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EVALUATION OF THE THERMOMECHANICAL PERFORMANCE OF A COMPRESSION IGNITION ENGINE USING ADDITIVE BIODIESEL

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Abstract. *In the northern region of Brazil a large part of the electric energy is obtained from petroleum by burning these fuels in internal combustion engines (MCI). These power generation systems are called Thermoelectric Power Plants (UTE). However, the production of electricity by the UTE's has a high cost of production, which is directly related to dependence on fossil fuels. An alternative that is currently being used to reduce this dependence is the use of Biodiesel. This work aimed to evaluate the thermomechanical performance of Diesel cycle engines operating with several mixtures of marine (B0) diesel and Biodiesel additives (B100), the following B0, B5, B7 and B10 fuels were used. The methodology used in this work began with the preparation and characterization of the fuels (PCS, PCI) in the Labmotor, and then the fuels were tested in a diesel generator group Yanmar, direct injection, four cylinders and 20 kVA. The loads chosen to perform the test were 30, 50, 70 and 100% of the nominal load. The results show that B5 fuel was the one that obtained the best efficiency, specific consumption and lower level emissions, compared to the pure diesel (B0), which was the reference parameter, although the biodiesel produced delay of the combustion the use of the additive raising the PCI has helped to alleviate this problem. This effect of the combustion delay is visualized on the B10 fuel, which despite the use of the additive obtained the worst efficiency and emission indices due to the increase of the biodiesel content in its composition.*
Keywords: *Diesel Engines, Biodiesel, Thermoelectric Plants, Biofuels.*

1. INTRODUCTION

The generation of electric energy from petroleum products occurs through the burning of these fuels in boilers, turbines and internal combustion engines (ANNEL, 2008). These power generation systems are called Thermoelectric Power Plants (UTE). In this context, the use of diesel generating groups, which are basically an internal combustion engine coupled to an electric motor, is responsible for the generation of electric energy by a large portion of the thermoelectric plants operating in the country, especially in regions not served by the National Integration (SIN), mainly in the North region of the country. According to ANEEL's Generation Information Bank (BIG, 2018), Brazil currently has 3002 UTEs, which are responsible for the production of 43.28 TWh (terawatts-hour) which corresponds to 26.21% of the total energy produced in the country, see figure 1.

The use of thermoelectric plants in several regions of Brazil, besides being related to serving regions not integrated by the SIN, is an alternative to supply the national demand when the main source of electric energy in the country that is the Hydraulics presents decreases of productivity, due to of climate for example. The UTEs are of low implementation cost and fast construction, however they demand a high operational cost, since the vast majority operate with fossil fuels. According to (ANEL, 2008) these thermoelectric plants may, consequently, be decommissioned, especially those of smaller size or of low efficiency, since the costs of the oil used are passed on to all the electric energy consumers of the country, for the Fuel Consumption Account (CCC), embedded in the final tariff.

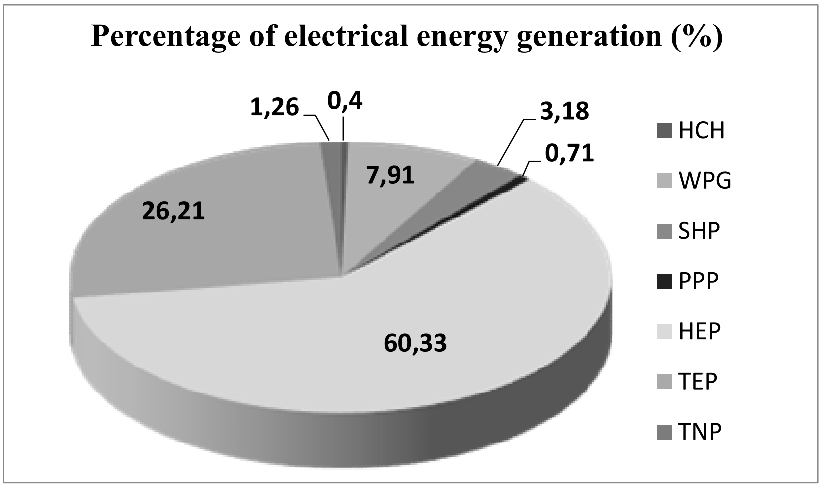

Figure 1. Percentage of electricity production in Brazil and 2015, Legend: HGP (Hydropower Generating Plant; WPG (Wind Power Generator); SHP (Small Hydropower Plant); PPP (Photovoltaic Solar Power Plant); HEP (Hydroelectric Plant); TEP (Thermoelectric Plant) e TNP (Thermonuclear Plant).
Source (BIG, 2018).

An alternative to try to reduce the dependence of fossil fuels on the production of electric energy coming from the UTEs is the adoption of biofuels, that is to say, to use a renewable and financially accessible source of energy that can substitute fossil fuels in the internal combustion engines, maintaining efficiencies of generating sets. The fuel that has played this role is Biodiesel, this one is already commercialized in Brazil in percentages of 8% mixed with the commercial diesel oil. According to (FONTANA, 2011) the main advantages of Biodiesel are:

- The vehicular emission of Biodiesel burning is less offensive, lower levels of HC and CO;
- Biodiesel being an oxygenated fuel presents a more complete combustion;
- Biodiesel works on conventional engines without any need for modifications either to the injection system or to the combustion engine itself.;
- Biodiesel is renewable, and can be used alone or mixed in any proportion with petroleum diesel, ie, from BI to B99, or even in its pure B100 form.

In this context of the use of Biodiesel in Diesel engines the present work aims to use different percentages of the mixture of Commercial marine diesel (S500), identified as B0 because it does not have Biodiesel, and pure Biodiesel (B100), mixing these fuels and obtaining 4 different fuels (B0, B5, B7 and B10), in order to test the operating parameters of a generator set (specific consumption and emissions), and check to what extent it is feasible to use Biodiesel without compromising the efficiency of the generator set .

1.1 The Diesel Engine

It is an internal combustion engine, consisting of a set of parts synchronized with each other, which transforms the heat energy into mechanical energy, resulting from the burning of a fuel caused by the high temperature of the gases due to compression. Compression ignition (ICO) engines can operate on both four-stroke and two-stroke cycles. However, the vast majority operate in the four-cycle cycle (MARTINS, 2011). The nomenclature "diesel" is due to its inventor, the engineer Frances Rudolf Diesel, who developed the first engine, between the years of 1893 to 1898 in Augsburg - Germany.

In the diesel engine in the initial times, see figure 2, which are of admission and compression, air is drawn and compressed inside the cylinder, in diesel engine the compression ratio is of the order of 14: 1 to 25: 1, and the internal temperature cylinder exceeds 700 ° C. The third time that corresponds to combustion or expansion, the injection of a jet of fuel with pressure higher than that in which the air is found. The combustion process happens by autoignition, when the fuel comes in contact with the air, which was heated by the elevation of pressure (MARTINS, 2011). In the fourth and last time, called the exhaust or discharge the exhaust valve is opened and the gases are expelled by the discharge pipe. The fuel commonly used is commercial diesel, however other fuels can be used, such as Biodiesel.

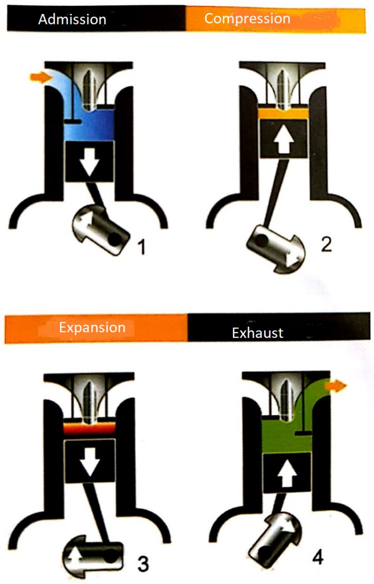

Figura 2. Stages of a Diesel cycle engine.
Source: Fontana, 2011

1.2 Diesel Engine Parameters

Power indicated

It is the power developed within the cylinder of the engine, which can be measured by a pressure gauge, which allows to trace the cycle. The work indicated by cycle is obtained by integrating along the curve of the corresponding graph by equation 1, in units in the SI (MARTINS, 2011).

$$W_i(J) = \oint pdV \quad (1)$$

The indicated power is calculated by equation 2.

$$P_i\,(kW) = \frac{W_i\,(kJ)\,N\,(rev/s)}{n_r} \quad (2)$$

Where W_i is the work indicated, p is the pressure, Pi is the indicated power, N is the engine speed, dV is the volume change in the cylinder and nr is the number of revolutions of the crankshaft to complete a cycle. In four-stroke engines nr equals two and in two stroke engines nr equals one (MARTINS, 2011).

Effective power

The effective power is the power measured in the motor axis, that is, the power indicated less to the losses by friction and can be calculated by equation 3.

$$Pe\,(kW) = 2\pi N\,(rev/s)\,T\,(N.m) \times 10^{-3} \quad (3)$$

Where Pe is the effective power, N is the rotation of the motor and T is the torque. Torque is the engine's ability to perform work, while power is the rate at which that work is produced (Martins, 2011).

Effective mean pressure

The effective mean pressure (emp) of the cycle, which is constantly applied to the piston head along the expansion stroke, produced the cycle work (HEYWOOD, 1998), can be calculated by formula 5.

$$pme(kPa) = \frac{Pe(kW)\, n_r}{V_d(m^3)\, N(rev/s)} \tag{5}$$

Where emp is the effective mean pressure and Vd is the engine displacement.

Specific consumption

The specific consumption parameter (CoEs), measures the mass flow of fuel per unit of output power. It measures how much the engine is efficient in the use of fuel for the production of work. Equation 6 calculates the specific consumption.

$$CoEs(kg/kW.h) = \frac{\dot{m}_c(g/h)}{P_e(kW)} \tag{6}$$

Where CoEs is the specific fuel consumption, $\dot{m}_c$ is the mass flow of fuel.

Eficiência Global

Overall efficiency is an essential engine parameter. It is defined by the ratio between the effective power of the motor (Pe) and the amount of heat supplied per unit of time $(\dot{Q} = \dot{m}_f PCI)$, or fuel power. This is the product of the fuel mass flow with the lower calorific value of the fuel (BRUNETTI, 2012), its usual unit is (kW). Equation 7 shows how to calculate the overall efficiency of an engine.

$$ng(\%) = \frac{P_e(kW)}{Q_c(kW)} \tag{7}$$

Heat power

The calorific value of a fuel is used to quantify the maximum amount of heat that can be released by combustion with air. The amount of heat released by the fuel combustion will depend on the stage in which the water is in the products. If the water is in the vapor phase, the total value of the released heat is considered as the Lower Calorific Power (LCP). When water presents itself in the liquid phase, it means that additional energy can still be extracted and in this case, the total energy released is called High Calorific Power (HCP). Equation 8 expresses the calculation of the LCP as a function of the HCP.

$$PCI(MJ/kg) = PCS - \frac{m_{h2o}}{m_c}.h_{lv} \tag{8}$$

Where HCP is the High Calorific Power of the fuel, where mH2O, is the mass of water conditates in the exhaust gas, mc is the mass of fuel that generated that water and hlv is the enthalpy of vaporization of the water at the exhaust gas pressure. This work assumed that the exhaust gas pressure is 1 atm and therefore the enthalpy of vaporization at 100 ° C is 2258 kJ / kg.

2. METHODOLOGY

2.1 Energy Assessment of Fuel

The energy evaluation of the fuel aims to determine its energy potential the LCP, obtaining the HCP and elemental analysis it is possible to calculate the LCP. From the LCP the fuel consumption, the power indicated the thermal efficiency, and other variables of the engines are determined. The fuel analysis presents the characteristics of the fuels used in this work and seeks to draw a baseline for comparing the results of the engine with pure diesel (B0), which is currently marketed as marine diesel, with the mixtures with Biodiesel B5, B7, B10 .

Elemental analysis was performed on a Perkin-Elmer CHNS / O 2400 Series II Elementary Analyzer. The upper calorific value was determined on an Ika Werke C2000 calorimeter pump.

Table 1 presents the results of the determination of the upper and lower calorific power in MJ / kg and of elemental analysis in mass fraction of each element. The B-100's HCP was 5% above B-0. Expected is just the opposite. The control of the LCP and HCP tests revalidated these values, that is, Biodiesel has an additive (LCP of the additive is 43.74 MJ / kg), which is raising its HCP and consequently the LCP.

Table 1. Elemental analysis and calorific powers of B-0, B-5, B-7, B-10 and B100.

	B-0	**B-5**	**B-7**	**B-10**	**B-100**
HCP (MJ/kg)	45,98	46,10	46,15	46,22	48,29
LCP (MJ/kg)	40,45	40,60	40,65	40,74	43,25
C	84,5	84,19	84,06	83,88	78,4
H	13,6	13,54	13,51	13,48	12,4
N	--	--	--	--	--
S	1,9	1,89	1,89	1,88	1,7
O	--	0,38	0,54	0,77	7,5

Source: Authorship

The density was measured in a fuel control kit. The density determination procedure consists in adding one liter of the fuel to be measured in a beaker, then the immersed column thermometer is placed and the temperature of the fuel is measured. The thermometer is then withdrawn and the densimeter is glued to the desired scale and the density is measured where the densimeter is scaled to the surface of the fuel. Table 2 presents the results of density measurement. The largest and smallest values found were the B-100 and B-7, values that are corrected according to the engine operating temperature.

Table 2. Measured fuel density corrected to 20 ° C.

Fuel	Density
B-0	0,852
B-5	0,854
B-7	0,856
B-10	0,858
B-100	0,874

Source: Authorship

2.2 Termomechanical Performance Analysis

To evaluate the thermomechanical performance of the generator-group consists of obtaining the following operating parameters: specific power, specific consumption, overall efficiency, temperatures and emissions. In order to obtain these performance curves an experimental apparatus had to be mounted on bay 1 of the UFPA Motors Laboratory (Labmotor). The tests were performed in a diesel generator set with Yanmar 4TNV88 4-stroke GGE series, direct injection, simply aspirated, 4 cylinders, 2.19 liters, compression ratio 19.1: 1, and synchronous generator KOHLBACH of 20 kVA and rated specific consumption from 220 g / kWh to 3000 rpm. The engine was instrumented with volumetric fuel consumption meter, electric power meter, voltage and frequency, air temperature gauge, fuel gauge, coolant at the radiator inlet, exhaust gas at exhaust manifold and at the point of exhaust gas collection for gas concentration measurement there is a Tempest 100 gas analyzer. The exhaust gases being measured are CO, NO, O_2 and SO_2.

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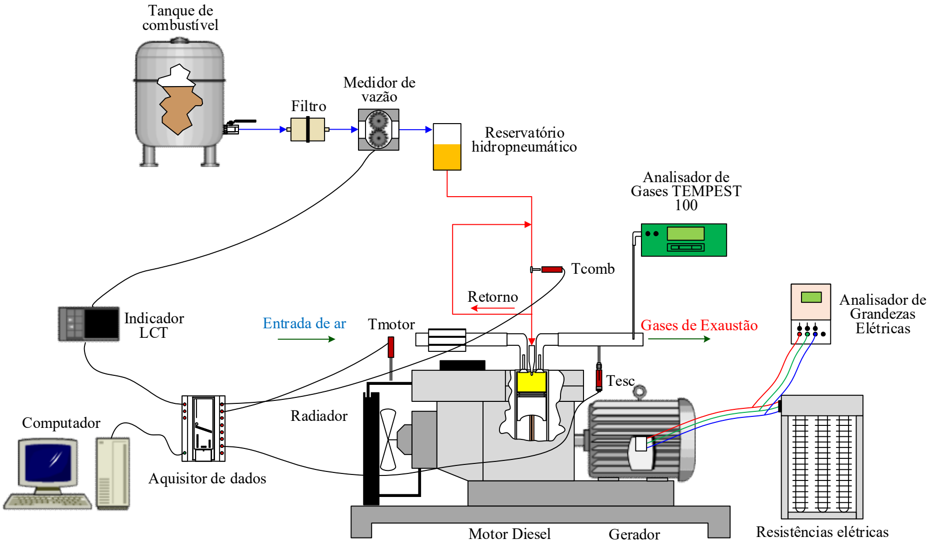

Figure 3. Experimental apparatus to perform the tests of thermomechanical performance of the generator group YANMAR 4TNV88-GGE.
Source: Authorship

The test is initiated by setting the motor at constant speed 1800 rpm (rotation of a 4-pole generator set to produce energy at the 60 Hz frequency), with no load and keeps it operating until it reaches the steady state, which is characterized by maintaining temperature of the exhaust gas and the engine. The Tgas, Tmotor x time curves are plotted to verify that the RP was reached, 30 minutes after the engine reaches this condition, the values of volumetric flow of the fuel, temperatures, electrical quantities and emissions are recorded. Then the load on the generator is raised to 30% of the capacity of the generator set and the procedure described above is repeated, then the performance tests are performed for 50, 70 and 100% of the generating capacity. After all the inserted loads the data are collected and the performance curves mentioned above are traced and the thermomechanical performance of the generator set is found.

3. PRELIMINARY RESULTS

The results obtained in the generator group Yanmar 4TNV88-GGE are part of the application of the methodologies mentioned in section 2 of this work. The fuels used were: B0, B5, B7 and B10 and the data analyzed are: Temperatures (exhaust gas, coolant and fuel), effective power, specific consumption, thermal efficiency and emissions.

3.1 Temperatures

Temperatures are the main variable to be monitored in the test of an internal combustion engine, in particular that of the exhaust gas and the coolant, in which we identify when the engine enters steady state, which occurs when temperatures are constant, regions where the data were collected are highlighted in red in the temperature graphs shown in figures 4, 5 and 6, and from this we can start collecting valid engine data. The tests are performed with the engine at a constant speed of 1800 rpm, with only the fuel compositions (B0, B5, B7 and B10) being modified, and the operating loads applied, respectively, 30%, 50%, 70% and 100 %.

Figure 4 shows the engine temperatures as a function of the load applied to the different fuels. It is possible to observe a maximum and minimum temperature control of the engine, this is accomplished by the thermostatic valve, which controls the passage of water to the radiator by regulating the temperature average of the same, in relation to the loads there is elevation of the temperature according to the inserted load and on the fuels there is no significant variation between the temperature of the motor for the different fuels used.

The graphs in figure 5 show the exhaust gas temperatures according to the applied load and the fuels used, similarly to the graphs in figure 4, the gas temperature rises with the lifting of the loads, this is due to the fact that increase the power of the engine to raise the new demand of the generator, thereby increasing the fuel injected by the engine injection pump by intensifying the combustion process which is reflected in the exhaust. In relation to fuels, there was no significant change in gas temperatures.

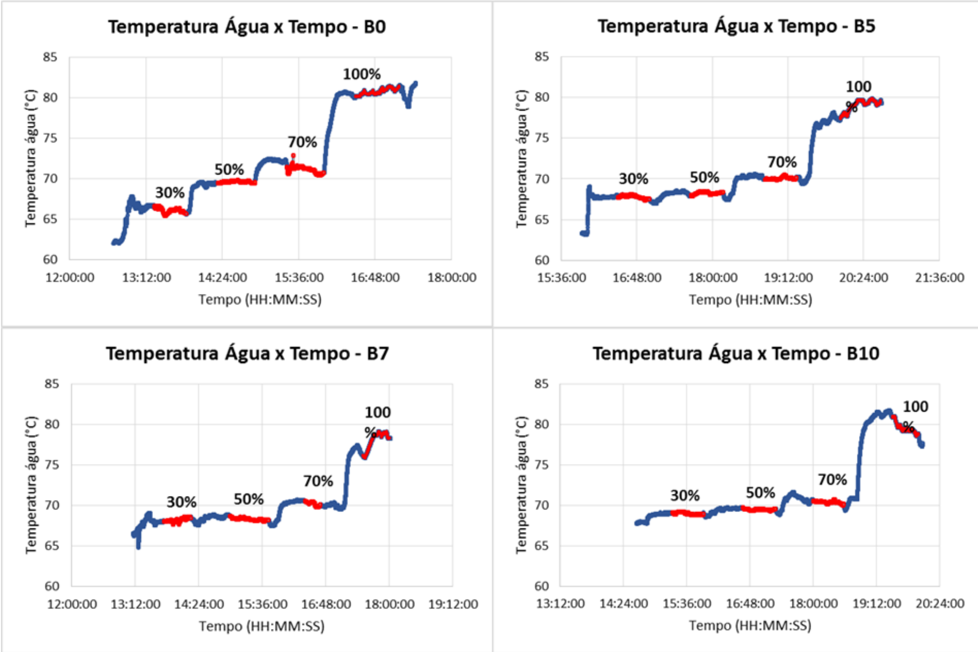

Figure 4. Variation of engine water temperature over time during the entire test with B0, B5, B7 and B10
Source: Authorship

In relation to the fuel temperatures obtained in the tests, it was used to analyze the influence of the temperature on the specific mass of the fuels, see figure 6, it is important to take into account that there is variation of the temperature as a function of the loads and that the mass flow of fuel injected by the injection pump and nozzles and nozzles in each load, the elevation of the fuel temperature is explained in part by the transfer of heat by conduction and irradiation between the combustion region (head and block) and the injector pump and the and in another part by the return of the fuel to be reinserted in the main line, which is part of the methodology adopted to measure the mass flow rate.

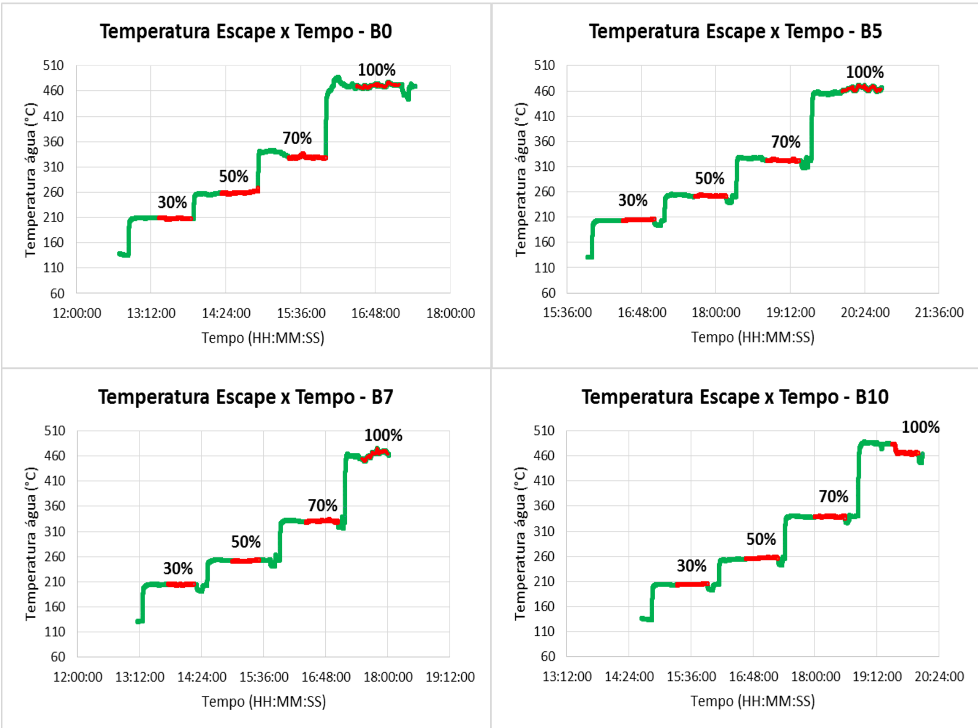

Figure 5. Variation of the temperature of the gases with time throughout and test with B0, B5, B7 and B10.
Source: Authorship

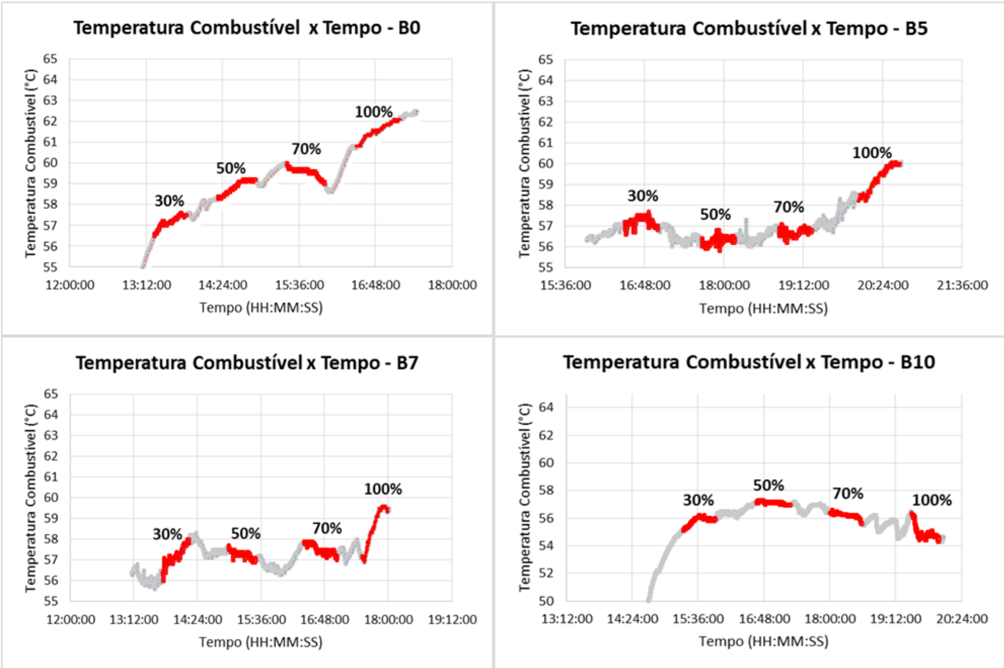

Figure 6. Variation of fuel temperature with time throughout the test of B0, B5, B7 and B100.
Source: Authorship

3.2 Specific Consumption and Thermal Efficiency

Specific Consumption and Thermal Efficiency are crucial parameters in the analysis of thermomechanical performance in internal combustion engines, they represent the efficiency in the utilization of the available energy in the fuel in a thermal machine.

The specific consumption of an engine represents how much mass of fuel is required to develop a given power, which in the generator sets is represented in loads, so there is a relation between a better specific consumption and the LCP, which of the biodiesel added is more reflecting the (B6). However, according to Portilha (2016), the cetane number is lower for Biodiesel, which delays the start of combustion, with the addition of biodiesel to marine diesel from 10% the opposite occurred there was a decline in efficiency, this is explained by the fact that the biodiesel in greater proportion produce a delay in the combustion reducing the effective average pressure of the cycle, thus contributing to the loss of efficiency that is visualized in the curve with the B10, see figure 7.

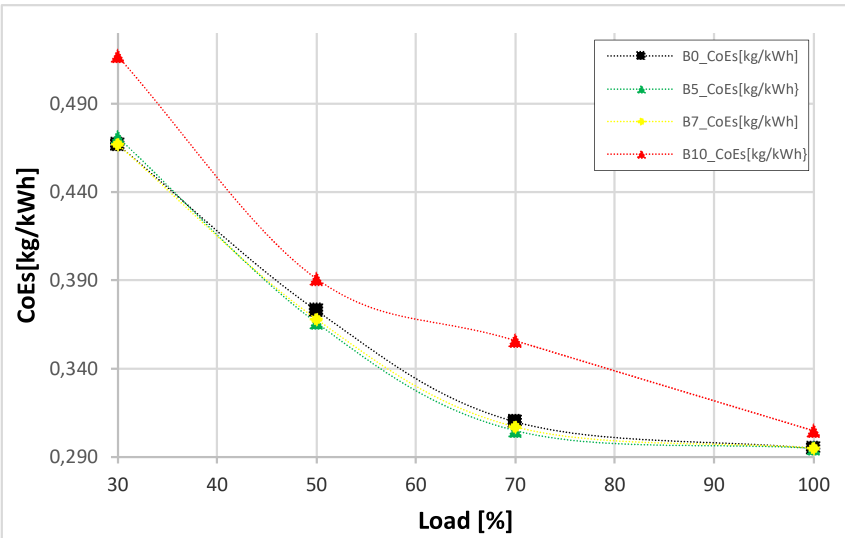

Figure 7. Specific consumption of generator set operating with: B0, B5, B7 and B10, depending on the loads applied.
Source: Authorship

Thermal efficiency represents what the engine uses of the energy supplied by the fuel, one way to obtain it is by the ratio of effective power to the power of the fuel. For generator sets, global efficiency is a decisive parameter because it represents the feasibility of using the engine, ie motors with very low thermal efficiency are wasting fuel (ANTONILSON, 2015). The thermal efficiency, see figure 8, follows the same standard of the specific consumption, presenting in percentage terms the energy used by the motor, obtaining the best thermal efficiency of B5 and B7 in relation to B0 and a lower thermal efficiency of B10 by greater biodiesel addition.

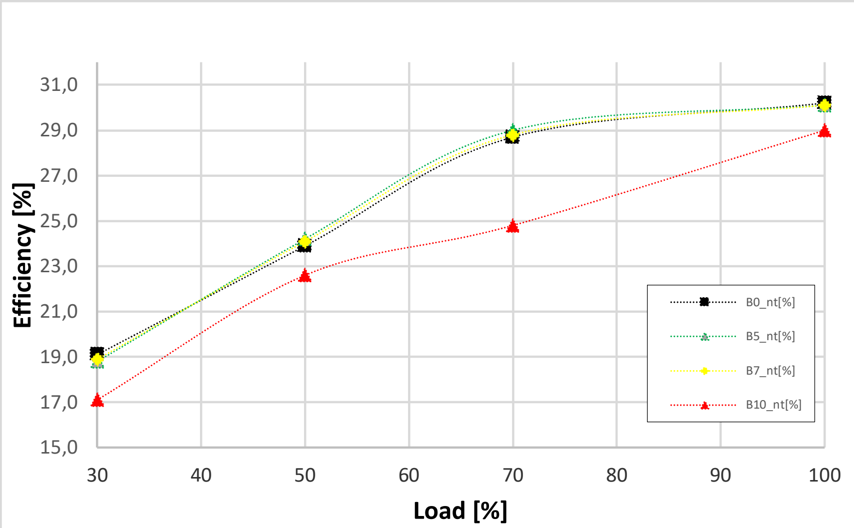

Figure 8. Thermal efficiency of the generator set operating with: B0, B5, B7 and B10, depending on the loads applied
Source: Authorship

3.3 Emissions

The emissions reflect the performance of the engines for each fuel used, so the gas analysis for O_2 [%], CO [ppm] and NO [ppm] and SO_2 [ppm] is expressed in the following graphs as a function of resistive load [%] of the engine for each fuel from B0 to B10.

Figure 9 shows the level of O_2 emissions. The amount of oxygen measured at the maximum load was in the range of 9% to 11%, indicating the oxygen consumption to convert the carbon of the fuel into CO and CO2. Note that with the increase the biodiesel content reduces the consumption of oxygen, since it contains this species in its composition and also a higher thermal efficiency of the combustion consumes more O_2. The lowest value of O_2 obtained in the analysis was 9.56%, found at the maximum load (100%) for B5; while the maximum was 16.64%, for the B7 with half the load (50%).

The concentration CO, expressed in ppm, is seen in Figure 10, and this species is an intermediate product of combustion which indicates the quality of the combustion: the larger the, the worse the combustion. It is observed that with the increased power of the engine, initially the concentration grows and then decays. The CO content depends on the amount of carbon injected into the cylinder and the maximum temperature of the combustion. Initially the injected carbon increases, but the maximum temperature is not in the same ratio then the CO concentration increases. Then the temperature increases by reducing its concentration.

Figure 11 shows the results of NO emissions. NO emissions are indicative of the maximum temperature value in the combustion chamber and by how many degrees of the crankshaft this temperature has remained high: the higher the NO emission the higher the temperature by more degrees. Consequently, it is expected that by increasing the amount of fuel, since the amount of air remains constant because the engine operates at constant speed, increase NO emissions. According to Miranda (2013), there is a reduction in the NO emission for biodiesel fueled engines, according to him as the biodiesel has O_2 content, the increase of oxygen in the mixture, a decrease in the ignition delay, this reduces the amount of pre-mixed fuel and maximum combustion temperature, thereby reducing NO emissions. Note that increasing the biodiesel content, decreased emissions for the same load which indicates a decrease in the maximum temperature of the gases.

The production of SO_2 depends on the total sulfur brought by the fuel and the maximum temperatures inside the chamber. B100 has less sulfur than B0, so B10 is expected to emit less than B0, but the presence of the additive in sulfur-containing biodiesel has raised emission levels, see figure 12. According to Miranda (2013), the reduction of SO_2 reduces the risk of acid rain and improves air quality, which highlights the benefits of increasing the amount of biodiesel added to diesel oil. The highest value of SO_2 was captured at the B10 operating at 100% of the resistive load of the motor, indicating 38.6 ppm and the lowest found value 15.5 ppm for the B7. It is worth remembering that for the

SO_2 analysis, emission values from 70% of the load were considered, since according to the resolution of the gas analyzer values below 70% of the load for SO_2 only, they were imprecise and random.

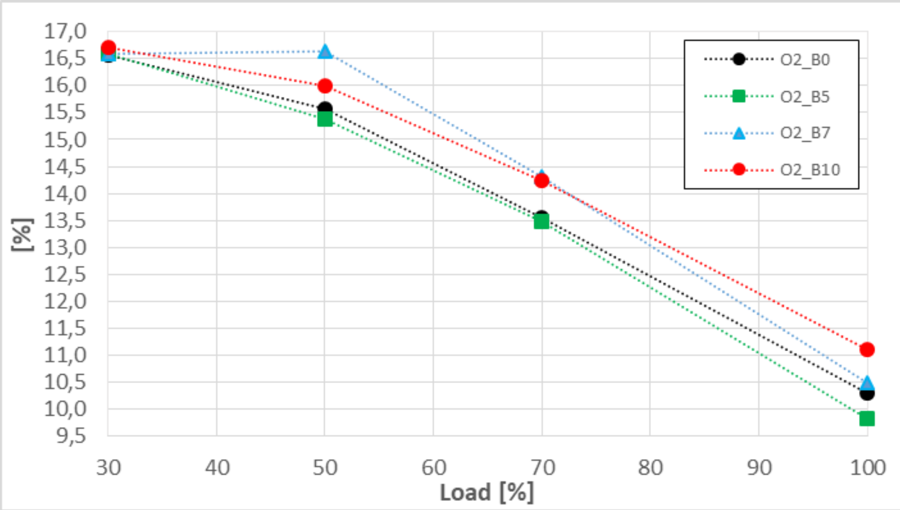

Figure 9. O_2 emissions, for all fuels, depending on the load.
Source: Authorship

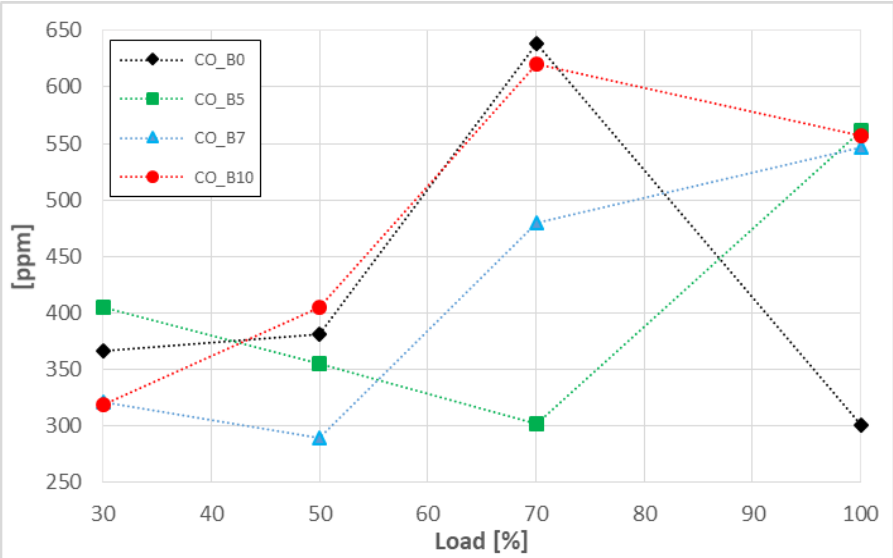

Figure 10. CO emissions for all fuels, depending on the load.
Source: Authorship

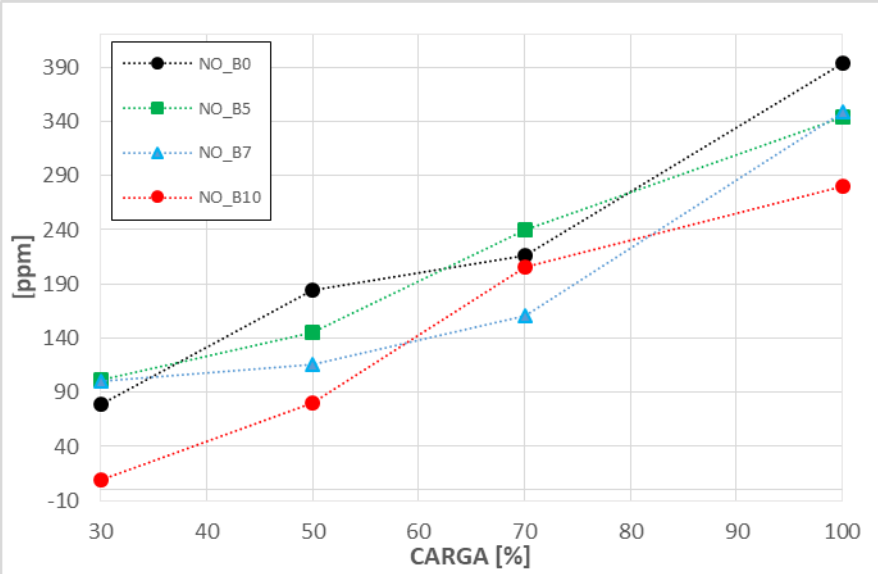

Figure 11. - NO emissions, for all fuels, depending on the load.
Source: Authorship

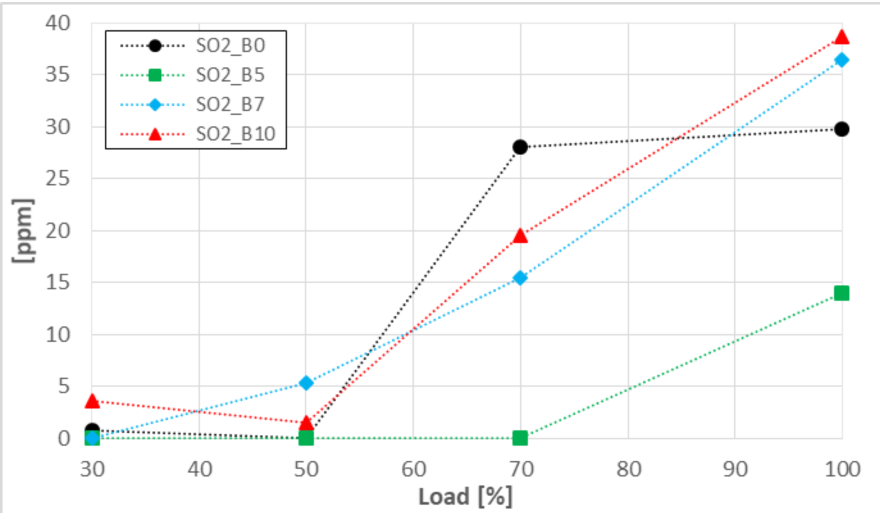

Figure 12. SO_2 emissions, for all fuels, depending on the load.
Source: Authorship

4. CONCLUSIONS

The present work presented a study on generator sets using Biodiesel mixed with commercial marine diesel (B0, B5, B7 and B10). In addition to developing methodologies for fuel energy analysis, obtaining thermomechanical performance in compression ignition engines.

The temperatures of the gases, the engine and the fuel did not vary greatly with the type of fuel selected, but with the applied load.

The B5 fuel was the one that obtained the best efficiency, specific consumption and lower level emissions, compared to the pure diesel (B0), which was the reference parameter, although the biodiesel produced delay in the combustion the use of the additive raising the LCP contributed to soften this problem. This effect of the combustion delay is visualized in the B10 fuel, which despite the use of the additive obtained the worst efficiency and emissions indexes due to the increase of the biodiesel content in its composition.

5. ACKNOWLEDGEMENTS

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