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Combustion analysis of ternary mixtures of diesel oil, biodiesel, and refined soybean oil: a view of cylinder pressure

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ABSTRACT. Currently, the high consumption of fossil fuels is causing problems, perhaps, irreversible to the planet, investing in green energy is an essential point for the sustainable development of any country. Concomitant to this, biomass fuels, in particular natural vegetable oils, appear as an option for the total or partial replacement of these fuels in the production of energy in the current world energy matrix. Corroborating this pretext, the objective of this work is to analyze the effects of using different mixtures of Brazilian commercial diesel oil (92% diesel, 8% biodiesel) with refined soybean oil from the effective cylinder pressure of a stationary diesel generator set. To achieve this purpose, the generator set of the Branco brand, model BD-6500, was used, with the aid of the pressure acquisition system of the Austrian company AVL. Analyzes of the requested fuels were carried out in addition to the experimental tests. The results presented show that the use of mixtures with volumetric ratios of soybean oil may show a drop in the cylinder pressure.

Keywords: diesel generator sets; fuel mixtures; B8 diesel oil; refined soybean oil; AVL.

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Introduction

Currently, fossil fuels are burned in large quantities to satisfy the high global energy demand resulting in the emission of polluting gases that seriously damage the ecosystem on a global scale (Jia, Alva, & Fang, 2019). The decarbonization of the energy sector is a prerequisite for the sustainable growth of the economy. The global energy sector is expected to undergo notable changes and includes a significant increase in the production of energy from renewable sources (Sedlar, Vulin, Krajačić, & Jukić, 2019).

Bearing this in mind, with the advance of modern technology, there are several renewable energy sources, among them, we can mention, based on Inayat and Raza (2019), Werner (2017), and Owusu and Asumadu-Sarkodie (2016), energy biomass, hydroelectric energy, geothermal energy, solar energy, wind energy and ocean energy (tide and waves), which are also the best approaches to combat the environmental challenges generated by fuels used today.

Although the most familiar forms of renewable energy sources are wind and solar, according to Tajeddin and Roohi (2019), historically biomass has been one of the oldest and most dominant sources of energy, having been used since humans discovered fire. This source, in turn, is also the raw material used to produce liquid, solid and gaseous fuels.

According to Bórawski et al. (2019), liquid fuels from biomass including natural vegetable oils, biodiesel, bioethanol, and biometanol, have several applications in the face of modern society. That said, based on the author, the situation on the market and the growing demand for green energy suggest that the production of this type of energy will increase until 2030, contributing exponentially to the development of this sector.

Thus, several countries, in the last decades, have been developing research aiming at such energy sources, making research on natural vegetable oils, for example, generating a great repercussion in scientific circles and having a varied range of references (Pechout et al., 2019; Danish & Wang, 2019; Nanlohy, Wardana, Hamidi, Yuliati, & Ueda, 2018; Delalibera et al., 2017; Capuano, Costa, Di Fraia, Massarotti, & Vanoli, 2017; Campos, Martins-Nogueira, & Lima-Tostes, 2015).

Concomitantly to this, in Brazil, fossil fuels have several uses, ranging from transporting people and loads (Loureiro, Figueiredo, Campos Filho, & Filgueiras, 2022) to even generator sets used to meet the demand for electricity from communities isolated from the electricity grid, mainly in the northern region of the country. Thus, in some areas of the interior of the aforementioned region, energy service is provided by the "Isolated Systems" program, basically composed of a high number of small generating units consuming diesel oil and characterized by great difficulty in supply logistics (ONS, 2018). However, the thermal generating units have low conversion efficiency inherent to losses from internal combustion engines. These units are regulated by the National Electric Energy Agency (ANEEL) which establishes targets for fuel consumption limits to pressure generating companies to seek alternatives and more efficient operating methods (Brasil, 2017).

Data provided by EPE, Energy Research Company (Empresa de Pesquisa Energética [EPE], 2017) of the Ministry of Mines and Energy of Brazil (MME), report more than 2.16 million cubic meters of diesel oil were used in power generation in Brazil in 2016, and the use of just over one million cubic meters for the generation of 1,812,831 megawatts planned for 2019, only in isolated systems in northern Brazil (Operador Nacional do Sistema Elétrico [ONS], 2018).

With this in mind, there is a clear need to increase efficiency in the use of renewable fuel mixtures in the country, being an area of knowledge explored in different ways in the literature, not only in Brazil, but worldwide, and it can cite works by countless authors, biodiesel-diesel mixtures (Mirhashemi & Sadrnia, 2019; Pires de Oliveira & Caires, 2019) as mixtures of natural vegetable oil and mineral diesel (Al Omari, Hamdan, Selim, & Elnajjar, 2019; Deivajothi, Manieniyan, & Sivaprakasam, 2018; Hashimoto et al., 2018; Emberger, Hebecker, Pickel, Remmele, & Thuneke, 2015).

Thus, soy oil appears as a viable option for the fuels used today, since Brazil is the second-largest producer of grain in the world (Teixeira & Neto, 2018; Lameira, Filgueiras, Botter, & Santos Saavedra, 2020) at a cost relatively low, and according to Faleiro and Andrade (2009) and Menegatti and Barros (2007), the product can be genetically adapted for planting in any region of the country, even in areas poorly adapted to cultivation, causing logistical problems, for example, are minimized.

In addition to this, it is also necessary to study strategies that enable the adaptation of compression ignition combustion engines to new fuels (Kannan & Anand, 2012; Papagiannakis, Krishnan, Rakopoulos, Srinivasan, & Rakopoulos, 2017), since the geometric construction relationships and operating parameters are developed to consume mineral diesel oil. To reach the point of calibration and regulation of such parameters, several operational ranges of the generator set must be evaluated, such as pressure, emissions, and operating temperatures, for example.

Based on this problem of an economic, political, environmental, and technical nature, the objective of this work is to analyze the effects of using different mixtures of commercial Brazilian diesel oil (92% diesel, 8% biodiesel) with refined soybean oil from the pressure of the cylinder of a stationary diesel generator set. Upon completion of this procedure, numerous economic and environmental advantages are expected from the generation of cleaner and quality energy at a lower cost.

Fuels

Diesel oil

Diesel oil, which was named after the German engineer Rudolf Diesel, is a fuel of complex composition derived from petroleum, consisting basically of paraffinic, olefinic, and aromatic hydrocarbons and, to a lesser extent, of substances whose chemical formula contains atoms of sulfur, nitrogen, metals, oxygen, among others (Ferreira, Santos, Souza, Polito & Módolo, 2008).

Traditionally, diesel oil is used in compression ignition combustion engines, which bear their name (Diesel cycle engines), used in the most diverse applications, such as automobiles, vans, buses, trucks, small marine vessels, large machines, locomotives, ships, and stationary applications (electric generators, for example) (Confederação Nacional De Transportes [CNT], 2012). The production of this oil takes place through the fractional distillation process, at a temperature between 250 and 350°C.

Diesel oil is the most consumed petroleum derivative in Brazil due to the predominance of road transport, both for passengers and cargo (Agência Nacional de Petróleo [ANP], 2018). In the country, according to article 2 of Resolution no. 42, of December 16, 2009, of (Agência Nacional de Petróleo [ANP], 2009), diesel oils are classified, to the addition of biodiesel, as diesel oil A, fuel produced from petroleum refining and natural gas processing processes, without adding biodiesel; and diesel oil B, obtained from the addition of biodiesel to diesel oil A, and currently, according to law 13,263, of March 23, 2016 (Brasil, 2016), Brazilian commercial diesel (B8) is required to contain 8% by volume of its biodiesel composition.

Refined soybean oil

Vegetable oils are substances insoluble in water, hydrophobic, and formed mainly by triglycerides (esters), being present in proportions of 90-98%, together with a smaller percentage (1-5%) of free fatty acids. Triglycerides are products originating from the condensation of one molecule of glycerol (glycerin) and two (or even three) fatty acid molecules; and are classified as simple and mixed, according to their composition (Kathirvelu, Subramanian, Govindan, & Santhanam, 2017). According to in general, vegetable oils are composed of 98% mixed triglycerides, which are classified as such by presenting the three groups of fatty acids (radicals) in their molecular structure. The general chemical structure of vegetable oils is shown in Figure 1, according to Rocha (2017).

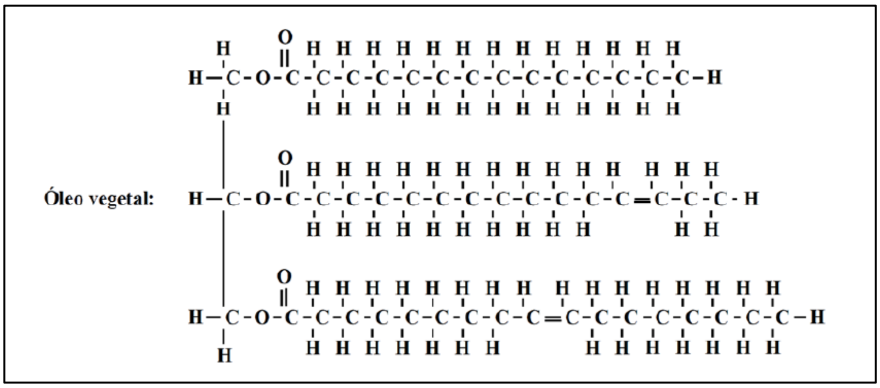

Figure 1. Molecular structures typical of vegetable oil.

Soybean oil, extracted from soybean seed, is strongly used as a food source and with new technologies, it can also be used as biofuel. Soy (Glycine max (L) Merrill) belongs to the legume family, plants whose seed is inside pods. To extract the oil, as well as most vegetable oils, it is necessary to place its seeds in a high-pressure press that will squeeze them until all the oil contained in them is removed. The high pressure causes positive temperature variations which makes the oil dark in color and taste strong. After the press, the clarification and refining process is carried out to eliminate impurities. The final product is called virgin oil, which must be free of solid particles and foreign bodies.

Concomitantly to this, according to Almeida, Andrade, and Santos (2018), Brazil is a country mainly agricultural and has a vast amount of fertile land and a climate conducive to the cultivation of different oil crops, data from Teixeira and Neto (2018) and Lameira et al. (2020) state that, in 2017, Brazilian soy production reached historical records, and in 2018 it reached 107 million tons, with most of this product having the purpose of export and making the country considered the second-largest producer of grain on the planet, with a share of more than 18% of world production.

In addition to this, there are several advantages to the use of soybean oil in combustion engines, especially in the case of isolated areas, for example. The main ones, according to Campos, Martins-Nogueira, and Lima-Tostes, (2015):

- It is a renewable fuel.
- Its physical and chemical characteristics allow its replacement in place of diesel oil.
- Can be produced close to its consumption, simplifying supply logistics.
- It makes it possible to concentrate financial resources in the production region.

However, according to Bousbaa et al., 2012 and Leenus et al (2012), characteristics intrinsic to vegetable oils in general, such as flash point, low volatility, accumulation of carbon residues, and high viscosity interfere with the performance of the MCI by causing a blockage in the injector nozzles, carbonization of the chamber of combustion, clogging of the fuel filter, contamination of the lubricating oil, worsening the situation with the operation of the generator set at low loads. To minimize some of these interoperations, this research opted for the use of refined soy oils, reducing the number of particulates and preventing contamination of the lubricating oil for example.

Material and methods

To elucidate the analysis in the best way, Figure 2 presents a flowchart with the methodology applied to this research. The methodological approach was divided into two parts. Being objective and direct, the first section, named fuels, has as its main focus the detailed study of the physicochemical characteristics of B8 diesel oil and refined soybean oil; and the second section, intended to achieve the general objective of this research, named Branco, aims to analyze the effects of adding soybean oil to Brazilian commercial diesel on the pressure inside the cylinder of the internal combustion engine Branco, model BD-6500 CF3E. The following sections are intended to present the methodology clearly and concisely.

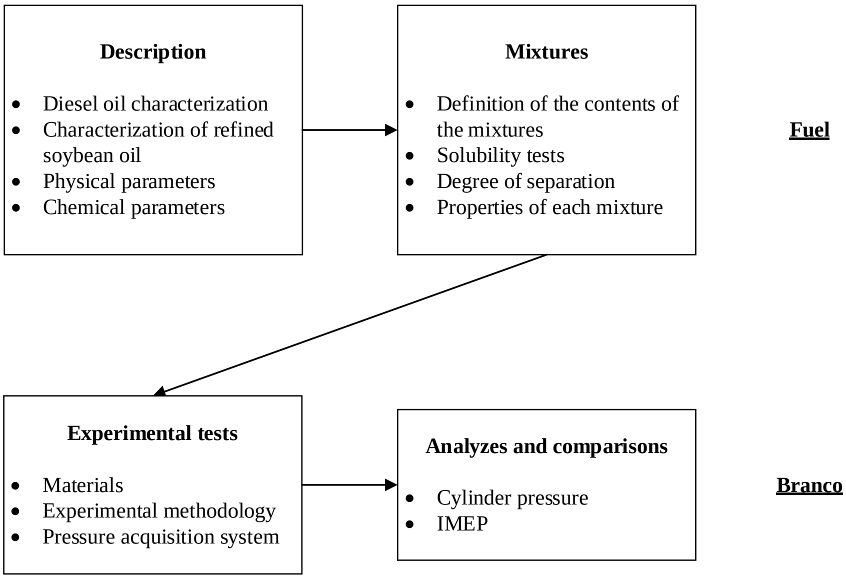

Figure 2. Graphic systematization of the research.

Selected fuels

The fuels selected for this research were diesel oil S-10 B8, composed of a mixture of 8% biodiesel by volume in diesel oil and refined soybean oil. The main physical and chemical properties of both fuels are shown in Table 1, according to the Biofuel Characterization Laboratory of the Federal University of Pará - LACBIO / UFPA and the authors Agência Nacional de Petróleo (ANP, 2013); Rocha (2017) and Capuano et al. (2017).

Table 1. Physical and chemical characteristics of the fuels used.

Properties	Diesel B8	Refined soybean oil
Empirical chemical formula	$\approx C_{6,9}H_{14,8}O_{0,05}S_{0,026}$	$C_{6,2}H_{11,42}O_{0,38}N_{0,46}S_{0,05}$
Aspect	Clear	Clear
Flashpoint [°C]	38	254–334
Density. at 20°C [kg m^{-3}]	872.7	910–924
Viscosity 40°C	2.9	33
Cetane number	48	37
PCS [kJ kg^{-1}]	43942	40580
PCI [kJ kg^{-1}]	40687	38070
h_f° [kJ kmol^{-1}]	-461218	234230
C [%]	83.42	74.4
H [%]	14.91	11.42
O [%]	0.81	7.725
N [%]	0.00	6.455
S [%]	0.84	1.79

The percentages of the mixture, in volume, selected for the experimental run were defined, these are shown in Table 2, the miscibility analysis was performed, and no separation was found after observation for 30 days of the selected mixtures.

Table 2. Mixtures used in the research.

B8	SOYA 2%	SOYA 6%
Pure B8 diesel	98% B8 diesel + 2% Refined soybean oil	94% B8 diesel + 6% Refined soybean oil

Branco generator set

For this research, the air-cooled single-cylinder generator set, brand Branco, model BD-6500 CF3E (Figure 3), with a maximum power of 10 hp (7.35 kW), 2.70 kgfm (2000 rpm), was used. Table 3 follows the general information of the generator set according to Branco (2012).

Table 3. General information on the Branco generator set.

Information	
No. of cylinders	1
Cooling type	Induced air
Start	Manual
Type of fuel	Diesel
Combustion System	Direct injection
Fuel injection angle	16° BTDC
Jacket diameter (mm)	86
Piston stroke (mm)	70
Displacement (cm^3)	406
Compression ratio	19:01
Maximum power	10.0 cv (3600 rpm)
Continuous Power	9.0 cv (3600 rpm)
Maximum Torque	2.70 kgfm (2000 rpm)
Weight (kg)	46
Lubrication	Forced by the oil pump
Noise Level (dBA)	79

Figure 3. Branco generator set.

Cylinder pressure acquisition system

The cylinder's real-time pressure acquisition system was supplied by AVL, to the Engine Laboratory of the Federal University of Pará - LABMOTORES / UFPA and is composed of a piezoelectric transducer responsible for generating the signal indicating the pressure, a pressure sensor. The rotation maps the angular position of the crankshaft, a device that processes and acquires the recorded data, as well as two software that provides thermodynamic models to determine combustion process parameters from the pressure measurement and graphical tools for monitoring the process in real-time.

The piezoelectric transducer is used as a pressure sensor in this work this sensor is built by a metallic body that covers the piezoelectric crystal and is instituted by a diaphragm at one of its ends. When subjected to a pressure variation, the diaphragm deforms acting on the piezoelectric crystal and producing an electrical signal proportional to the magnitude of the pressure applied to the diaphragm (Oliveira, 2016; Rocha, Pereira, Nogueira, Belchior, & Tostes, 2017). The technical data of the sensor are shown in Table 4 according to AVL (2016).

Table 4. Transducer specifications.

Specification	
Supplier	AVL
Model	GU21D
Pressure range	0 a 250 bar
Overload	300 bars
Life Estimate	⩾ 10^8 cycles
Linearity	⩽ 0.3 %
Natural frequency	≈ 85 kHz
Operating Temperature	-40 °C a 400 °C
Uncertainty	± 0.4 bar
Thread specification	M7x0.75
Installation torque	3.0 Nm

In the studies of phenomena in MCI, measurements are made on an angular basis, because it is more practical to analyze the behavior of the quantities relative to their positions, such as in the PMS, for example. For this work, the angular encoder for the crankshaft used was the Encoder 365C, with 0.5° precision, supplied by AVL, which works in sync with the pressure sensor. Figure 4 shows the sensor and Table 5 shows its technical information.

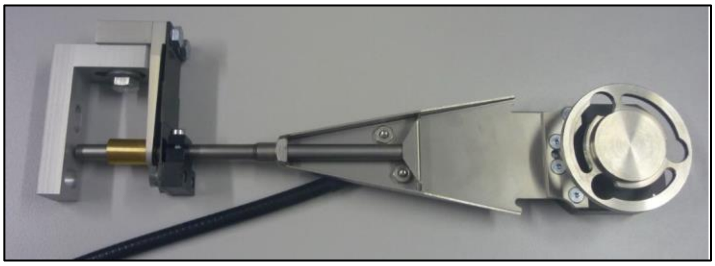

Figure 4. Rotation meter.

Table 5. Technical information of the rotation sensor.

365C Optical Sensor Encoder	
Manufacturer	AVL
Measuring range	50 a 20000 rpm
Allowable eccentricity	⩾ 0.1 mm
Resolution	0.5°

The next member of this acquisition system, the AVL Indimicro 602, is the unit responsible for data processing combining amplification and acquisition of the indicated pressure measurement and crank angle. The equipment still allows monitoring and analyzing the combustion process in real-time by making available graphic tools and thermodynamic models for the post-processing of data integrated into the AVL Indicom software platform. Figure 5 shows the basic layout of the system.

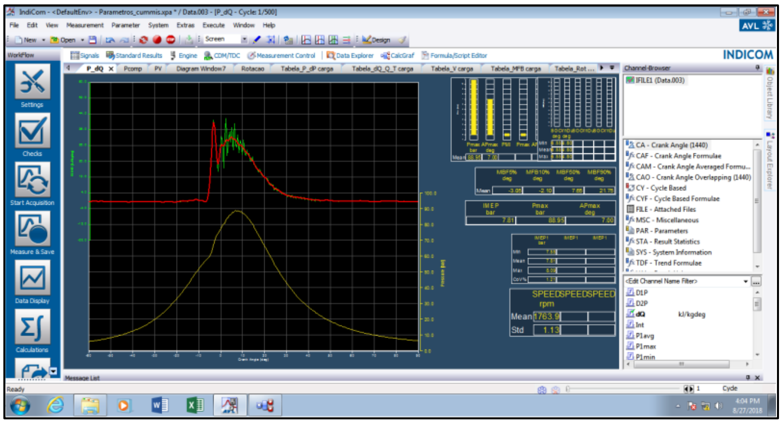

Figure 5. AVL Indicom software monitoring interface.

The thermodynamic models predefined by AVL Indicom are two, Thermodynamics1 and Thermodynamics2. For diesel cycle engines, AVL recommends using the Thermodynamics2 model because it considers the effects of changing the gas mass during combustion due to fuel injection (AVL, 2015). According to the AVL, the unit of the heat release rate and heat released parameters calculated, are standardized to the mass of gas (Kj kg^{-1} deg), to the volume (kJ m^{-3} deg), or the maximum heat release in percentage unit (%) (AVL, 2014).

The indicated mean pressure ($IMEP$) is the average pressure during the piston's downward stroke, and expansion, producing the same net work done by the cycle. It is calculated using equation (1), the integral of the curve of effective pressure $p(\theta)$ versus cylinder volume $V(\theta)$ for each crankshaft position.

$$IMEP = \frac{1}{V_d}\int p(\theta) \, . dV(\theta) \qquad (1)$$

Experimental tests

The experimental tests on the Branco generator set were conducted following these steps: initially, enough of each selected mixture were prepared to keep the generator set running constantly and without any interruption due to lack of fuel. Afterward, the tests were started consisting of feeding one of the selected fuels to the generator set and applying a total of three loads, starting with a load considered low, 40.64% of the engine power, moving to two higher loads, these being 81.55 and 100%, maintaining a time interval between loads sufficient for the system to operate at steady state and repeating the procedure for each fuel mixture.

Results

After all the proposed activities have been carried out, the figures below show the curves of effective pressure x crankshaft angle, comparing B8 diesel oil; SOYA2%; SOYA6% for each of the various loads applied. To have a better view of the burning event, it was decided, firstly, to display the complete cylinder pressure curve (Figures 6, 7, and 8), secondly, the specific range of occurrence of the combustion phenomenon, being specifically between -40 to 70° (Figures 9, 10 and 11).

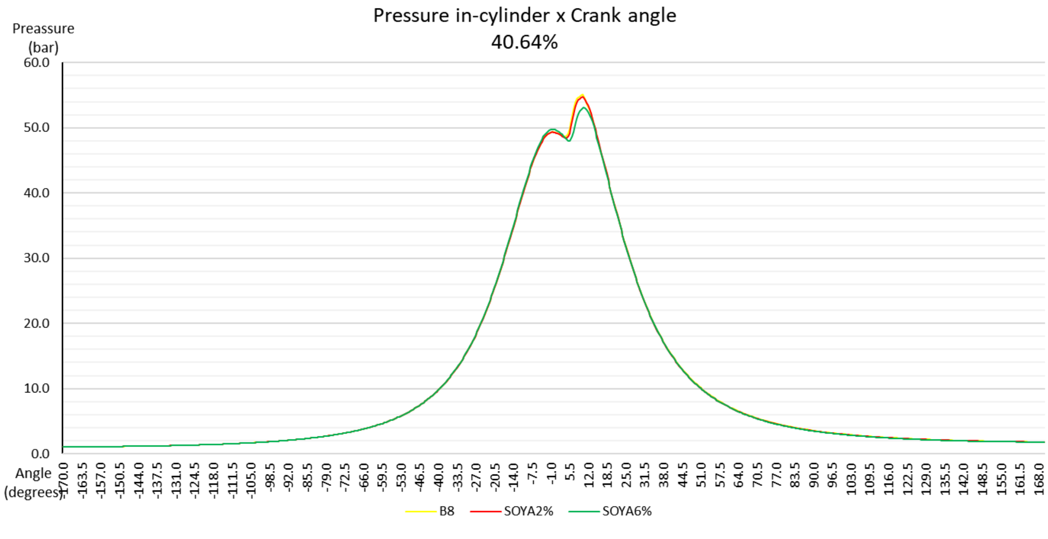

Figure 6. Pressure curve in-cylinder x crank angle for 40.64% load.

Analyzing the results for all loads (40.64, 81.55, and 100%) the pressure behaviors were approximated along the entire profile of the curves. However, it can be noted that all loads have a deviation in the profile of the curve located in the region of greater pressure, between the beginning and end of combustion, designated as the combustion zone.

The maximum pressure inside the cylinder mainly depends on the rate of fuel burned in the initial phase of combustion and is related to the amount of flammable air-fuel mixture formed during the ignition delay, thus, the increase in the maximum peak of pressure was the result of a large amount of heat released in the premixed combustion phase (Kuszewski et al., 2017).

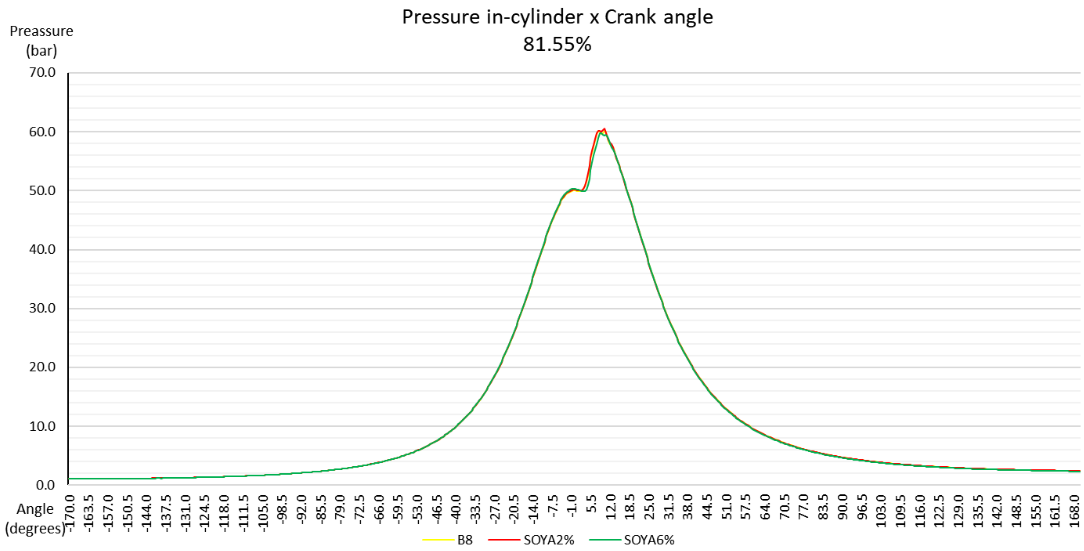

Figure 7. Pressure curve in-cylinder x crank angle for a load of 81.55%.

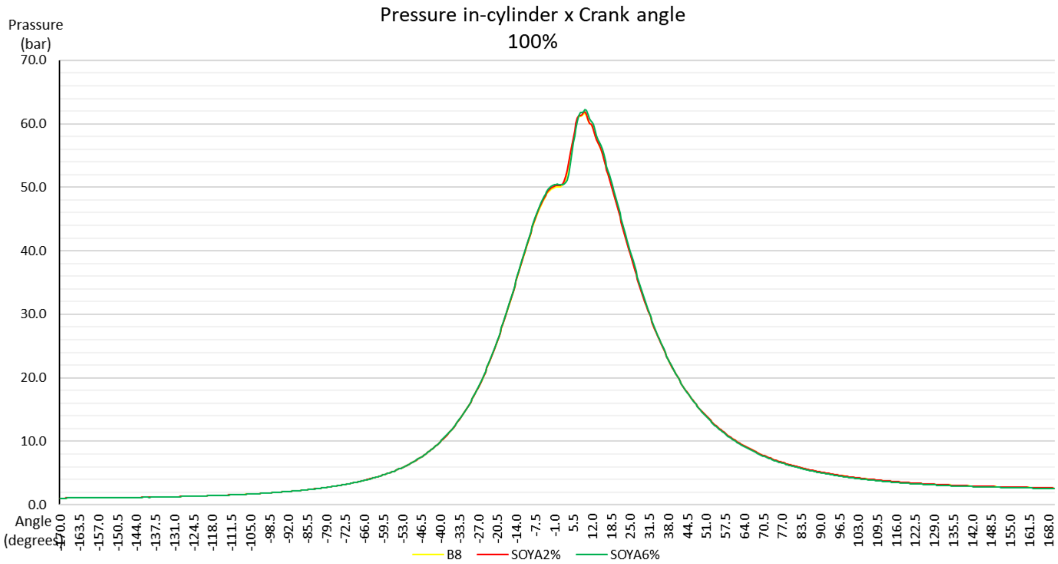

Figure 8. Pressure curve in-cylinder x crank angle for 100% load.

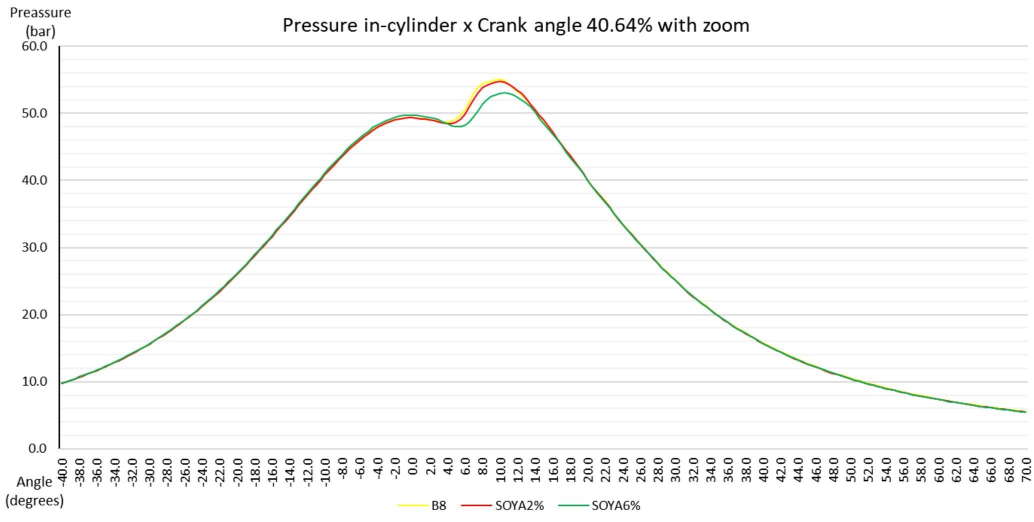

Figure 9. Pressure curve in-cylinder x crank angle for 40.64% load with zoom.

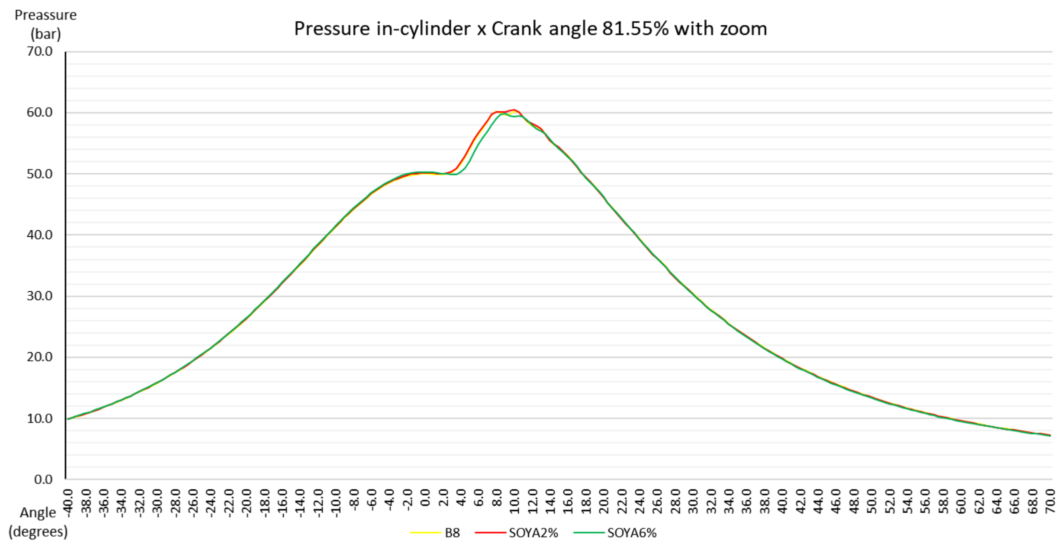

Figure 10. Pressure curve in-cylinder x crank angle for 81.55% load with zoom.

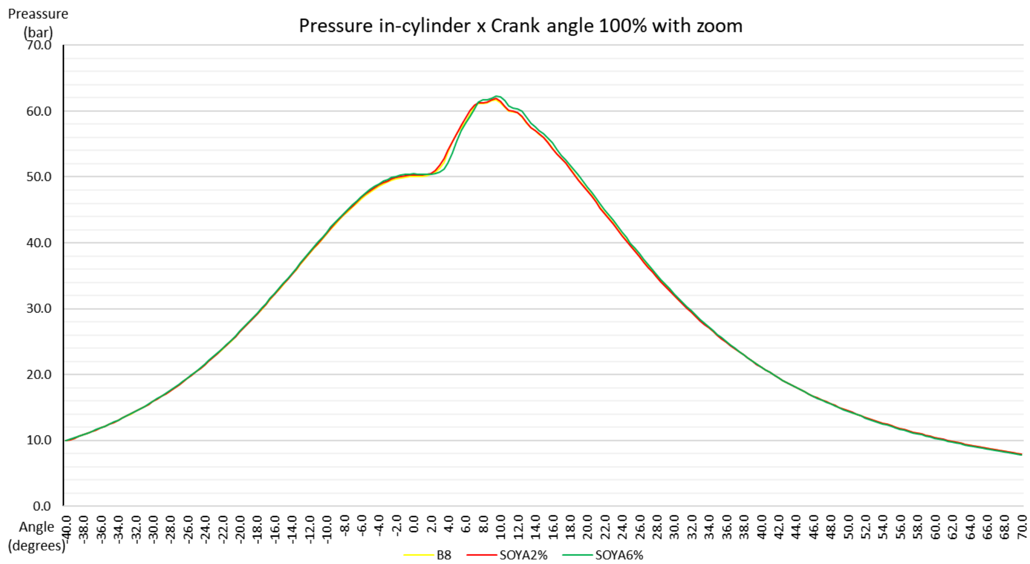

Figure 11. Pressure curve in-cylinder x crank angle for 100% load with zoom.

On the other hand, it is noticeable that the SOYA6% mixture (in green) obtained the lowest pressure values, within the pre-mixed combustion zone, even obtaining similar results to the baseline and SOYA2% for the 100% load. In turn, the SOYA2% mixture obtained results closer to the baseline, being close throughout the curve for all loads.

In comparison with the bibliography of the area, the results presented by Soltic, Edenhauser, Thurnheer, Schreiber, & Sankowski (2009), who experimentally investigated the combustion of mineral diesel oil, gas fuel for liquids (GTL), pure rapeseed methyl ester (RME), pure rapeseed oil and pure soybean oil, show a great similarity to the pressures achieved in the cases studied. Another peculiar point to be compared is that in their study, unlike the one presented in this section, the fuels showed almost no pre-mixed combustion for all fuels for all cases studied. The behavior was justified, as the study was carried out in a large ICE at low rotation, based on other authors in the area.

Partially differing from the curves presented in this work, Koder et al. (2018) – who studied the combustion and emission characteristics of a diesel engine fueling them with jatropha oil, soybean oil, and diesel – present results with diesel oil having the highest peak pressure in the pre-mixed combustion phase and practically the entire curve, considering that, despite having a higher value for the first peak than jatropha oil, soybean oil equals it for the rest of the curve; using this fact to justify the clear faster start of combustion for the two vegetable oils, which, for this work, there is a much smaller visible change.

For better comparative effect, the following tables (Tables 6, 7, and 8) show the value of the indicated average pressure ($IMEP$) of the cycle for each fuel and each selected load, as well as the percentage difference to the baseline made up of B8 diesel oil.

Table 6. $IMEP$ of mixtures for load 1 (40.64%).

	Load 1 - 40,64%		
	B8	SOYA2%	SOYA6%
$IMEP$ (bar)	2.48	2.42	2.38
Mixture/B8 (%)	0.000%	-2.419%	-4.032%

Table 7. $IMEP$ of mixtures for load 2 (81.55%).

	Load 2 - 81,55%		
	B8	SOYA2%	SOYA6%
$IMEP$ (bar)	4.47	4.44	4.28
Mixture/B8 (%)	0.000%	-0.671%	-4.251%

Table 8. $IMEP$ of mixtures for load 3 (100%).

	Load 3 - 100%		
	B8	SOYA2%	SOYA6%
$IMEP$ (bar)	5.14	5.12	5.09
Mixture/B8 (%)	0.000%	-0.389%	-0.973%

The indicated effective pressure is the one that meets the engine operating load. The IMEP increases for higher loads, since the amount of fuel injected, is greater (Papagiannakis et al., 2017). For load 1, lower $IMEPs$ were found for all mixtures due to the lower amount of fuel injected into the cylinder, producing less heat release and lower operating temperatures in the air-fuel mixture. Thus, following this logic, when increasing the load value, there is a higher compensatory fuel consumption due to the need to increase the release of heat and cause an increase in the IMEP, leading to an increase in the fuel-air ratio, occurring at a higher speed of reaction and resulting in less delay of the ignition and in the advance of the beginning of the combustion, thus, presented a larger IMEP for loads 2 and 3.

It is also worth mentioning that, according to the error range of the piezoelectric sensor, the indicated mean pressure results are very close. Thus, to have an in-depth analysis of the use of these fuels, other points of observation are needed to complement the cylinder pressure, such as specific fuel consumption and global efficiency, which are points of analysis for the future of this research.

Conclusion

The main objectives of this research were achieved. After the fuels were analyzed for their physical and chemical characteristics, the experimental apparatus was assembled and adapted to the selected single-cylinder, air-cooled generator set, brand Branco, model BD-6500 CF3E with a maximum power of 10 hp (3600 rpm) or 7, 35 kW, 2.70 kgfm (2000 rpm), the tests were performed generating the pressure curves and the indicated average pressure.

Firstly, it is exposed that the applied methodology is extremely efficient for the type of analysis sought, showing accurate results and consistent with the area's recurrent bibliography, being possible to be replicated in different ways for different generators and different fuels.

From the analysis of the experimental results, we can conclude that there is a decrease in the average theoretical pressure indicated by the comparative baseline, diesel oil B8, for the mixtures SOYA2% and SOYA6% in practically all the loads executed is noticeable.

Finally, analyzing the research as a whole and looking at the perspective of future work to make it more relevant to the area of combustion, it is necessary, first, an analysis of the overall efficiency of the selected fuels to measure how efficient they are compared to the baseline. To further deepen this research, it is necessary to redo the experimental tests with the aid of an exhaust gas analyzer, to measure more precisely the burning behavior and the production of pollutants.

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