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PERFORMANCE AND EMISSIONS ANALYSIS OF A COMPRESSION IGNITION ENGINE USING VARIOUS PROPORTIONS OF BIODIESEL

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Abstract. *Internal combustion engines' emissions, one of the biggest concerns in modern days, particularly on diesel ones, places a critical role since the design stage inside manufacturers' headquarters. Searching for practical solutions that can deliver substantial performance results is becoming an industry standard. Predictable oil shortage and global environment awareness drive researchers to non-conventional energy sources and new – and less harmful for Earth – combustion processes. Biodiesel presents itself as one possible solution for this equation for internal combustion engines (ICE), where its main quality is to avoid diesel's critical problems. To achieve these results, tests have been made on a chassis roll dynamometer with a 2016 model year Chevrolet S10 LT truck on fully stock specifications, using common S10 diesel (that already contains 10% of biodiesel), B15 diesel (loaded with 15% biodiesel) and B100 diesel (pure biodiesel). To make sure if this alternative can fulfill the society's needs and be used on current vehicles and light trucks, several parameters were measured, such as exhaust gas opacity, peak torque and power and greenhouse gases concentration. This study made possible the analysis of biodiesel's effect on the engine, showing that this renewable energy source makes substantial benefits performance-wise, being the reduction in gas opacity and oxides of nitrogen (NOx) levels and a 7 whp increase the most notable achievements.*

Keywords: *compression ignition engines, biodiesel, dynamometer, pollutants emissions, performance analysis.*

1. INTRODUCTION

Compression ignition engines are used as a power source, being indicated not only to promote locomotion, but also in a stationary way on industrial machines axles and electric power generators. Emissions generation concerns are linked to your project and are a reason for constant research, looking for more and more viable alternatives that present significant results.

According to Demirbas (2008), most of the energy that is used today comes from fossil sources such as oil, coal and natural gas. Although these sources are being produced continuously by nature, the consumption rate is greater than production, turning them into a finite resource, especially oil. By 2040, about half of the energy supply will come from renewable sources. Thus, the foreseeable shortage of fossil fuels is a reason for studies on alternative fuel sources for this purpose.

Due to the incomplete burning of fuel in compression ignition engines, polluting residues (NOx) are formed and expelled in the exhaust process (Crolla, 2011). NOx elimination through the reaction with oxygen in the exhaust (excess air) is difficult and the catalytic converters efficiency in engines of this type is lower when compared to Otto cycle engines, making this pollutant emission an environmental problem.

To reduce emissions and obey current standards, there are alternatives such as turbochargers, exhaust gas recirculation system, intake and exhaust valves opening time control, selective catalytic reduction system, dual cycle use and ottolization of compression ignition engine. However, with biodiesel percentage updating in standard diesel fuel and changes in emissions legislation, a greater and constant effort will be necessary to reduce pollutants effects.

Until January 1st, 2023, the Air Pollution Control Program for Motor Vehicles phase 8, *(Programa de Controle da Poluição do Ar por Veículos Automotores fase 8, Proconve P8)*, will come into effect in Brazil. This new phase follows the standards of the European standard Euro 6, into effect in Europe since 2013, and which allows about 80% less emissions than Euro 5, on which Proconve P7 is currently based in Brazil. Proconve P8 will be regulated by National Environment Council *(Conselho Nacional do Meio Ambiente, Conama)* Resolution 490/2018, which is about the pollutants gases emissions and noise control for new heavy-duty vehicles. Another regulatory factor to be taken into account is Resolution 16/2018 of the National Energy Policy Council *(Conselho Nacional de Política Energética, CNPE)*, which establishes the gradual addition of 15% biodiesel to standard diesel until 2023.

Aiming a quick solution, which did not require engine or vehicle modifications and which met the pollutant legislation and the requirement to add biodiesel to diesel oil, the use of biodiesel in greater proportion in pure diesel oil and pure biodiesel was analyzed. For this, tests were carried out with three fuels: standard diesel, with 10% biodiesel (B10), to serve as a basis for comparison; pure diesel with the addition of 15% biodiesel (B15), in order to assess the biodiesel percentage increase effects proposed by CNPE Resolution 16/2018; and pure biodiesel (B100) to analyze the using possibility of this fuel without the diesel oil need.

On chassis dynamometer tests with each fuel in one vehicle, maximum torque and power were measured. At the speeds at which one of these points occurred and at idle speed, measurements of exhaust gases opacity and composition were made.

When talking about emissions reduction, one should also remember this type of research importance for the population well-being and not just as a mandatory technological update. With Proconve P8 implementation, there will be a reduction of up to 99% of emissions, as particulates. This will be a great contribution to Brazilian’s life quality, as it may reduce the risks of heart disease, lung cancer and stroke and, with that, the costs of medical care (MMA, 2018).

1.1 National Energy Balance

The National Energy Balance *(Balanço Energético Nacional, BEN)* is the all energy sources types sum that have been offered and consumed over a year, covering the activities of primary energy resources extraction, their conversion into secondary forms, import and export, distribution and the energy end use (EPE, 2018).

Among the most common sources produced by Brazil are: hydroelectric power, gasoline, diesel oil, biodiesel, ethanol, natural gas and mineral coal.

According to BEN 2018, renewable energies share in the Brazilian Energy Matrix was 42.9% and remained among the highest in the world. The increase in natural gas was mainly offset by wind (21.3%), bleach (50.6%) and biodiesel (19.7%). Also, according to BEN 2018, biodiesel had a 11.8% increase in the 2017 compared to 2016.

Regarding energy consumption in transportation in 2017, there is a considerable difference between diesel oil (44%) consumption and other fuels (gasoline: 29.4%; ethanol 16.4%; natural gas 2.1%) consumption, including biodiesel (3.3%), which is still used only in the mixture with diesel oil.

Concerning energy production generated emissions, SEEG (2018) shows that the main branch of activity responsible for the generation of greenhouse gases (GHG) is transport (4.8 million tons).

Among transport, SEEG (2018) states that diesel oil consumption was considerably higher than other fuels, surpassing the mark of 35 million tons, while the second placed, automotive gasoline, reached about 25 million tons.

Conforming to SEEG (2018), the use of diesel oil accounted for 55% of greenhouse gas emissions in 2017, becoming this another reason for the application of its gradual reduction and, later, replacement by a lesser source harmful, such as biodiesel.

2. METHODOLOGY

The tests were carried out on the Servitec Model 2020RB chassis dynamometer at the Rocket Performance workshop, located at Avenida Barão de Mamanguape, 334, Torr, in João Pessoa/PB.

2.1 Equipment

2.1.1 Vehicle and engine

A vehicle Chevrolet S10 LT, year of manufacture and model 2016, was used to carry out the tests, with all the original factory systems. This vehicle was kindly provided by the UFPB Garage and had appropriate characteristics such as a compression ignition engine, the ability to transport both loads and passengers, a modern electronic injection system, as well as a suitable size for the dynamometer.

The Chevrolet S10 turbocharged engine technical specifications are shown in Table 1. It is necessary to pay attention to the fact that the maximum torque and power data presented in Table 1 are measured on a bench dynamometer. The engine torque is measured at each rotation and the power is the result of torque and rotation multiplication (Mollenhauer; Tschoeke, 2010). In this type of measurement, transmission-to-wheels losses, water pump operation losses, tires-to-ground friction losses, among others, are disregarded. Therefore, values shown in Table 1 are higher than those obtained during the test on the chassis dynamometer with common diesel oil.

Table 1. Chevrolet S10 year/model 2016 turbocharged engine data (adapted from Chevrolet, 2015).

TYPE	Longitudinal
NUMBER OF CYLINDERS	4 (in line)
DISPLACEMENT	2768 cm³
COMPRESSION RATIO	16.5:1
IGNITION SEQUENCE	1-3-4-2
POWER	147 kW (200 CV) @ 3.600 rpm
TORQUE	500 Nm (51 mkg.f) @ 2000 rpm
IDLE SPEED	740 ± 50 rpm

The Chevrolet S10 automatic transmission ratios are: 1st gear 4.06: 1; 2nd gear 2.37: 1; 3rd gear 1.55: 1; 4th gear 1.16: 1; 5th gear 0.85: 1; 6th gear 0.67: 1; reverse gear 3.20: 1 and differential transmission ratio 3.42: 1 (Chevrolet, 2015).

2.1.2 Digital Opacity Pump

The digital opacity pump, or opacimeter, has the function of determining soot concentration present in exhaust gases from the combustion system. With this information, it is possible to assess whether these systems are within the permitted limits.

The opacimeter used in this work was model 308 of the German brand Testo, shown in Figure 1.

Figure 1. Testo 308 opacimeter (1) Filter paper, (2) Probe tube, (3) Access to filter paper, (4) Maintenance cover, (5) Condensate reservoir, (6) Condensation outlet opening, (7) Gas outlet, (8) Screen, (9) Function buttons, (10) On/off button (Author, 2019).

This instrument has a photodiode sensor, responsible for converting the light signal into an electrical signal that can be processed by its electronic circuit and printed as a circular grayish soot, exemplified in Figure 2. Its resolution is 1 cf, accuracy of +/- 0.2 cf and measurement samples volume of 1.63 +/- 0.1 reference liter (Testo, 2012).

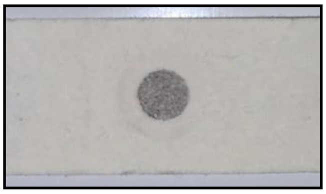

Figure 2. Soot stain printed on filter paper (Author, 2019).

To use this opacimeter, it is necessary to start with a leak test by drawing air for up to 30 seconds with the probe tube closed. If the instrument is watertight, before the end of the test, the message “Test OK” is displayed. Then, press “End”, make the test setup and select whether the fuel used is derived from petroleum or not. Finally, it must be checked that the condensate tank, the particulate filter and the measuring cap are as indicated in the manual. After all preparation, the tip of the probe tube can be placed at the point where the exhaust gas temperature is highest and press “Start”, initiating the measurement. The panel indicates the elapsed measurement time and, when completed, a soot stain is printed on the filter paper and the registered opacity index is displayed on the screen (Testo, 2012).

2.1.3 Gas Analyzer

The gas analyzer is responsible for capturing a certain exhaust gas flow from a vehicle and analyzing its composition informing the concentration of gases that have been selected by the user.

In this paper, a gas analyzer of the MRU brand, model OPTMA 7, shown in Figure 3, was used, which makes it possible to select fuel type, carrying out tests conditions, the gases to be evaluated and measurements limits (Confor, 2013).

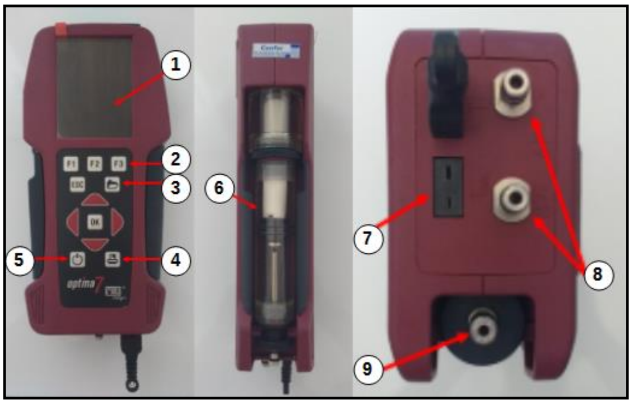

Figure 3. MRU OPTMA 7 gas analyzer (1) Screen, (2) Function keys, (3) Menu key, (4) Print key, (5) On/off, (6) Condensation separator, (7) Thermocouple connector, (8) Pressure connectors, (9) Sampling connector (Author, 2019).

To start a test, it is necessary to first perform the equipment zeroing process. Then, a pre-defined analysis program and the fuel must be selected. Finally, the thermocouple and the probe are attached to the equipment. After these steps, the measurement begins by inserting the sampling probe, which can be seen in Figure 4, in the vehicle's exhaust pipe and awaiting the measurement completion. During the test, gases come out of the analyzer through openings in the rear that must not be blocked at any time. After the test is completed, it is necessary to purge the remaining gases.

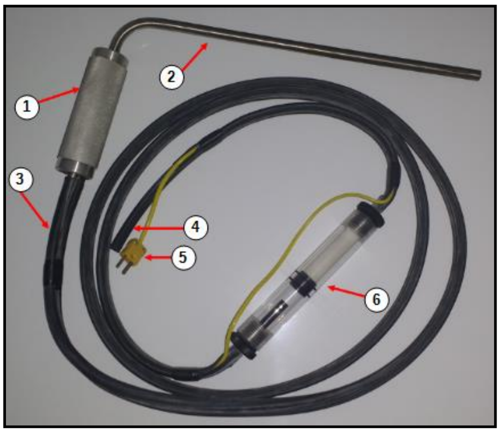

Figure 4. Probe (1) Handle, (2) Sampling probe, (3) Sampling hose, (4) Sampling connector, (5) Thermocouple connector, (6) Filter holder (Author, 2019).

2.1.4 Inertial Chassis Dynamometer

A chassis dynamometer of the Brazilian brand Servitec, model 2020RB shown in Figure 5, was used during the tests and is one of the most modern found today. This equipment is powered by a voltage of 220 V, supports vehicles with power up to 1043.98 kW and a maximum speed of 300 km/h (Servitec, 2019).

Figure 5. Servitec Model 2020RB Dynamometer (Author, 2019).

Its structure is reinforced and composed of an 18-inch roller with high precision balancing, external control panel, electromagnetic brake, without friction, which allows the vehicle to be controlled through the parameters of rotation, of speed, of time or percentage of braking. It also dispenses with the vehicle's brake use to make quick stops and load cell, allowing to perform torque and power measurements in real time. All collected data are presented using the WinSSDino software (Servitec, 2019).

2.2 Tests Description

During the tests, maximum torque and power, exhaust composition and opacity were evaluated.

For each of the analyzed parameters, three tests were performed. In the first test, standard diesel was used, currently sold at gas stations and which contains 10% of biodiesel (ANP, 2019). In the second test, a mixture of 15% biodiesel was used in pure petroleum diesel (obtained at the distributor before the addition of biodiesel), in order to analyze the effect of this biodiesel percentage, which should be present in the standard diesel by the end of the year 2023, according to CNPE Resolution 16/2018.

The last test was done using 100% biodiesel to analyze the effects of using this pure fuel on the parameters that were analyzed.

The steps for carrying out the tests were as follows: first, it was necessary to attach the vehicle on the dynamometer platform using straps (Figure 6). Then, the exhaust fans were turned on, both for cooling the vehicle and for circulating air in the environment where the tests were taking place.

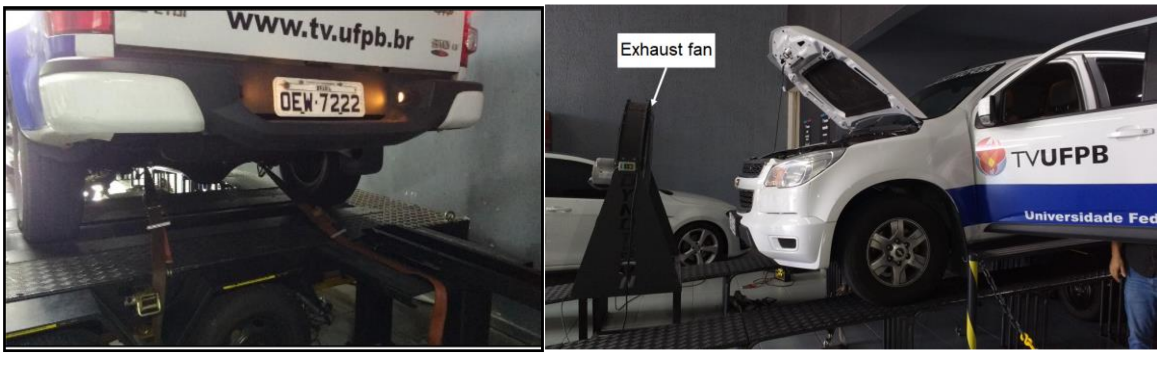

Figure 6. Vehicle attaching to the dynamometer base and exhaust fan for cooling (Author, 2019).

Initially, for each fuel, maximum torque and power measurements were made. Then, the opacity and the gas analysis were obtained at idle speed, at the maximum torque rotation and at the maximum power rotation. Therefore, these steps were repeated three times: once for B10, once for B15 and once for B100. For each fuel and speed range evaluated, opacity measurement and gas analysis were performed for one minute, as shown in Figure 7.

Figure 7. Example of analyzer and opacimeter positions (Author, 2019).

Due to the high temperature of the equipment (dynamometer and opacimeter), it was necessary to make an interval between the opacity measurements and gas analysis from one rotation range to another, so that there was time to return to the proper operating temperature. The exhaust gas parameters measurement was made after stabilizing the speed at which it was desired to collect the data. The same happened in the tests at the maximum power speeds.

3. RESULTS

During measurements related to exhaust gases at maximum power rotation, the load cell was maintained at 0.7 kgf.m. In maximum torque rotation, the value was between 0.6 and 0.7 kgf.m.

Table 2 shows the speed values obtained for idling, maximum torque and maximum power in each tested fuel.

Table 2. Rotations for each condition analyzed (Author, 2019).

FUEL	CONDITION	SPEED [rpm]
B10	Idle speed	740 ± 50
	Max. torque	2220
	Max. power	3500
B15	Idle speed	740 ± 50
	Max. torque	2320
	Max. power	3480
B100	Idle speed	740 ± 50
	Max. torque	2350
	Max. power	3480

3.1 Exhaust gases

3.1.1 Opacity

Table 3 shows the opacity index values obtained in each test. Testo 308 device measuring range varies from 0 to 6 and values above this indicate that the opacity is outside the limit established by the standard of your country of origin, Germany. In Brazil's case, where Proconve P7 is in effect and allows higher values, there is no mistake in finding results greater than 6.

Table 3. Results of exhaust gas opacity (Author, 2019).

	CONDITION	B10	B15	B100
OPACITY	Idle speed	5,2	4,9	5,7
	Max. torque	7,8	6,6	**6,3**
	Max. power	7,3	6,9	**6,5**

When analyzing the values in Table 3, it is noted that B10 biodiesel, current standard diesel, presented worse values than the others in two conditions where the engine is more required and which can occur with a certain frequency, especially when it comes to vehicles carrying a large number of passengers or cargo. On the other hand, the B100 proved to be much more efficient in these situations, presenting, with the exception of the idling condition, lower values of opacity than the B10 and B15.

The B100 opacity evaluation showed a 19.23% reduction as the best result compared to B10 in the maximum torque condition, indicating that less particulate matter is present in the exhaust gases when the B100 is used.

3.1.2 Gas Composition Analysis

Table 4 and Table 5 show the results obtained for CO2 and NOx in the exhaust gases concentration.

Regarding CO_2 emissions, the tests show that the B100 achieved positive results only in the idle situation, while the B15 was better at maximum torque and the B10 at maximum power. However, it is necessary to emphasize that the cultivation of vegetable sources for the production of biodiesel absorbs part of this CO2 when carrying out the photosynthesis process during its growth, reducing the emission impact of this particular gas.

Table 4. CO_2 percentage present in the exhaust gases (Author, 2019).

	CONDITION	B10	B15	B100
CO_2 (%)	Idle speed	0,89	1,24	**0,82**
	Max. torque	7,49	7,41	7,47
	Max. power	2,71	3,05	3,8

Table 5 shows that in tests the B100 was able to obtain positive results in practically all conditions. According to Demirbas (2008), NOx forms oxidants such as ozone (O_3), which causes eyes and respiratory system irritation and constitutes smog, a fog of pollution that makes visibility difficult, contributing to the greenhouse effect and acid rain, its reduction being an important factor in favor of biodiesel.

Table 5. Concentration of NO, NO_2 and NOx in the exhaust gases (Author, 2019).

	CONDITION	B10	B15	B100
NO (ppm)	Idle speed	126	133	**109**
	Max. torque	622	590	**180**
	Max. power	260	217	235
NO_2 (ppm)	**CONDITION**	**B10**	**B15**	**B100**
	Idle speed	34	23	**19**
	Max. torque	238	291	**49**
	Max. power	76	116	140
NOx (ppm)	**CONDITION**	**B10**	**B15**	**B100**
	Idle speed	160	156	**128**
	Max. torque	860	881	**229**
	Max. power	336	333	375

3.2 Performance

Performance tests carried out with the Chevrolet S10 followed the SAE J1349 standard, which certifies that the power and torque values provided are true (SAE, 2019).

3.2.1 Maximum power

Figure 8 shows the power graph (whp - power on the wheel) per rotation of the three fuels analyzed.

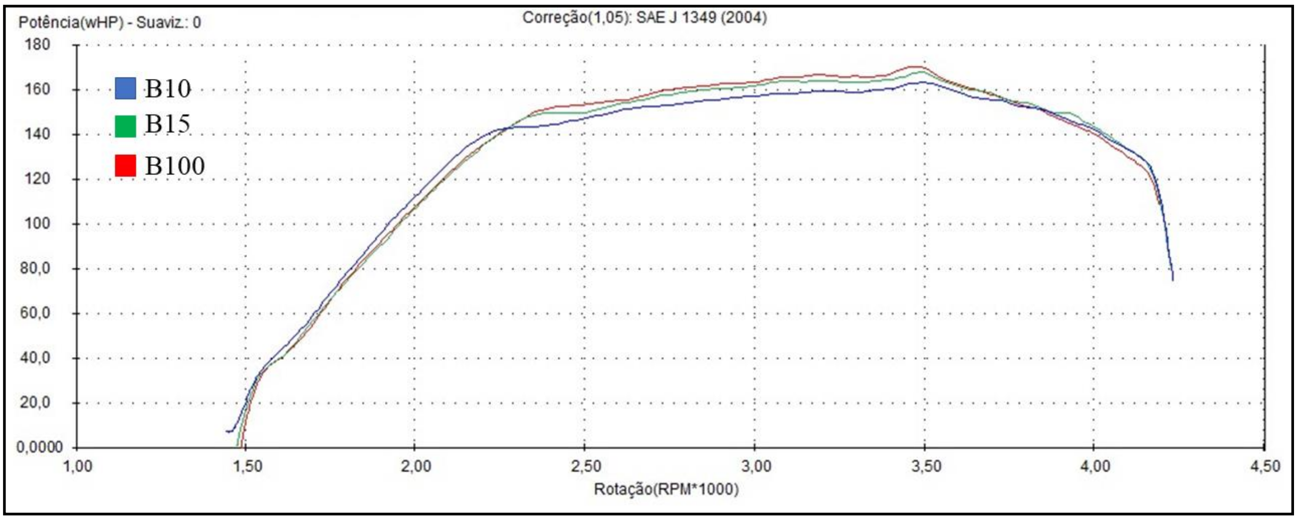

Figure 8. Power curves for B10, B15 and B100 (provided by Rocket Performance, 2019).

From the graph, it is possible to see that the B100 showed a slight advantage over the others. Table 6 shows the maximum values obtained for the powers and conditions under which the tests were performed.

Table 6. Maximum power results for B10, B15 and B100 (Author, 2019).

Fuel	Maximum power (wHP)	Speed (rpm)	Pressure (kPa)	Temperature (ºC)	Relative humidity (%)
B10	163,21	3500	100	34,7	44,40
B15	167,91	3480	99,9	36,3	39,20
B100	170,53	3480	99,9	36,1	42,80

3.2.2 Maximum Torque

Figure 9 shows the graph of torque per rotation of the three fuels analyzed.

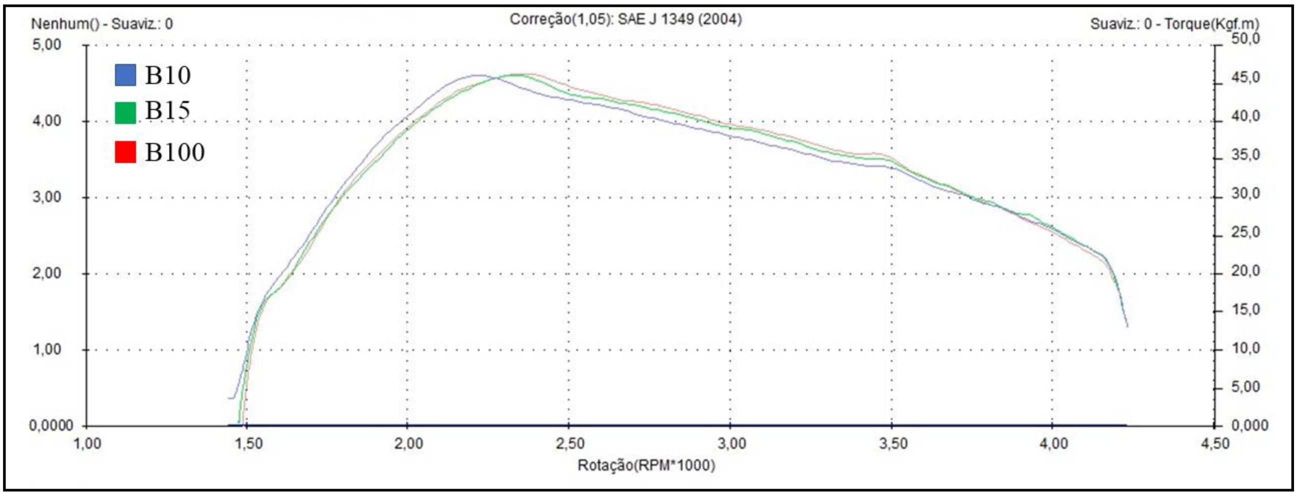

Figure 9. Power curves for B10, B15 and B100 (provided by Rocket Performance, 2019).

Table 7 shows the maximum values obtained for the torques and the conditions under which the tests were performed.

Table 7. Maximum torque results for B10, B15 and B100 (Author, 2019).

Fuel	**Maximum torque (kgf.m)**	**Speed (rpm)**	**Pressure (kPa)**	**Temperature (ºC)**	**Relative humidity (%)**
B10	46,04	2220	100	34,7	44,40
B15	46,1	2320	99,9	36,3	39,20
B100	46,26	2350	99,9	36,1	42,80

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