by Equation (4).

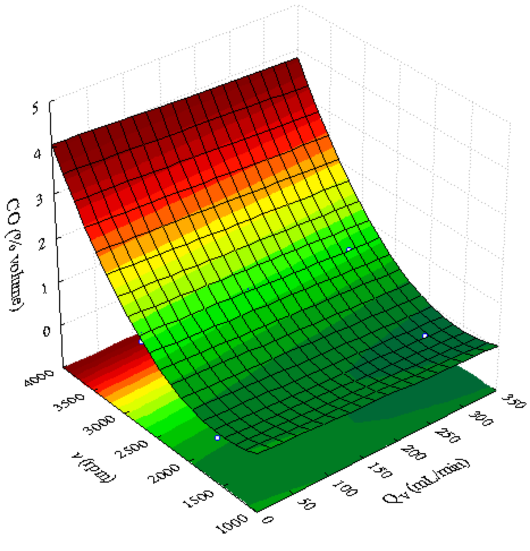

Figure 10. Response surface for the emission of monoxide carbon (CO).

$$Y(X1, X2) = 0.90- 0.12\, X_1 + 1.78X_2 + 0.91X_2^2 \qquad R^2 = 0.99 \qquad (4)$$

where Y is the for the emission of carbon monoxide, X_1 is the flow rate of hydrogen and X_2 is the engine speed, in coded variables. R^2 is the determination coefficient.

From the analysis of Figure 10 and the regression coefficients, it can be stated that the influence of the engine speed of rotation is much more important than the flow of hydrogen in the emission of carbon monoxide. In addition, it can be observed that the increase of the rotation speed contributes positively to the increase of the emission of this pollutant, while the increase of the hydrogen flow decreases the emissions. The experimental data were well adjusted.

Figure 11 shows the mean values of carbon dioxide emissions, as a function of engine speed, at the different flow rates of hydrogen.

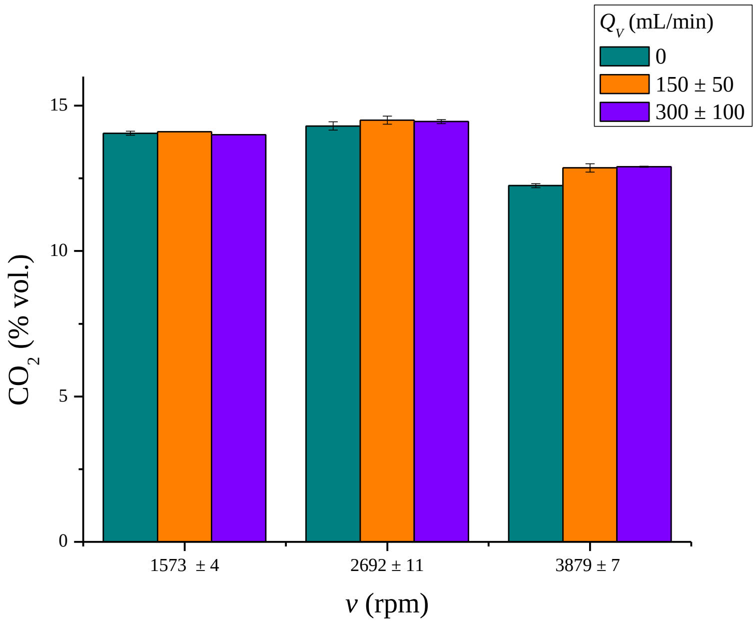

Figure 11. Emissions of carbon dioxide, as a function of engine speed, in the different flow rates of hydrogen

According to Figure 11, it was possible to notice that there was a small increase in the emission of carbon dioxide with addition of hydrogen. There was an average increase of 0.38 to 5.31% in relation to the operation without hydrogen.

Combustion with hydrogen as a supplementary fuel contributes to the lower emission of carbon compounds, since H_2 fuel does not include any carbon element. However, this expected reduction in carbon dioxide emissions may have been counterbalanced by the oxidation of CO to CO_2, due to the more complete combustion provided by the addition of hydrogen, evidenced by the reduction of carbon monoxide.

The response surface is presented in the Figure 12 and the equation in the Equation (5).

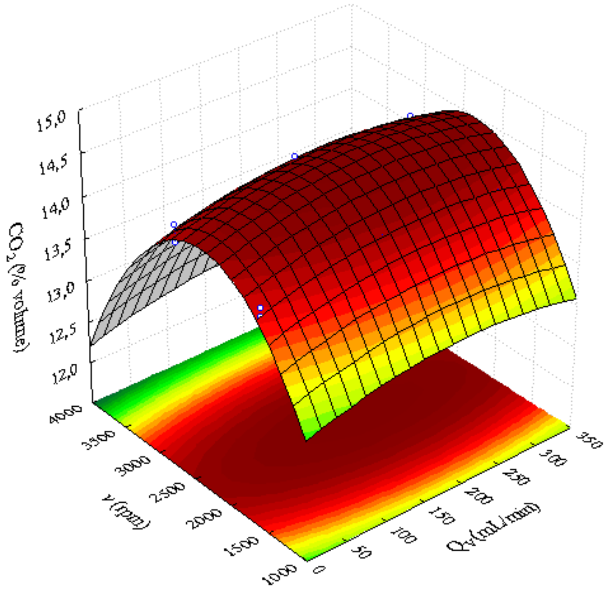

Figure 12. Response surface for the emission of dioxide carbon (CO_2).

$$Z(X_1, X_2)=14.53 + 0.12X_1-0.17X_1^2-0.68X_2-1.05X_2^2 \qquad R^2=0.96 \qquad (5)$$

The experimental data were well adjusted. It was noted that the influence of the speed of rotation was more significant than the flow rate of hydrogen.

4. CONCLUSION

The use of hydrogen as supplementary fuel presented satisfactory results regarding both engine performance and pollutant emissions. According to the results, the emissions of unburned hydrocarbons and carbon monoxide decreased, while carbon dioxide emissions increased with the addition of hydrogen. The specific fuel consumption suffered reductions of between 0.20 to 10.43% when compared to the operation without hydrogen. There was an increase in engine torque and power, however, for rotations above approximately 4500 rpm, the addition of hydrogen did not result in changes in these properties. MBT and MBP values presented an average increase of 5.8 and 7.6%, respectively. The most significant effects were obtained with the introduction of 300 mL/ min of hydrogen.

It is believed that relevant results can be obtained with the addition of larger quantities of hydrogen and with the control of the other parameters of the engine.

5. ACKNOWLEDGEMENTS

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