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## PERFORMANCE, COMBUSTION AND EMISSIONS ANALYSIS OF A DIESEL ENGINE FUELED WITH SOYBEAN OIL PREHEATED BY MICROWAVE IRRADIATION

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**Abstract.** *This work presents the experimental study and the performance analysis of a compression ignition internal combustion engine fueled with commercial Brazilian diesel oil and preheated straight soybean oil. The preheating was developed through two methods: electrical resistance and microwave irradiation. Tests on a dynamometric bench were carried out to compare the engine performance with the soybean oil preheated by both methods and the diesel oil as the standard fuel. The engine was tested at different speeds and a load condition. The performance parameters obtained were indicated specific fuel consumption (ISFC) and indicated thermal efficiency. Emissions of unburned hydrocarbons (HC), carbon monoxide (CO) and nitrogen oxides (NO<sub>x</sub>) were also measured during the tests. Additionally, in-cylinder pressure was measured and used to obtain the heat release rate (HRR) from a zero-dimensional modeling of the combustion chamber. The HRR data with each fuel tested supplied information about the combustion process. The results showed differences in emissions, combustion and performance in the engine operation with preheated straight soybean oil by the two preheating methods.*

**Keywords:** *compression-ignition engines, straight soybean oil, diesel oil, microwave irradiation.*

### 1. INTRODUCTION

Vegetable oils have been studied as an alternative fuel of compression ignition internal combustion engines. Nevertheless, the use of straight vegetable oil (SVO) as fuel for diesel engines is a challenge due to the different physical-chemical properties in comparison to diesel oil. Vegetable oils are biodegradable, non-toxic and with a great potential to reduce the pollutant emissions and soot formation because their oxygen content (Jain *et al.*, 2017). Furthermore, it can be handled and stored with safety because their high flammability limits and low volatility. Vegetable oils are mostly polyunsaturated triglycerides. In consequence, the unsaturation bonds and the large molecular size lead to high viscosity, high density, low volatility and minor Lower Heat Value (LHV) when compared to diesel oil (Agarwal *et al.*, 2008; Rakopoulos *et al.*, 2006). High viscosity causes poor atomization, large droplet size and high penetration of the jet. The fuel is not well mixed with air to burn in the combustion chamber, leading to poor combustion with loss of power (Agarwal *et al.*, 2008; Franco and Nguyen, 2011). The use of vegetable oils in diesel engines can cause some problems of operation and durability (D'Alessandro *et al.*, 2016). The SVO heating, as well as the transesterification process and the blending with diesel or additives are some methods used to match the physico-chemical properties to that of diesel oil.

Heating by electrical resistances is the most common method for the heating of the vegetable oil before of its injection into the diesel engine (Garzón *et al.*, 2015; Yilmaz and Morton, 2011). Heat transfer from exhaust gases is another common method used to preheat the vegetable oils (No, 2017; Sonar *et al.*, 2015). These methods only influence on the physical properties (reducing the viscosity and the density), but they do not influence on chemical properties such as molecular size and chemical bonds, which could improve the combustion process with vegetable oils.

In this context, the microwave irradiation appears as an interesting alternative to preheat vegetable oils. Microwave irradiation uses a different process of heat transfer in comparison to conventional methods. As in the microwave irradiation the heat transfer occurs at molecular level, the heating is volumetric and fast. In the case of the conventional methods, the heat transfer follows the conduction and convection mechanisms, being therefore, a superficial and slow heating (Sajjadi *et al.*, 2014).

In the electromagnetic radiation spectrum, microwaves are located between infrared radiation and radio waves with wavelengths between 1 mm and 1 m. The microwave heating is caused by molecular actions such as dipole rotations and migration of ions (Sanseverino, 2002). In addition, microwaves are inert for non-polar molecules. However, polar molecules with a high dielectric constant can selectively absorb the radiation. This selective heating could lead to the formation of micro zones with higher temperatures than the overall temperature of the reaction bulk mixture (Sajjadi *et al.*, 2014).

The technical literature has only reported the use of microwave irradiation in the transesterification process to product biodiesel oil. Studies using microwave irradiation to preheat vegetable oil have not been found in the technical literature. Chen *et al.* (2012) studied the biodiesel production when is used in the transesterification process conventional heating methods and microwave irradiation. The biodiesel production from conventional heating showed less efficient and slower (96.6 %, 90 min) than biodiesel production from microwave irradiation (97.9 %, 3 min). Refaat *et al.* (2008) also analyzed the biodiesel production from the two methods. The microwave irradiation reduced the reaction time in 97 % (60 min to 2 min) and the separation time of products in 94 % (480 min to 30 min). Additionally, the conversion efficiency of the biodiesel production from microwave irradiation was 100 % while for conventional method heating was 96 %. Yuvarajan and Ramanan (2016) analyzed emissions and performance of a single-cylinder diesel engine fueled with biodiesel produced from traditional method and produced from microwave irradiation and ultrasound. The physico-chemical analysis showed that microwave radiation produced a biodiesel with lower viscosity, slightly higher heat value and lower density than biodiesel produced from traditional method. The engine operation with biodiesel produced from microwave irradiation showed lower specific fuel consumption, higher thermal efficiency, lower ignition delay and lower CO, HC, NO<sub>x</sub> and soot emissions than the operation with biodiesel produced from traditional method.

In this work, the fuels tested were straight soybean oil preheated by microwave, straight soybean oil preheated by electrical resistances and diesel oil, as baseline. The comparison was developed through tests on a dynamometric bench, obtaining performance parameters, combustion parameters and emissions. According to the experimental results, the microwave irradiation is an alternative method for the heating of vegetable oils tested in diesel engines, because to the improving of the combustion process.

## 2. EXPERIMENTATION

### 2.1 Experimental set-up

Experiments were carried out in an Agrale, model M95W single cylinder, four-stroke, compression ignition engine with mechanical fuel injection. The main technical specifications of the engine are presented in Table 1.

Table 1. Technical specifications of the diesel engine tested.

Item	Specifications
Cylinders	1
Bore x Stroke	95 x 105 mm
Connecting Rod	168 mm
Sweep Volume	744 cm <sup>3</sup>
Compression ratio	21:1
Number of valves	2
Fuel supply	Direct injection – Mechanical system
Injection pressure	21 MPa
IVO – IVC	29° (BTDC) – 229° (ATDC)
EVO-EVC	240° (BTDC) – 22°(ATDC)

The diesel engine tested is coupled to an eddy current dynamometer that allows both torque and speed control. The engine was instrumented with a piezoelectric pressure sensor (Kistler, model 6041B) in the combustion chamber, an incremental encoder (Dynapar, model B58N) in the crankshaft and thermocouples to measure intake, exhaust, lubricant

oil, fuel and cooling water temperatures. Figure 1 shows a schematic overview of the instrumentation of the experimental set-up.

The in-cylinder pressure was measured with the piezoelectric pressure sensor which was connected to a charge amplifier (AVL, model flexIFEM) and its signal was synchronized with the incremental encoder to determine the in-cylinder pressure as a function of the crank angle. Thus, the in-cylinder pressure data were acquired with a resolution of 0.4° crank angle (CA). Data acquisition was performed with two National Instruments DAQ cards and LabVIEW software. The exhaust emissions were measured with a multi-component analyzer (AVL Sesam i60 FTIR) and the fuel consumption was measured with a graduated burette in 1.0 ml. This test bench is available in the Engine Laboratory at Federal University of Santa Maria.

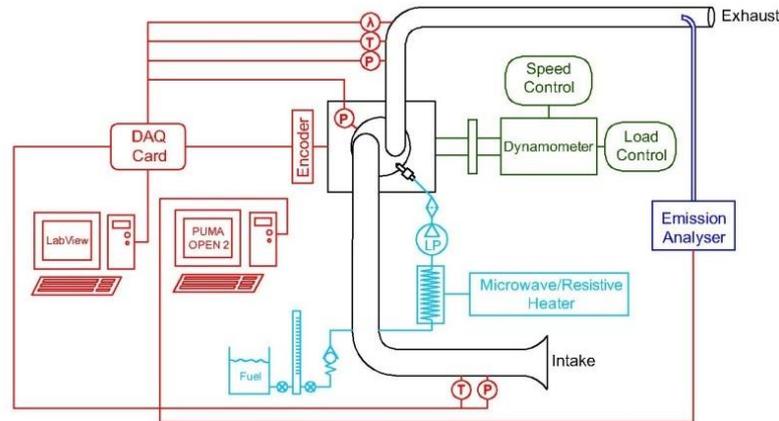


Figure 1. Schematic overview of the experimental set-up.

An industrial microwave device provided by the Chemistry Department of the Federal University of Santa Maria was used for microwave heating. An electric resistance heater comprised of an aluminum tube, electrical resistance and ceramic insulation was manufactured for resistive heating. The microwave device and electric resistance heater was both installed close to the engine, providing fuel at a constant temperature of 80 °C to high pressure pump. During the tests, the microwave power was controlled via LabVIEW in order to keep constant fuel temperature. In the case of the electric resistance heater, the temperature control was made by means of a PID controller. The heating systems and their assembly close to the engine are shown in Figure 2.

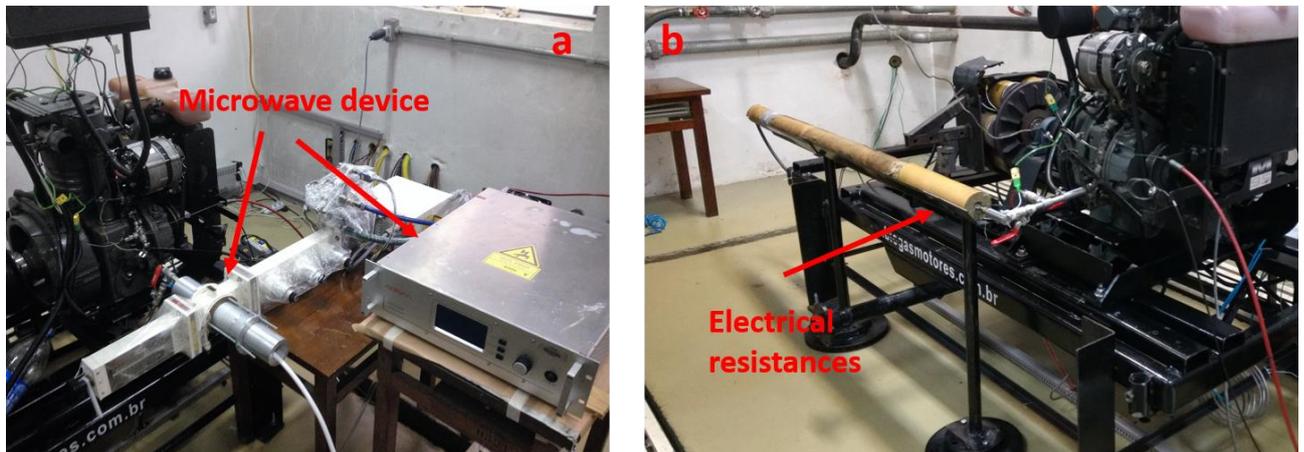


Figure 2. Heating systems: (a) microwave and (b) electrical resistances.

## 2.2 Fuels

Fuels tested were straight soybean oil heated to 80 °C and commercial Brazilian diesel oil at room temperature. Table 2 presents physico-chemical properties of diesel oil at 25 °C and soybean oil at two temperatures, 25 °C and 80 °C. One observes the highest density and dynamic viscosity of the soybean oils at 25 °C when compared with diesel oil at the same temperature. Likewise, it is observed the heating effect with the significant reduction of these properties when the soybean oil is heated. In relation to LHV, the LHV of diesel oil is 13 % higher than soybean oil.

The fuels tested were labeled as: 100S/MW - soybean oil preheated by microwave, 100S - soybean oil preheated by electrical resistances and 100D diesel oil.

Table 2. Physico-chemical properties of diesel oil at 25 °C and soybean oil at 25 °C and 80 °C.

Property	Diesel oil	Soybean oil	
Temperature (°C)	25	25	80
Density (kg/m <sup>3</sup> )	829	915	879
Dynamic viscosity (mPa.s)	3.50	49.53	10.53
LHV (kJ/kg)	42435	36950	

### 3. METHODOLOGY

This work was based on the experimentation on the dynamometer bench and the comparison of results related to performance parameters, combustion process and emissions.

Indicated mean effective pressure (IMEP) was used as a reference parameter to carry out the tests. Consequently, this parameter was kept constant at 500 kPa for all tests. For this IMEP, three speeds were tested: 1800 rpm, 2200 rpm and 2600 rpm. Performance data, such as indicated specific fuel consumption (ISFC) and indicated thermal efficiency were obtained for each fuel and operation condition. Emissions of unburned hydrocarbons (HC), carbon monoxide (CO) and nitrogen oxides (NO<sub>x</sub>) were measured. Combustion process was evaluated using the heat release rate (HRR) analysis based on the first law of thermodynamics, according to Eq. (1), using the experimental pressure data and the respective dimensions of the cylinder to calculate the volume.

$$\frac{dQ_f}{dt} = \frac{\gamma}{\gamma-1} p \frac{dV}{dt} + \frac{1}{\gamma-1} V \frac{dp}{dt} + \frac{dQ}{dt} \quad (1)$$

where  $dQ_f/dt$  is the heat release rate of the fuel,  $p$  is the in-cylinder pressure,  $V$  is the cylinder volume,  $\gamma$  is the ratio of specific heats of the gas and  $dQ/dt$  is the heat transferred to the wall.

Uncertainties analysis was performed for all variables, measured and calculated.

### 4. RESULTS AND DISCUSSION

Tests with the fuels 100S/SW, 100S and 100D allowed determining performance parameters, emissions and combustion parameters. ISFC and indicated thermal efficiency are the performance parameters analyzed. Heat release rate curves obtained from experimental pressure data and measurements of the NO<sub>x</sub>, CO and HC emissions are presented. Results are compared, observing the effect of the heating by microwave irradiation on the engine performance and the combustion process.

Figure 3 shows the ISFC as a function of the speed for the three fuels tested at 500 kPa IMEP. One observes that the ISFC increases with the engine speed because more fuel is necessary to keep constant the IMEP. 100D oil presented the lowest ISFC in comparison with 100S/MW and 100S oils, which is attributed to the highest heat value of the 100D fuel. Comparing 100S/MW and 100S oils, the soybean oil heated by microwave irradiation presented lower values of ISFC than soybean oil heated by electrical resistances, showing a significant difference at 1800 rpm. In this operation point, the highest differences were found between 100S/MW and 100S oils for other parameters presented below.

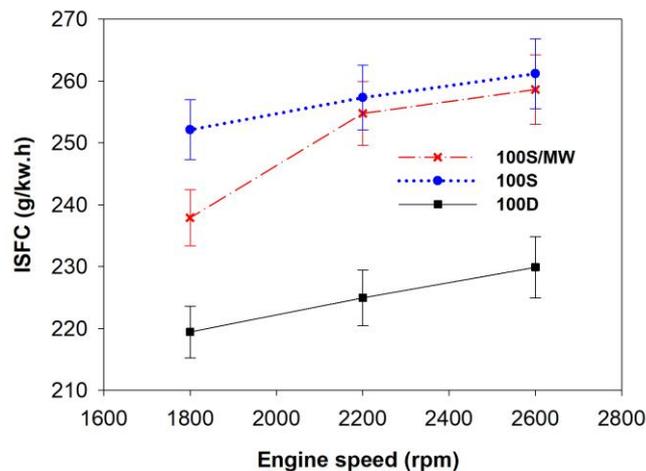


Figure 3. ISFC versus engine speed for the three fuels tested at 500 kPa IMEP.

Figure 4 shows the indicated thermal efficiency as a function of the speed for the three fuels tested at 500 kPa IMEP. Considering the expanded uncertainties, it is not observed significant difference in the indicated thermal efficiency of 100D, 100S and 100S/MW fuels at 2200 rpm and 2600 rpm. In the case of 1800 rpm, 100S/MW oil presented the highest indicated thermal efficiency and 100D and 100S fuels showed similar indicated thermal efficiency. At low engine speeds, the fuel consumption and fuel flow velocity are lower than at high speeds, which represents more residence time of the vegetable oil inside the microwave device. The longest residence time inside the microwave device can explain the best results for 100S/MW oil in this operation condition. In spite of expanded uncertainties, one observes a tendency to decrease indicated thermal efficiency with the engine speed. This behavior indicates that the best operation condition of the diesel engine tested is at low speeds, which is verified by the results of the heat release rate.

In relation to electrical power supply to heat the soybean oil, it was verified that this additional energy does not significantly influence the efficiency results.

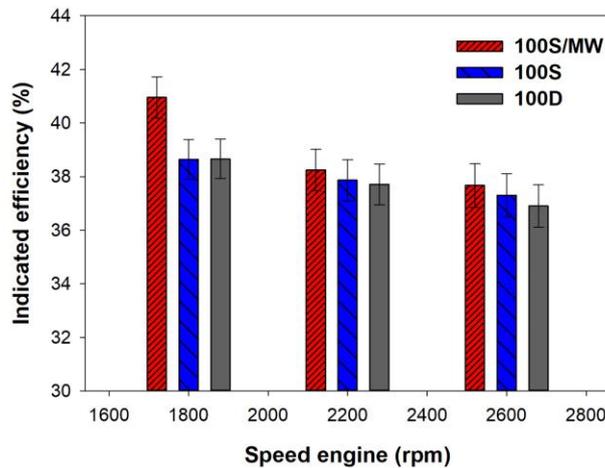


Figure 4. Indicated thermal efficiency versus engine speed for the three fuels tested at 500 kPa IMEP.

Heat release rate curves for 100D, 100S and 100S/MW fuels at 1800, 2200 and 2600 rpm are shown in Fig. 5, 6 and 7, respectively. The typical combustion of a diesel engine is characterized by two peaks in the heat release rate curve. The first peak represents the premixed combustion phase and the second peak corresponds to the diffusive combustion phase. In this context, one observes that the combustion of 100D oil did not present premixed combustion phase, burning mainly in the diffusive phase. This effect can be attributed to the high compression ratio of the engine tested (21:1). High compression ratios increase the pressure and temperature in the combustion chamber, such that at the instant of the fuel injection, the high pressure and temperature favor the ignition, decreasing the ignition delay and, therefore, the premixed combustion phase. Analogously, one observes that this condition favored the combustion of the soybean oil. The highest premixed combustion rate was presented by 100S/MW oil at three speeds tested. Possible changes in the physico-chemical properties produced by the microwave heating, favored the atomization, ignition and combustion process. Furthermore, it is observed that the 100S/MW diffusive phase is faster than that of 100D and 100S fuels. This indicates that 100S/MW oil presented a faster combustion process and lower combustion duration.

The premixed combustion phase peak decreased with the engine speed because the time for the mixture formation is shorter at high speeds. This also explains the indicated thermal efficiency reduction at high speeds. It is observed that the premixed combustion rate decreases and the diffusive combustion rate increases with the engine speed, which is related to the increase in the amount of fuel injected to keep the IMEP at high speeds.

At 2200 rpm, the combustion of 100S/MW oil did not follow the same trend that in the operation conditions at 1800 and 2600 rpm. The diffusive combustion phase was longer and slower, indicating that combustion efficiency decreased for this operation condition. This result can be influenced by the effect of the increase of the quantity of fuel injected with reduction of the speed, which is more significant at 2200 rpm than 2600 rpm, as observed in the ISFC curves.

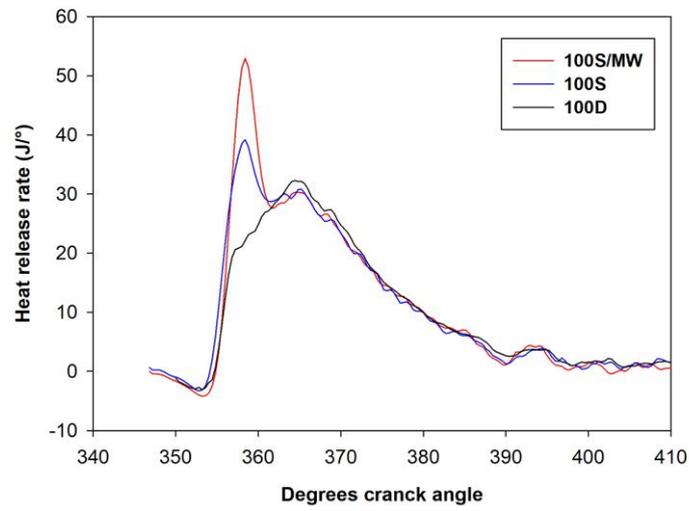


Figure 5. Heat release rate at 1800 rpm and 500 kPa IMEP for the three fuels tested.

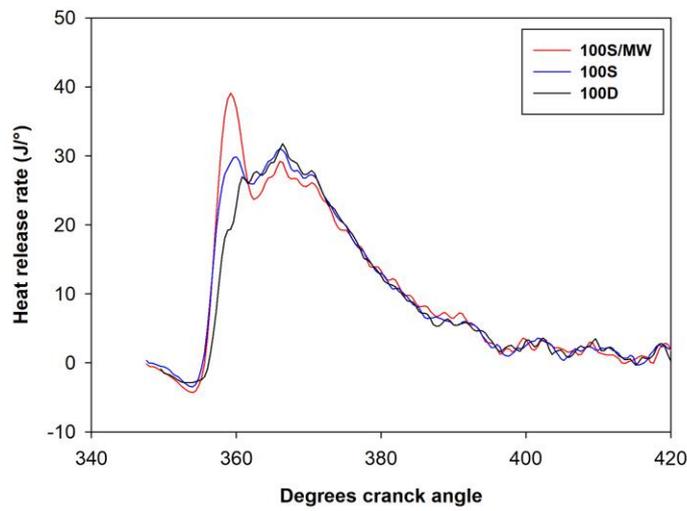


Figure 6. Heat release rate at 2200 and 500 kPa IMEP for the three fuels tested.

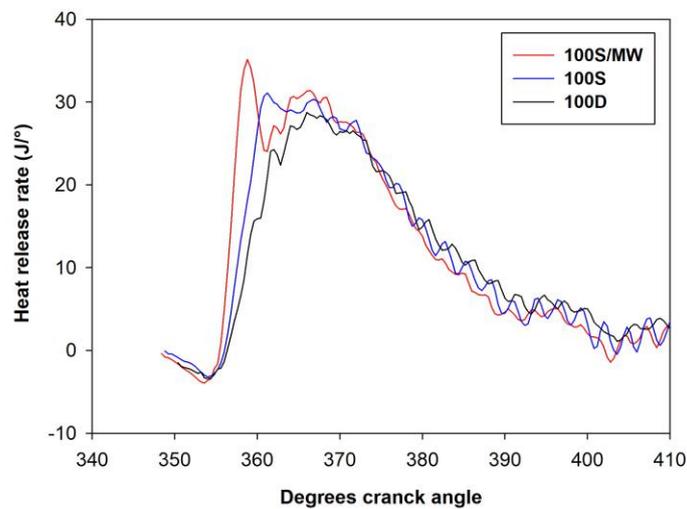


Figure 7. Heat release rate at 2600 and 500 kPa IMEP for the three fuels tested.

Figure 8 shows the NO<sub>x</sub> emissions for 100D, 100S and 100S/MW fuels tested at three speeds and 500 kPa IMEP. The 100S/MW oil showed the highest NO<sub>x</sub> emissions at 1800 and 2600 rpm, as a consequence of the greatest premixed combustion phase peak and the fastest diffusive combustion phase that, consequently, increased the in-cylinder temperature. This behavior agrees with results found in the technical literature as the work reported by Hsu (2002). At 2200 rpm, the diffusive combustion phase was long and slow, increasing the combustion duration and subsequently the engine heat losses. As a result, the in-cylinder temperature decreased favoring the reduction of NO<sub>x</sub> emissions.

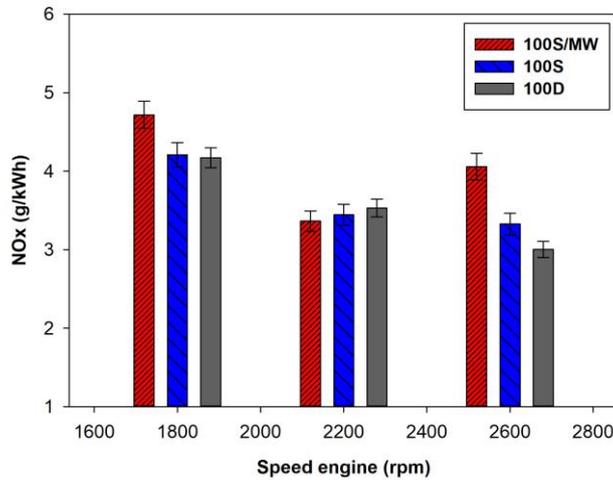


Figure 8. NO<sub>x</sub> emissions versus engine speed for the three fuels tested at 500 kPa IMEP.

Figure 9 presents the CO emissions as a function of the speed for the three fuels tested at 500 kPa IMEP. It is observed a significant reduction in the CO emissions in the engine operation with 100S/MW for all conditions tested. The lowest CO emissions with 100S/MW oil can be attributed to significant changes in the physico-chemical properties as a consequence of the microwave irradiation on the soybean oil molecule, favoring its atomization and combustion process. The actual molecular effect of the microwave heating is not known but it is possible that some bonds are broken, and the molecular structure is modified. For 100S and 100S/MW fuels, the highest CO emissions were observed at 2200 rpm (lower combustion efficiency). In the case of 100D oil, the CO emissions increase with the engine speed, being representatively higher at 2600 rpm.

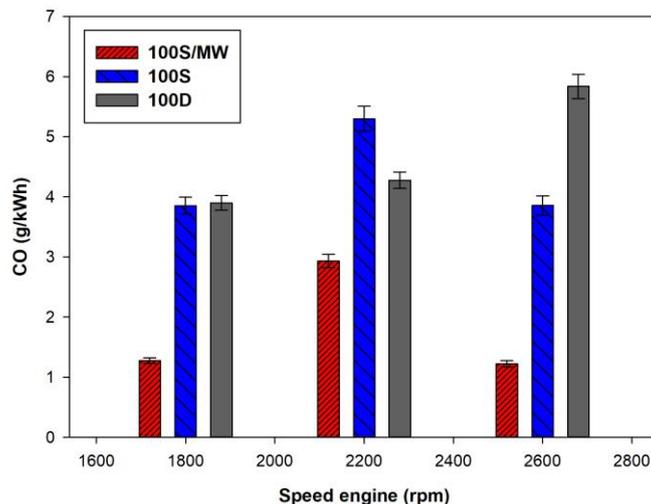


Figure 9. CO emissions versus engine speed for the three fuels tested at 500 kPa IMEP.

Figure 10 presents the HC emissions for 100D, 100S and 100S/MW fuels tested at three speeds and 500 kPa IMEP. The highest HC emissions were presented for the engine fueled with 100D fuel. This result can be explained due to a dominant diffusive phase and longer combustion duration. On the other hand, the injection timing could be late for 100D fuel, favoring the liquid fuel impingement on the piston bowl. Furthermore, it can be highlighted that the lowest HC emissions were obtained for 100S/MW and 100S oils. However, there is not significant difference in the HC emissions between the two methods of heating.

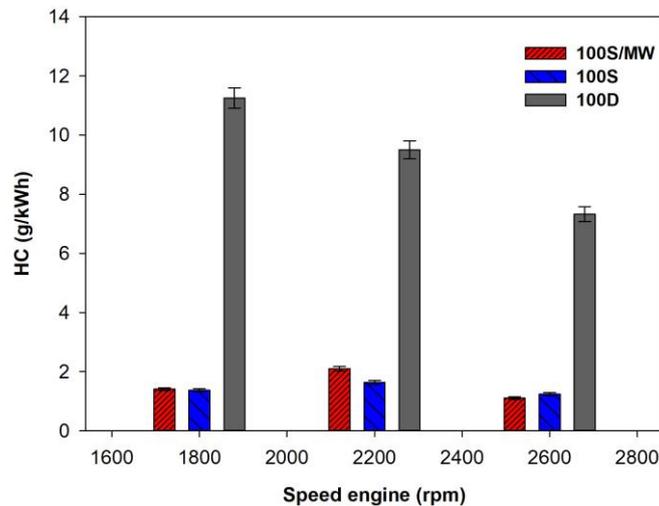


Figure 10. HC emissions versus engine speed for the three fuels tested at 500 kPa IMEP.

## 5. CONCLUSIONS

A compression ignition internal combustion engine fueled with diesel oil and straight soybean oil preheated was tested on a dynamometric bench. Resistance and microwave irradiation heating methods were used and compared. Emissions, performance and combustion parameters were obtained from experimental data. For all tests, indicated mean effective pressure (IMEP) was kept constant at 500 kPa and three speeds were tested: 1800 rpm, 2200 rpm and 2600 rpm. The microwave heating as an alternative to use vegetable oils in compression-ignition engines is not still reported in the technical literature.

For three speeds, 100D oil presented the lowest ISFC in comparison with 100S/MW and 100S oils, which is attributed to the highest heat value of the 100D fuel. Comparing 100S/MW and 100S oils, at 1800 rpm, the soybean oil heated by microwave irradiation presented lower values of ISFC than soybean oil heated by electrical resistances.

It was not observed significant difference in the indicated thermal efficiency of 100D, 100S and 100S/MW fuels at 2200 rpm and 2600 rpm. In the case of 1800 rpm, 100S/MW oil presented the highest indicated thermal efficiency and 100D and 100S fuels showed similar indicated thermal efficiency.

The high compression ratio of the diesel engine tested favored the combustion of the 100S/MW and 100S oils due to the high pressure and temperature of the combustion chamber at the moment of the fuel injection. Conversely, the combustion of the diesel oil was more inefficiency, presenting only diffusive combustion phase because the reduction of the period of ignition delay. For three speeds, the highest premixed combustion rate were presented for the 100S/MW, indicating better atomization, ignition and combustion process, attributed to the microwave heating.

The highest premixed combustion phase influenced on the high  $\text{NO}_x$  emissions observed when the engine operated with 100S/MW oil.

Heating allowed testing straight soybean oil in the diesel engine. In relation to heating by microwave irradiation, results found at 1800 rpm evidenced some effect of the microwave irradiation on the soybean oil molecule. The highest indicated thermal efficiency, the lowest CO emissions and the highest premixed combustion rate were presented by 100S/MW oil at 1800 rpm. This can be attributed to changes in the physico-chemical properties as a consequence of the microwave irradiation on the soybean oil molecule, favoring its atomization and combustion process. This effect was significant at 1800 rpm (lower speed) due to increase in the residence time of the vegetable inside the microwave device.

The comparison of the results supplied information about the effect of the heating by microwave irradiation on the engine performance and the combustion process, showing that the microwave irradiation is a suitable heating method for the operation of a diesel engine with vegetable oils. Finally, further studies must be performed in order to determine the actual effect of the microwave heating on the vegetable oil.

## 6. ACKNOWLEDGMENTS

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