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PERFORMANCE AND KNOCKING ANALYSIS OF A MOTOR GENERATOR GROUP OPERATING IN THE OTTO CYCLE WITH GASOLINE AND WATER INJECTION

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Abstract. *The present work approaches a study about the influence of water injection into the intake manifold of an engine regarding the admitted air/fuel mixture temperature, engine performance and reduction of knocking phenomenon occurrence. Water injection promotes a decrease in the combustion chamber temperature and, consequently, a reduction in the engine tendency to detonate. For this reason, when using gasoline in a dual-fuel engine, water injection makes possible for the gasoline to operate at a higher compression ratio and close to ethanol's, allowing the engine to work more efficiently using both fuels without detonation. For the procedures, it was used a 1.4 engine, 4 cylinders, originally as bi-fuel, with a compression ratio of 10.4:1, operating at full load with E27 gasoline. The tests were carried out with different percentages of water injection and it was observed that it allowed the engine to operate with greater spark advances without knocking, which influenced in higher rotations and engine power output. Greater temperature reduction was achieved in the intake manifold, approximately 31.0°C, and 30.3°C in the exhaust using 72% of water injection in relation to the fuel mass flow. Still, a gain of 6.7% or 1.5 kW of output power was obtained with the highest percentage of water injected and fuel consumption remained constant in all tests performed.*

Keywords: *SI engine, Water injection, Knocking, Gasoline, Temperature.*

1. INTRODUCTION

The tendency of the automotive industry on the propulsion systems optimization, allied to legislation changes to the necessity of pollutant reduction and fuel consumption, is taking engines developer companies to search for new solutions to attend environmental standards without engine performance losses.

Nowadays, the tendency for techniques such as engine size reduction increase the mean effective pressure, leading to higher risks of knocking and anomalous combustion. Considering that knocking is avoided by retarding ignition timing and combustion phasing, this leads to a low thermodynamic efficiency and high exhaust temperature. The water injection technique enables, due to its great latent heat of vaporization, the admitted mixture cooling as the water evaporates. This cooling allows emission reduction, as nitrogen oxide for example, and enables the possibility to increase the compression ratio and spark advance, improving engine power and performance.

Another question is the production of medium and small size vehicles which are projected with spark ignition (SI) engines to operate, mostly, with both fuel ethanol and gasoline. Though, due to its physical-chemical differences, during SI engine projects, the stablished parameters must attend both fuels, a factor which limits its optimum operation. As the compression ratio is not intended for only one fuel, the use of gasoline in SI engines operating in higher compression ratios becomes limited (Zapata-Mina et al., 2020).

Therefore, technologies have been implemented to avoid anomalous combustion and optimize the heat release during combustion process, as the implementation of fuel direct injection in combustion chamber, the addition of anti-knocking substances in commercialized fuels and use of water injection, which was used in the engines of military planes in 2nd World War, to increase the efficiency and reduce knocking phenomenon (Rowe and Ladd, 1946).

Heywood (2018) defines knocking as the sound which is transmitted by the engine structures when anomalous combustion occurs. It results from the self-ignition of the last injected mixture part, located in front of the flame originating from the spark plug. When this phenomenon starts, an extremely fast chemical energy release occurs, creating high pressure regions and pressure waves through the combustion chamber. These waves make the engine to vibrate and radiate the originated sound through the surroundings. The pressure waves are reflected on the chamber walls and give origin to oscillatory pressures that propagate exciting all the combustion chamber, creating resonance. Normally, this phenomenon occurs when the engine is submitted to higher loads.

There are studies that evaluate the efficiency in performance and emissions when water is injected together with the fuel Recently, Matthias Hunger et al., 2018, aiming to reduce the pollutant gases emission and the knocking tendency in SI engines, proposed a water injection system directed to the combustion chamber, in order to cool it down and reduce the temperature at the end of compression. To perform the tests, a single-cylinder engine operating at 2500 rpm was used. The injector was positioned on the cylinder head, at 90 degrees in relation to the combustion flow, with injection pressure equals to 100 bar. The volume of water injected was varied from 25 to 50% by volume of fuel. Results showed that applying 25% of water volume, the conditions of water vaporization, essential for heat release, only prevail at -120° after top dead center (TDC), reducing the temperature at the end of compression and consequently, knocking tendency. It was also proved that by increasing the amount of injected water, the air/fuel mixture temperature constantly reduces, which can lead to a 125 K reduction under 50% of water volume. Other factors noted, when injecting 2L/h of water, were the increase of 5.5º CA on fuel burn time and a 1.5º CA delay on ignition. Lastly, it was found that the inert effect of water steam and its large mass quantity in the combustion chamber, reduced the temperature in the burnt and unburnt regions, which allows the reduction of HC and NOx emission.

This paper, therefore, aims to develop two systems: a water injection system, with electro-injectors positioned inside the intake manifold plenum and a system to identify the occurrence of knocking phenomenon for posterior analysis of the influence of water injection on the performance of an SI engine coupled to an electrical power generator. The interest of this research is to contribute to the development of more efficient engines, in a way that when using gasoline in flex engines, water injection makes it possible for gasoline to operate in higher compression ratio and closer to the ethanol's, allowing the engine to work more efficiently with both fuels without the occurrence of the knocking phenomenon.

2. EXPERIMENTAL PROCEDURE

As mentioned in the previous section, through water injection, technique improvements on the combustion process can be obtained. Aqian et al., 2020, stated that water injection reduces mean effective pressure and cylinder temperature and also provides a work per cycle reduction as the proportion of water increases, resulting in more engine efficiency.

Therefore, in this section, the experimental procedure used for this study, analysis method and engine tests, will be presented.

2.1 AFR Air/Gasoline

To initiate the study, it was necessary to determine the air-fuel ratio (AFR) necessary to complete the mixture burning in the combustion chamber. Through Table 2 and through mass balance between reactants and products, as shown in Eq. 1, where α is the mixture percentage in mass base [%], and considering gasoline as the commercialized fuel in Brazil, according to Agência Nacional de Petróleo (ANP) for the current 2022 year, it was calculated the stoichiometric AFR, equals to 13.2.

$$\frac{\alpha}{100}(C_aH_bO_C)+\left(1-\frac{\alpha}{100}\right)(C_aH_bO_C)+\left(\alpha+\frac{b}{4}-\frac{c}{2}\right)(O_2+3.773N_2)=\alpha CO_2+\frac{b}{2}H_2O+3.773\left(\alpha+\frac{b}{4}-\frac{c}{2}\right)N_2 \tag{1}$$

Table 1. Molar mass from chemical elements.

Chemical Element	Molar Mass [kg/kmol]
Carbon (C)	12.011
Hydrogen (H)	1.008
Oxygen (O)	15.999
Nitrogen (N)	28.014

2.2 Experimental Setup

Coupled to a generator that offers resistance to rotation, it was used a 1.4 Fire Flex engine, four cylinders in line and a displacement volume equaling to 1.368 L, as shown in Fig. 1. The electrical power produced by the engine-generator group is dissipated as thermal energy through a resistive load bank with reduced inductance. The load bank has a capacity of 55 kW, in 220V, with electrical loads grouped in modules of 2.5 kW, 5 kW and 10 kW, allowing load additions from an initial value of 2.5 kW.

For the calibration, it was used the FuelTech FT500 electronic module capable to control the engine through programming, in real time, allowing injection and ignition mapping modifications in function of rotation and load demand.

Fuel consumption was measured through mass control in a reservoir at the start and at the final of experiment for each engine work condition, according to Eq. 2. For the mass flow calculus, the reservoir was positioned on top of a weight balance, so the values of initial and final fuel mass after each test battery could be collected during a certain period of time.

$$\dot{m} = \frac{dm}{dt} \tag{2}$$

Where "ṁ" is the gasoline mass flow in the engine [kg/s], "dm" is the gasoline mass variation in the reservoir and "dt" is the experiment period of time.

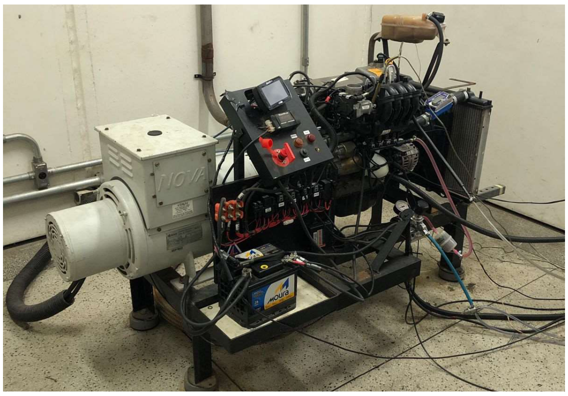

Figure 1. Experimental setup of the Fire 1.4 Flex engine connected to the electrical power generator.

In order to investigate the effects of water influence on inlet and outlet temperatures, two type K thermocouples were installed, one in the intake manifold to verify the admitted mixture temperature and the other in the exhaust manifold, right before the catalyzer and next to the oxygen sensor.

The injectors used for water injection were injectors IPE057 55257414 Marelli, installed inside the intake manifold plenum, which the drive control was made through an Arduino MEGA 2560 microcontroller, varying the energizing time in 5, 10, 20, 30, and 40 ms. The programming code was written in such a way that as soon as the microcontroller receives a drive signal, the system starts its operation. All the hydraulic circuit setup for the water injection systems are indicated in Fig. 2. To define the water mass flow rate and injection pressure used in experimental tests, it was carried out a procedure that consisted of measuring the electro-injector flow rate capacity at different line pressures of 2, 3, and 4 bar. For this purpose, a water pump was immersed inside a reservoir filled with water and the hydraulic circuit line was pressurized. The electro-injector was activated and the mass of water injected was measured in a given period of time. Therefore, the values calculated for the water flow rate used in the experimental procedures, were equal to 2.363 kg/h at 2 bar, 4.726 kg/h at 3 bar and 7.089 kg/h at 4 bar. In terms of water proportion in relation to air-fuel mixture, the values are equal to 24%, 47%, and 71%, respectively.

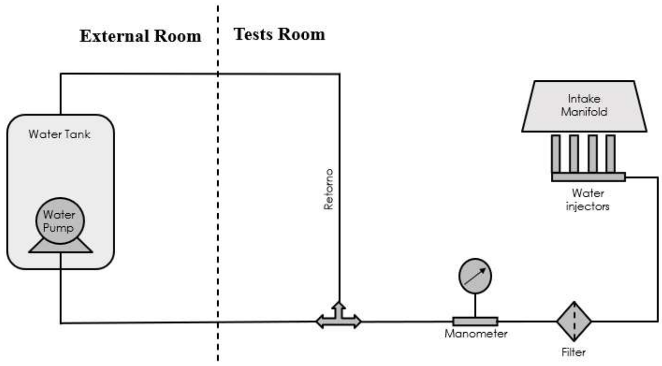

Figure 2. Schematic of the hydraulic circuit setup for water injection.

2.3 Knocking Analysis

The evaluation of knocking phenomenon during the engine operation is extremely important for the evolution of this paper. Therefore, a knocking sensor NTK 8709, connected to an oscilloscope, was used. In order to improve the phenomenon visualization, it was created a band-pass filter, fixed on the engine block, to filter the sign produced between the engine knocking frequencies, 5 to 20kHz, according to Brunetti (2018). As a form of comparison to validate the knocking frequencies modes presented by the oscilloscope, it was developed an analytical calculation as stated by Schaberg (1991), from Cape Town University. When the knocking phenomenon occurs, pressure waves chock against the cylinder walls, originating vibration. The frequency produced from pressure oscillations is calculated through the sound velocity inside the combustion chamber multiplied by a non-dimensional coefficient α that is associated with the transverse mode of pressure distribution in a plane ended cylinder, and divided by the cylinder diameter, as shown in Eq. 3.

$$f_{mn} = C a_{m,n}/[2R] \tag{3}$$

Where "$f_{m,n}$" is the frequency mode, "C" is the sound velocity, "$\alpha_{m,n}$" is the non-dimensional coefficient and "R" is the cylinder radius. Calculating sound velocity through Eq. 4, where "T" is the temperature inside the chamber and "T_0" is the room temperature, it was found a value of 976.97 m/s for a chamber temperature of 2100ºC, according to Schaberg (1991).

$$C = 331.45\sqrt{\frac{T+273.15}{T_0+27.,15}} \tag{4}$$

Using the αm,n of the first five transverse modes of pressure distribution of a plane ended cylinder shown by Schaberg (1991) and knowing the bore diameter of the engine (72mm), it was obtained by the Eq.3 the five first knocking frequences modes, listed in Table 2.

Table 2. Five first modes of knocking frequencies.

1st Frequency Mode	7.95 kHz
2nd Frequency Mode	13.18 kHz
3rd Frequency Mode	16.54 kHz
4th Frequency Mode	18.14 kHz
5th Frequency Mode	22.96 kHz

For the knocking evaluation during the tests, it was used the oscilloscope settled on the Fast Fourier Transform (FFT). For the knocking phenomenon visualization, the first two frequency modes were evaluated, which can be seen by positioning the vertical cursors on the two calculated knocking frequencies and correlating the tension variation of the knocking sensor with the audible noises produced by the engine when the phenomenon is occurring. Figure 3 shows a print screen from the equipment when knocking was occurring. On the left image, the visualized wave represents the engine operating without knocking and on the right image, it can be stated that the tension peaks occur on the calculated frequencies, proving knocking occurrence.

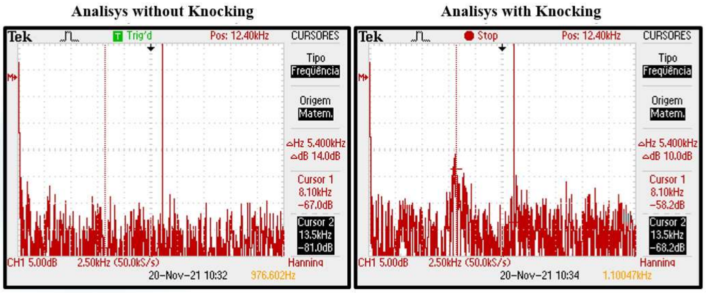

Figure 3. Fast Fourier Transform for knocking analysis.

In Fig. 4 it is possible to evaluate knocking through the amplitude variation sign presented by the sensor in function of time and correlating with both Fig. 3 and audible noise. For this analysis, it was defined time intervals of 5ms in the oscilloscope and amplitude equal to 100mV.

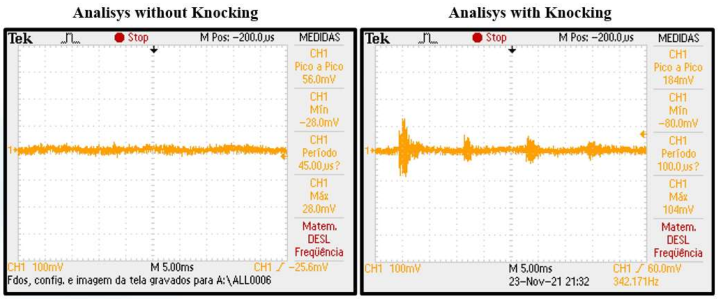

Figure 4. Knocking evaluation via oscyloscope from knocking sensor signal amplitude in function of time.

It was stated that the tension peaks occurred in intervals of approximately 10ms, which in this case represents about ¼ of the engine cycle when operating around 2500 rpm. Therefore, the knocking fenomen in this specfic cycle of Fig. 4, occured in all four cylinders.

2.4 Experimental engine tests

In this paper section, it will be presented the following tests procedures for the engine operating with gasoline E27, according to the ANP (Agência Nacional de Petróleo) standards, and, in sequence, with water injection.

2.4.1 Adjustment on engine operation

For engine electronic management, it was used a FT500 programmable central from FuelTech brand, in order to adjust air flow rate, spark advance and fuel injection parameters. Fuel flow rate was calibrated in function of intake manifold pressure and engine rotation. Initially, for the fuel calibration, it was used a closed loop control system, where, from a fuel injection value suggested by the FTManager and from a lambda (air-fuel mixture in relation to stoichiometric value) target value, the central itself worked on the correction of time injection, seeking to reach the desired air-fuel mixture. From the fuel correction values presented by the central, it was defined the energizing time adjustment for the electro-injectors in fuel map to work at open loop with a value closer to the selected one for the air-fuel mixture percentage.

As for lambda (λ), it was settled a value of 0,90 for all the fuel table, which means that mixture contains a fuel excess of 10% in relation to stoichiometric value of a complete oxidation between E27 fuel and air. The selection for this richer mixture value its justified by the temperature and pressure curve vs. lambda (Brunetti 2018), in order to preserve the engine during the tests. For ignition timing, it was varied the spark advance to obtain a base table for the tests in a way that the ignition angle was adjusted in function of engine rotation and intake manifold pressure. The values of spark advance were settled during the engine operation, using 5º CA before TDC and increasing the advance until it knocking was noticeable during the engine operation.

2.4.2 Test procedure

The tests were divided into two sections, the first one is characterized by the engine operation without water injection, aiming to find the maximum spark advance without the appearance of the knocking phenomenon. The second test section counts with the use of a water injection system inside the plenum of the intake manifold to eliminate the detonation and evaluate water influence on the possibility of increasing spark advance and, consequently, the energy release. It was defined a period of 30 seconds for the test and all the temperature, fuel consumption, rotation and power data were collected. Once all the temperatures were stable in the test room during the engine operation in idle condition, the throttle valve was fully opened to increase engine rotation and then, the loads on the generator were triggered.

The loads added on the generator contribute for engine rotation reduction by providing resistance to the spin, hence the load addition on the generator allows the engine to operate with a wide open throttle (WOT) in lower rotation. This parameter was chosen for better visualization of the knocking phenomenon, by associating high mixture pressure inside the cylinder and low engine rotation, providing time for mixture heating during the compression phase and, consequently, creating a prone environment for detonation.

After determining these parameters, the spark advance was varied increasing its value until the point where it was possible to visualize the knocking phenomenon through oscilloscope. On the second test section, it was used the spark advance value from the first test procedure, when knocking was not occurring and with the engine operating without water injection. Then, established the parameters for the same operating conditions from the first test batteries, it was analyzed the water influence on detonation.

With an engine operating with the spark advance that induces detonation, water injection procedure was initiated from a water flow rate of 2.363 kg/h at 2bar into the intake manifold. In sequence, the following tests procedures were accomplished with the objective of evaluating the maximum spark advance for different proportions of water flow rate without knocking occurrence. As a result, it was obtained the spark advance limit in function of water mass contained into the mixture and therefore, evaluated engine power and rotation for each increase of spark advance.

3. RESULTS

In this paper section, values of admitted mixture temperature, exhaust gas temperature, output generator power, and fuel consumption were evaluated.

3.1 Power x WFR

For the generator output power evaluation, the full load capacity from load bank was applied to the engine and the WOT condition was maintained. As illustrated in Fig. 6, the output power presented a value of 20.9 kW for the operating regime without water injection. When water was added, results revealed that with a 2.363 kg/h water flow rate, the generator output power increased up to 21,3 kW. When applied a 4.726 kg/h water flow rate, power reached a value of 21.5 kW and 22.4 kW for 7.089 kg/h. For this reason, it can be stated that the spark advance increase, enabled by water injection, resulted in a power output gain of 1,5 kW compared to operating regime without water injection.

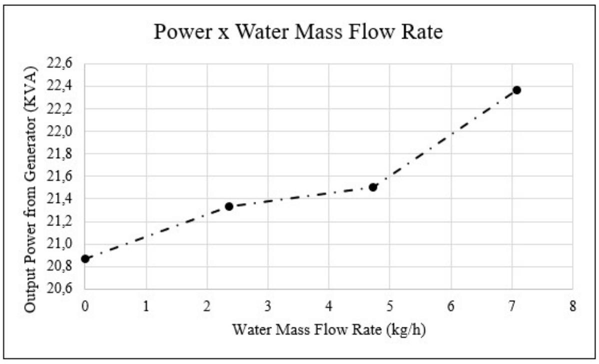

Figure 5. Power vs. water mass flow rate.

3.2 Spark Advance x WFR

As the spark advance increase is limited by the knocking phenomenon, it was used the greatest spark advance supported by the engine before knocking occurrence as an ideal value. The tests were carried out with an engine coolant temperature of 93ºC.

Figure 5 represents the spark advance behavior on the experimental procedures. Initially, the study with the engine operating without water injection was conducted, and it was noted that up to 11ºCA advance before TDC, the engine worked at WOT and without knocking presence. After this analysis, the spark advance was increased as the water was injected inside the intake manifold, varying the proportion of injected water from 24% to 71%. In this way, it was noted that water injection enables spark advance increase without knocking appearance, reaching its peak at 17°CA before TDC when the water was injected at a proportion of 71%.

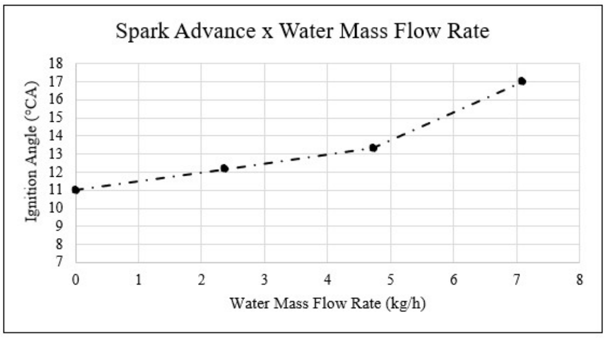

Figure 6. Spark advance vs. water mass flow rate.

It was also noticed that the increase in water amount, ally to its great enthalpy of vaporization, reduced the combustion chamber temperature, allowing the unburnt mixture to support higher pressures and temperatures inside the cylinder without causing spontaneous combustion.

3.3 Fuel consumption

For fuel consumption it was noted minimum variations, therefore it was assumed that it maintained constant during the experimental procedures, as indicated by Fig. 8.

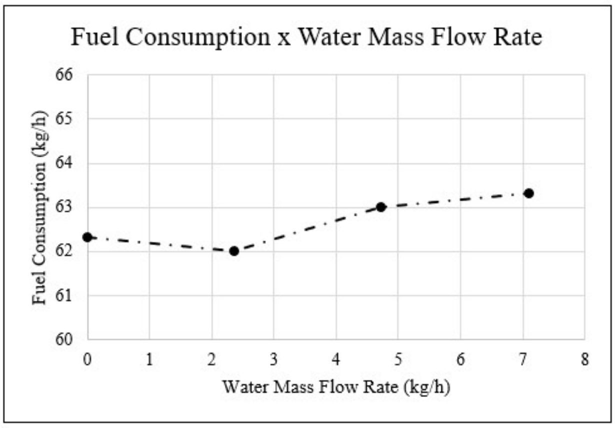

Figure 7. Fuel consumption vs. Water mass flow rate.

3.4 Temperatures x WFR

For temperature data acquisition, values were collected through NOVUS system with the engine working with and without water injection. As shown in Fig. 7, the intake manifold and pre-catalyzer temperatures without water injection were equal to 61.24°C and 777.26ºC, respectively.

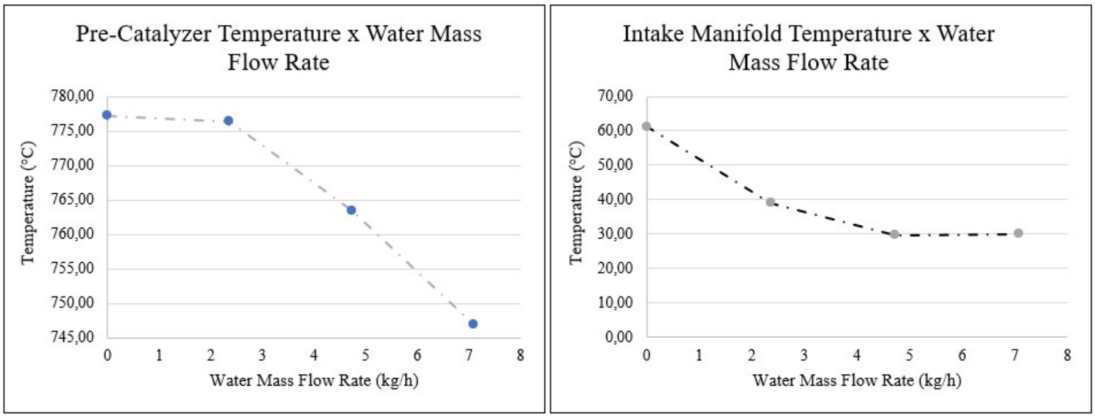

Figure 8. Pre-catalyzer and intake manifold temperatures vs. water mass flow rate.

With water being injected into the engine at a flow rate of 2.363 kg/h, temperatures presented values of 39.09ºC inside the intake manifold and 776.44ºC in the exhaust. For a water flow rate of 4.726 kg/h and 7.089 kg/h, the respective values for intake manifold temperatures.

4. CONCLUSIONS

A bi-fuel/Flex engine coupled to an electrical generator, working with E27 gasoline, was submitted to water injection during its operation to evaluate how water affects the engine performance. The conclusions of this paper are presented in the following topics.

• The experimental values of knocking frequencies modes identified by FFT function were consistent with the ones calculated through Schaberg (1991) study;

• The spark advance limit without water injection, in a way that detonation does not occur, was up to 11º. Above this value, the engine presented knocking symptoms;

• The increase of water injection provided greater spark advances during the test procedures without the appearance of detonation;

• Greater spark advances contributed to higher engine rotation and, consequently, higher output power;

• In a condition where knocking was present due to higher spark advances, water injection eliminated the evolution of this phenomenon for the same condition;

• Fuel consumption was not affected by water injection. It remained practically constant during the experimental procedures;

• It was achieved a gain of 1,5 kW of power output when injecting 71% of water in relation to the fuel mass rate, compared to the engine working without water injection;

• Using a proportion of 71% of water in relation to fuel mass rate, a 30.3ºC of exhaust temperature reduction was obtained, measured right before the catalyzer.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

Aqian L.; Zhaolei Z.; Tao P. “Effect of water injection on the knock, combustion, and emissions of a direct injection gasoline engine”. Fuel, v. 268, 117376, 2020.

Brunetti, franco. “Motores de combustão interna”: volume 1. São Paulo: Blucher,553p, 2012.

Heywood, John B. “Internal combustion engine fundamentals”. New York, McGraw-Hill, xxxiv, 930p, 1988.

Hunger M., Böcking T., Walther U., Günther M., Freisinger N., Karl G. “Potential of Direct Water Injection to Reduce Knocking and Increase the Efficiency of Gasoline Engines”. In: Günther M., Sens M. (eds) Knocking in Gasoline Engines. KNOCKING 2017. Springer, Cham.

Rowe, M.. and Ladd, G. “Water Injection for Aircraft Engines”. SAE Transactions Vol. 54, pp. 26-37, 1946.

Schaberg, P. 1991. "Knock-induced noise and vibration in I.C. engines". University of Cape Town.

Zapata-Mina et. al. "Exergy analysis of a diesel engine converted to spark ignition operating with diesel, ethanol, and gasoline/ethanol blends". *Sustainable Energy Technologies and Assessments*, Vol. 42, 2020, 100803.

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