# SMALL ENGINE-GENERATOR SET OPERATING ON DUAL-FUEL MODE WITH ETHANOL – CASTOR OIL BLENDS

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## ABSTRACT

The increase in greenhouse gas emissions and our dependence on fossil fuels have motivated researchers to seek the use of renewable fuels in internal combustion engines, which can be produced locally and have clean combustion. The blending method in diesel engines has been recognized as an effective alternative to partially or totally replace the use of diesel fuel. In this regard, this paper studied the operation of a small engine-generator set in mono-fuel mode (diesel fuel - DO) and in dual-fuel mode using hydrous ethanol (HET) and castor oil (OM) blends, indicating a total replacement of diesel fuel. Efficiency, power, specific fuel consumption and gaseous emissions were assessed in a single cylinder diesel cycle engine. The percentages in volume of the HET-OM samples were: 75% - 25%, 70% - 30%, 60% - 40%, and 50% - 50%. The exhaust gas temperature decreased with the mixtures. Carbon monoxide emission decreased 57%, carbon dioxide decreased 9.8%, and nitrogen oxides reduced 19%. It was also observed that the percentage of smoke opacity tends to decrease close to zero with addition of ethanol. Hydrocarbon emissions increased with rising of the OM concentration and the same for the specific fuel consumptions, which was 25.4% higher than diesel fuel. The best fuel conversion efficiency was achieved with the blend HET75-OM25, being 9% higher compared to diesel fuel operation. Power on diesel fuel operation showed a better result keeping stable, with the increase of the compression ratio and the delay of the start of injection. In general, the results confirmed that the performance is comparable to that of diesel fuel, indicating that renewable fuels appear as an alternative for the reduction of the environmental impacts and the reduction of fossil fuels consumption.

**Keywords:** internal combustion engine; ethanol; castor oil; dual-fuel operation

## NOMENCLATURE

| | |
|---|---|
| LHV | Lower Heating Value, kJ/kg |
| m | mass flow rate, g/s |
| P | power, kW |
| SFC | Specific Fuel Consumption, g/kWh |
| y | mass fraction, [-] |

### Greek symbols

| | |
|---|---|
| $\eta$ | conversion efficiency, % |

### Subscripts

| | |
|---|---|
| b | blend |
| e | electrical |
| f | fuel |
| HET | hydrous ethanol |
| OM | castor oil |

## INTRODUCTION

Nowadays, there is a growing interest in biofuels, especially those that contribute to the reduction of pollutant emissions. Due to the fossil nature of diesel fuel, it is necessary to study alternative biofuels to replace it, especially in internal combustion engines, which are equipment very present in the current society, both for vehicle propulsion and for electric power generation (Rosa et al., 2019a).

Renewable fuels, such as ethanol and straight vegetable oil (for example castor oil), appear to be very attractive fuels to replace conventional diesel fuel. The advantage of replacing diesel fuel for those biofuels is the use of fuels that can be produced from renewable feedstock and they are oxygenated and sulfur-free fuels (Canakci, 2005). However, these biofuels still require studies and experiments to prove their viability. Therefore, many research works, employing different methods, have been developed to explore the applicability of biofuels in internal combustion engines (Abedin et al., 2016).

The most common methods to replace the diesel fuel are the blend method (Singh et al., 2016; Al-Esawi, Qubeissi and Kolodnytska, 2019) and the fumigation method (Telli, 2018). The blend method is very simple, which consists of mixing two fuels, usually alcohols to conventional diesel fuel, biodiesel or straight vegetable oils. Thus, the blend is directly injected into the cylinder through the conventional diesel injector. The blend method can reduce engine emissions without significant impacts on engine performance and configuration (Beatrice et al., 2020).

Peralta and Barbosa (2001) assessed a Diesel Cycle engine operating with ternary fuel mixtures (DO - anhydrous alcohol - OM), where castor oil was used as a phase activator for the mixture and additive to alcohol. The mixtures were used by a simple process without any specific procedure to adapt to the engine and without any changes in the original parameters of injection and compression ratio. All samples showed better solubility with the addition of castor oil, and only a ternary mixture did not present phase separation (90% DO, 9% HET and 1% of OM), which was used for the experiments. The performance results were obtained in a dynamometric test using a 2-cylinder, four-stroke and direct injection engine. Several characteristics of performance were comparable to those using conventional DO, with small losses in power and efficiency. However, it has technically demonstrated that the application of this mixture is viable from an environmental point of view due to the lower intensity of soot level.

A study using castor oil biodiesel mixed with DO was carried out by Sattanathan (2015) in five different proportions (pure diesel, B25, B50, B75 and B100) in a 5.2 kW compression ignition (CI) engine, with 17.5:1 of compression ratio (CR), operating at 1500 rpm. The author noted that the higher the percentages of DO replacement, the lower the amounts of hydrocarbons and opacity was obtained. The performance results showed that there was a drop in thermal efficiency and emissions compared to DO operation, which was attributed to the lower heating value (LHV) and low flammability power of the biodiesel.

An experimental study carried out by Johnson, Barathraj and Dinesh (2017) was conducted in a 5.2 kW four-stroke single-cylinder diesel engine with a CR of 17.5:1, operating at 1500 rpm. Fuel samples were prepared containing DO, OM and ethanol in different proportions. The mixtures that showed the best results were: DO 90%, ethanol 7% and OM 3%, with which the highest thermal efficiency and lowest specific fuel consumption were achieved; the mixture of DO 90%, ethanol 5% and OM 5% showed the best results in relation to $CO_2$ and $NO_x$ emissions. All tests had a higher hydrocarbon emission compared to DO. Authors noted that with the addition of ethanol better thermal efficiency was obtained and $NO_x$ emissions was reduced. Specific fuel consumption of the engine was low for all blends at low to medium load, but higher than DO at high load. Specific fuel consumption at low to medium loads were 5% to 15% lower compared to DO. All blends showed lower $CO_2$ emissions, but hydrocarbon emissions were higher in relation to DO operation. $NO_x$ emissions for mixtures were lower than DO up to medium loads, but increased significantly when submitted at high loads.

Tabile et al. (2009) performed tests to evaluate the performance and smoke opacity of an agricultural tractor with a power of 73.6 kW operating with metropolitan DO mixed with OM biodiesel in seven proportions. In the specific fuel consumption tests, it was observed that in the mixtures with biodiesel there was no significant difference until B25. However, comparing B0 to B100 the fuel consumption increased 38.3%, due to the higher density and lower heating value in relation to the DO. The opacity decreased with the increase in the amount of biodiesel up to B75, however, from B75, the opacity increased again.

A 6-cylinder, 5.9 L, 123.5 kW, direct injection diesel engine, operating at 1800 rpm with mixtures of 80% OM and 20% DO was tested by Pimentel, Belchior and Pereira (2004). Fuel mixtures were preheated at 95 ºC to bring its viscosity close to the diesel fuel. Engine emissions and performance were studied, and the results indicated that carbon monoxide and hydrocarbon emissions decreased and $NO_x$ and particulate matter increased at high load. Regarding the specific fuel consumption, DO operation was more economical, showing a better performance, due to the greater LHV. The authors concluded that the use of OM proved to be advantageous from an environmental point of view, despite the operational issue in which engine design adaptations would be necessary for better functioning.

Prakash et al. (2018) evaluated the performance and emissions characteristics of a single cylinder, compression ignition engine operating on pure diesel fuel and pure castor oil. Moreover, the authors also studied three blends of diesel fuel, castor oil and bioethanol (BE) in different proportions. At full load, the results showed that the exhaust gas temperature increased about 8.5%, when the engine operated with pure castor oil. However, when the BE was used in the blends the exhaust gas temperature decreased. In addition, at full load, the specific NOx emission was 5.21 g/kWh for pure castor oil and 8.17 g/kWh for diesel fuel. CO emissions from castor oil were higher than diesel fuel. HC emissions from castor oil were higher as compared to diesel fuel. However, HC emissions from the blends were lower than pure castor oil but still higher than pure diesel fuel.

Vailatti et al. (2016) carried out tests on a 0.668 cm³ single-cylinder CI engine, operating in dual-fuel mode using ternary DO-HET-OM mixtures. The percentages of DO replacement in volume varied from 10% to 50%. Tests were also carried out with 100% replacement of DO by mixtures of HET-OM and in this mode of operation the samples were composed of 90%, 80% and 75% by volume of HET and the rest by OM. In HET-OM mixtures there was a 96% reduction in the opacity percentage, exhaust gas temperatures decreased by 17.6%, fuel consumption increased by 52.4% and the engine's thermal efficiency decreased by almost 1.7%.

Due to the concerns about the utilization of fossil fuels and the emissions of warming gases, this work aimed to analyze the thermomechanical and the emissions of a diesel engine operating in dual-fuel mode in controlled mixtures of hydrated ethanol and castor oil with different compression ratios and starts of injection. In addition, this article presented a complete replacement of diesel fuel by renewable fuels, ethanol – castor oil blends.

## MATERIALS AND METHODS

In the experiments, measurements of electrical power were made by means of an energy analyzer and the consumption of fuels gravimetrically by digital scale. With the measurements made, the specific fuel consumption (SFC) in [g/kW·h] was calculated according to Rosa et al. (2019b) by Eq. (1).

$$SFC = \frac{\dot{m}_f}{P_e} 3600 \quad (1)$$

where $\dot{m}_f$ is the fuel mass flow rate [g/s], and $P_e$ is the electrical power produced by a small engine-generator set in [kW]. The calculation of the fuel conversion efficiency of the motor-generator group was carried out according to Eq. (2):

$$\eta_f = \frac{P_e}{\dot{m}_f . LHV} \quad (2)$$

where *LHV* is the Lower Heating Value of the fuel (DO or HET-OM blends) in [kJ/kg]. For HET-OM blends, the $LHV_b$ was calculated by Eq. (3):

$$LHV_b = y_{HET}.LHV_{HET} + y_{OM}.LHV_{OM} \quad (3)$$

where $y_{HET}$ is the HET mass fraction, $LHV_{HET}$ is the HET lower heating value in [kJ/kg], $y_{OM}$ is the OM mass fraction, and $LHV_{OM}$ is the OM lower heating value in [kJ/kg].

Diesel fuel used in the experiments was the S500 type (up to 500 ppm of sulphur) with 7% of biodiesel (B7), which is commonly found at gas stations, as well as, hydrated ethanol (HET), with around 4% of water in volume in its composition. OM used in the experiments was purchased in commercial establishments and sold in 1-liter containers.

Four mixtures were tested with the following proportions in volume: 75% hydrated ethanol and 25% castor oil (HET75-OM25), 70% HET and 30% OM (HET70-OM30), 60% HET and 40% OM (HET60-OM40), 50% HET and 50% OM (HET50-OM50). From the specific mass of the HET of 0.806 kg/L and of 0.945 kg/L to OM, both measured in a pycnometer of 25 mL, Table 1 reports the mass fraction values and the *LHV* of the blends mentioned, on the basis of the $LHV_{HET}$, $LHV_{OM}$ and Equation (3).

Table 1. Lower Heating Value of the fuels used in the experiments.

| Blend | Fuel | Volume (mL) | Mass (g) | Mass fraction | *LHV* (kJ/kg) |
|---|---|---|---|---|---|
| - | DO | - | - | - | 41691.0* |
| - | HET | - | - | - | 25078.0** |
| - | OM | - | - | - | 35420.0* |
| HET75-OM25 | HET<br>OM | 750<br>250 | 604.50<br>236.25 | 0,719<br>0.281 | 27984.1 |
| HET70-OM30 | HET<br>OM | 700<br>300 | 564.20<br>283.50 | 0.666<br>0.334 | 28536.7 |
| HET60-OM40 | HET<br>OM | 600<br>400 | 483.60<br>378.00 | 0.561<br>0.439 | 29615.3 |
| HET50-OM50 | ETH<br>OM | 500<br>500 | 403.00<br>472.50 | 0.460<br>0.540 | 30659.5 |

*Araújo, et al. (2002); **Vlassov (2008)

The engine used in the experiments is Agrale brand, model M90, single cylinder, CI, direct injection, 4-stroke, air-cooled, displacement of 668 cm³, compression ratio of 20:1, start of injection (SOI) at 17º before top dead center (BTDC), torque of 39 N·m at 2350 rpm, power of 8.8 kW at 2400 rpm and specific DO consumption of 240 g/kWh. The electric generator is Kohlbach brand, model 132 LA, being coupled to the engine by belt-pulley transmission, with apparent power of 10 kVA, effective power of 8 kW, 220 volts and three-phase. The generated electrical energy was consumed in electrical resistors installed inside a tank with water circulation. Table 2 presents all apparatus used and Fig. 1 represents the assembly diagram of the components and instruments used in the experiments.

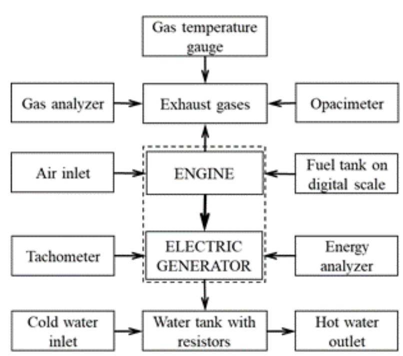


Figure 1. Experimental scheme.

Table 2. Apparatus used in the experiments.

| Apparatus | Brand and Model | Resolution |
|---|---|---|
| Energy analyzer | Embrasul, RE6000 | 0.01 V; 0.01 A; 0.01 kW; 0.01 Hz |
| Tachometer | Fueltech, FT300 | 1 RPM |
| Gas temperature gauge | Novus, N305 | 0.1 ºC |
| Gaseous emission analyzer | Napro, PC-Multigás | 0.01% to CO and $CO_2$;1 ppm to HC and $NO_x$ |
| Opacimeter | Napro, NA9000 | 0.01% |
| Digital scale | Marte | 0.01 g |
| Digital chronometer | Casio | 1 s |

The experiments were performed according to the following procedures:

a) the engine was warmed up using only DO from 20 to 30 minutes, with the engine unloaded and with an adjusted speed around 1800 rpm, measured with a tachometer;

b) after heating the engine, the electrical resistors were switched on, requiring a new adjustment of the generator rotation through the engine acceleration lever to maintain the frequency at 60 Hz, observed by an energy analyzer;

c) the time for each fuel sample tested was set at 30 minutes and at the end of each sample, the experiment was completed with the engine operating with pure DO for about 30 minutes. The tests were repeated, changing some engine parameters such as compression ratio and start of injection.

Thus, the tests were performed according to the following nomenclature: CR20-SOI11 - compression ratio of 20:1 and start of injection of 11º BTDC; CR20-SOI17 – CR of 20:1 and SOI of 17º BTDC; CR21.5-SOI17 – CR of 21.5:1 and SOI of 17º BTDC; and CR21.5-SOI11 - CR of 21.5: 1 and SOI of 11º BTDC.

It is also observed that the values of power and specific fuel consumption were corrected to the standard reference condition: barometric pressure of 100 kPa, air temperature of 298 K and relative humidity of 30%, described by ISO 3046, part I.

## RESULTS AND DISCUSSION

In this section, the main results obtained in the experiments are presented in the graphical mode with the respective error bars. At first, checking the results obtained, it is possible to observe that operating with DO a better adjustment and stabilization of the frequency was achieved, being stabilized at 60Hz. However, for the HET-OM mixtures the same result was not obtained even by adjusting the lever injection pump flow rate to its maximum stroke. The values came close to the DO in the tests where the CR increased, being the best result obtained with the HET50-OM50 sample. The values are shown in Fig. 2.

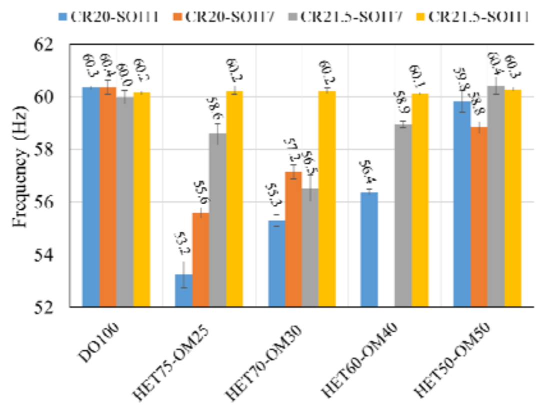


Figure 2. Frequency measured on the energy analyzer for different fuel blends and engine configuration.

Regarding to the power, the DO operation presented a better performance in relation to the HET-OM mixtures, remaining more stable and without oscillations. Throughout the tests with changes in the CR and SOI, an improvement in power was noted in the CR21.5-SOI11 test, where values close to the DO operation were obtained, as in the case of the HET50-OM50 mixture, confirming that the performance is comparable with that of DO. It is possible to observe that when increasing the percentage of OM in the mixture, the power values increase due to its higher LHV. Corrected power values are shown in Fig. 3.

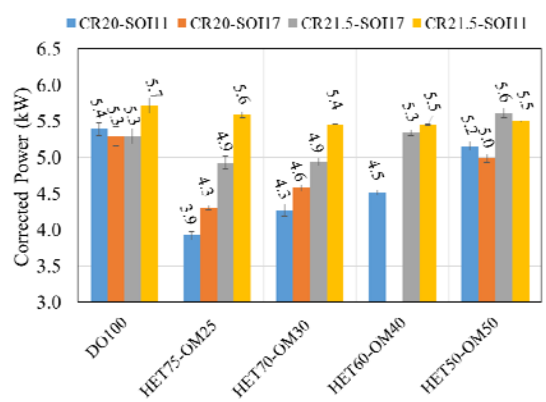


Figure 3. Corrected power for different fuel blends and engine configuration.

Concerning to the corrected specific fuel consumption, blends presented an increase of 25.4% compared to DO. In general, it is possible to affirm that the increase in specific fuel consumption with HET-OM samples, compared to DO, is caused by the lower LHV. Among the samples, the best result was obtained with the HET50-OM50 sample in the CR21.5 - SOI17 test with the highest LHV obtained between the blends. Similar results were obtained by Vailatti et al. (2016), where the consumption increased by 52.4% using controlled mixtures of HET-OM. According to Johnson, Baratharaj and Dinesh (2017), the fuel consumption of the engine was reduced for all mixtures at low and medium load, but higher than the DO with high load. For Tabile et al. (2009), when the engine operated with DO mixed with OM biodiesel, there was no significant difference until B25, however, comparing B0 and B100 consumption increased by 38.3%. Pimentel, Belchior and Pereira (2004) found similar results with a mixture of DO20-OM80, heated to 95 ºC, resulting in greater savings with OD100. Fig. 4 represents the values obtained in the tests to the corrected specific consumption.

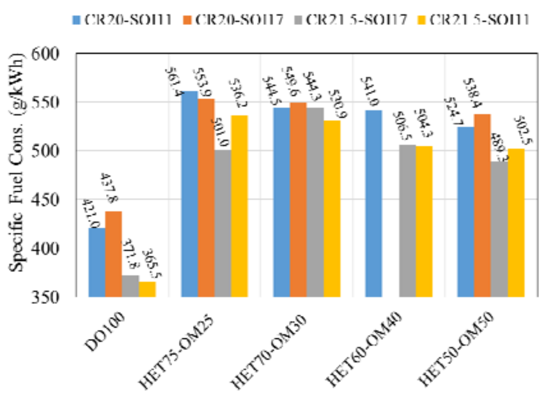


Figure 4. Corrected specific fuel consumption for different fuel blends and engine configuration.

The fuel conversion efficiency values obtained in the experiments are shown in Fig. 5. The sample with the greatest addition of ethanol (HET75-OM25) increase the fuel conversion efficiency about 9%, presenting the best result in comparison to DO. The CR was shown to be significant, increasing the efficiency in all samples, except for the HET70-OM30 sample, which remained unchanged. The improvement in the fuel conversion efficiency can be attributed to the amount of ethanol in the blends. The presence of ethanol in the mixtures contributes to the reduction in-cylinder temperature due to its high latent heat of vaporization, resulting in a reduction of the heat losses and, consequently, increasing fuel conversion efficiency.

According to Johnson, Barathaj and Dinesh (2017), with addition of ethanol to the sample with DO and OM, a better conversion efficiency was also obtained. For Vailatti et al. (2016), efficiency decreased by 1.7% using HET-OM. Sattanathan (2015) obtained a decrease in efficiency using percentages of OM to replace DO, but it did not use ethanol in its mixtures.

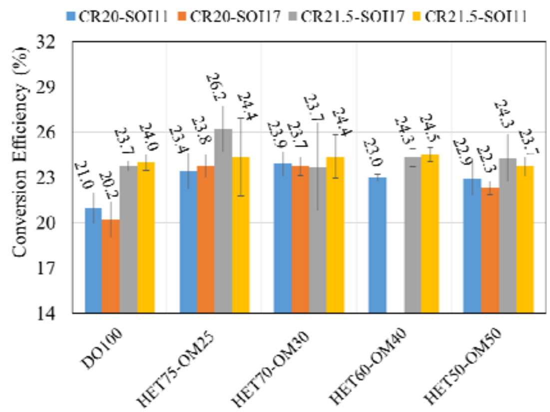


Figure 5. Fuel conversion efficiencies of the engine generator set.

The exhaust gas temperature decreased when using HET-OM mixtures, as can be seen in Fig. 6, however, it increased with the increase in the CR and with the increase in the proportion of OM in the mixture. In any case, the exhaust gas temperature values obtained in all experiments are lower when compared to DO. In this way, HET contributes to lowering the temperature in the combustion chamber, avoiding excessive thermal losses. Similarly, for Vailatti et al. (2016), who in their experiments obtained a decrease in the exhaust gas temperatures, whose reduction was 17.6%.

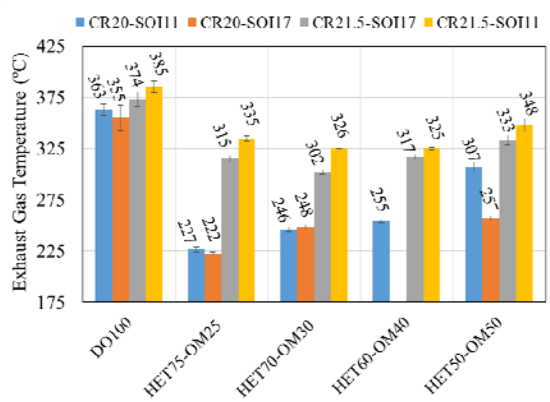


Figure 6. Exhaust gas temperatures for different fuel blends and engine configuration.

The smoke opacity was measured only to the condition CR21.5-SOI11 and is shown in Fig. 7. This parameter decreased by an overall average of 95% with the addition of ethanol attributed to the presence of oxygen in the HET, causing better combustion. The sample that obtained the best result was HET70-OM30 with 1.3% opacity. For Sattanathan (2015), the higher the percentage of substitution of DO by OM, the lower the opacity index, using a mixture of DO-OM with substitution percentages of 25%, 50%, 75%, 100%, without adding HET. Similarly, Tabile et al. (2009), with an engine operating with DO mixed with castor oil biodiesel, the opacity decreased as the amount of biodiesel increased to B75 and, from this mixture it increased again. Vailatti et al. (2016), operating with samples in the proportions HET90-OM10, HET80-OM20, HET75-OM25, obtained a reduction in opacity of 96%. By completely eliminating DO by HET-OM mixtures, the samples contribute to the reduction of opacity, however, there was an increase with the increase of OM concentration.

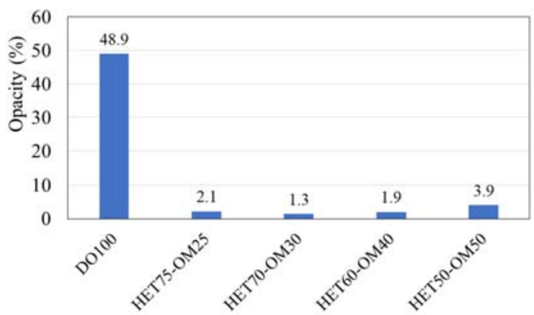


Figure 7. Opacity of the exhaust gases at CR21.5-SOI11 condition.

Carbon monoxide emissions are shown in Fig. 8. The results indicated a reduction about 57%, which is an expressive value compared to the DO operation, having its values reduced even more with the increase of the CR and SOI in the CR21.5-SOI17 condition for all samples, except for that HET70-OM30. Similar results were obtained by Pimentel, Belchior and Pereira (2004), using a blend of DO20-OM80.

Carbon dioxide emissions, on a general average, decreased by around 4% and the results obtained in the tests are presented in Fig. 9. According to Johnson, Baratharaj and Dinesh (2017), there was a decrease in $CO_2$ emissions in all of their samples studied.

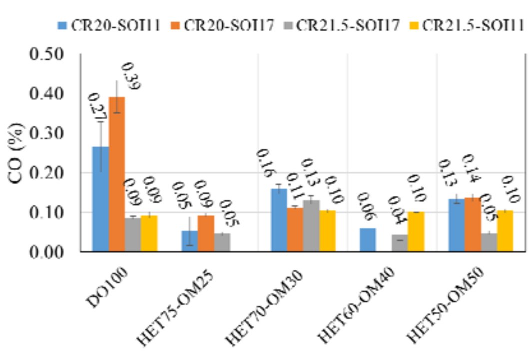


Figure 8. Carbon monoxide emissions.

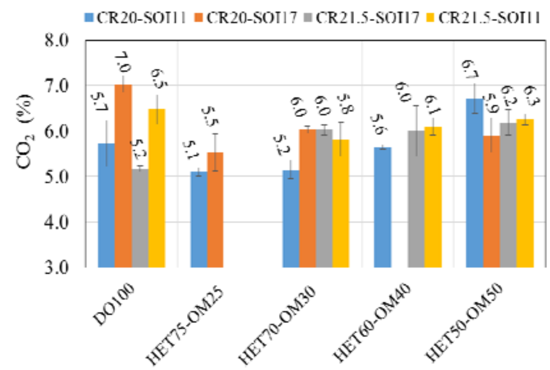


Figure 9. Carbon dioxide emissions.

Hydrocarbon emissions are shown in Fig. 10, which is observed that was not obtained a good result with the mixtures. Particularly, in the experiments in which the SOI was of 17º BTDC, there was a significant decrease with the increase of CR. These results contradict the results obtained by Sattanathan (2015), which was observed that the higher the percentages of substitution of DO by OM in the biodiesel blends evaluated, the lower was the hydrocarbon emissions. Pimentel, Belchior and Pereira (2004) also operating an engine with a mixture of DO20-OM80 found lower levels of HC emitted in the experiments. In the tests carried out by Johnson, Baratharaj and Dinesh (2017), all samples tested, being them DO90-HET7-OM3 and DO9-HET5-OM5, presented a higher index of hydrocarbons produced compared to DO operation.

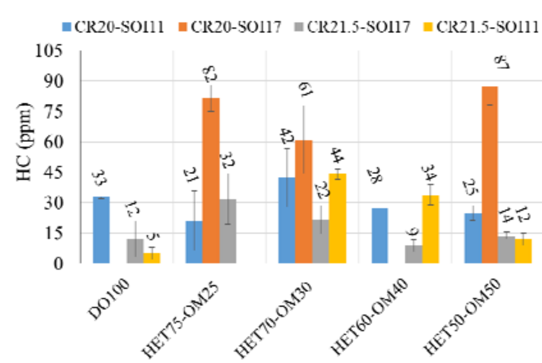


Figure 10. Hydrocarbon emissions.

In Fig. 11, $NO_x$ emissions are presented, being the CR20-SOI11 condition that one with the lowest $NO_x$ emissions for almost all blends tested. For the condition in which the start of injection was increased from 11º to 17º there was an increase in $NO_x$ emissions for all blends, except for the HET60-OM40 sample (not measured). With the increase in the compression ratio, $NO_x$ emissions increased, with a decrease only in the last condition, where the start of injection increased to 11º. This may be related to the high temperatures in the combustion chamber. In a general average comparing the mixtures of HET-OM with DO, $NO_x$ emissions decreased by about 19%. In the tests made by Johnson, Baratharaj and Dinesh (2017), with DO90-HET5-OM5, better results were obtained in relation to $NO_X$ emission, being lower than the DO up to medium loads. However, these values increased when subjected to high loads. In the tests conducted by Pimentel, Belchior and Pereira (2004), the $NO_X$ and particulate material values also increased with the increase in load imposed on the engine.

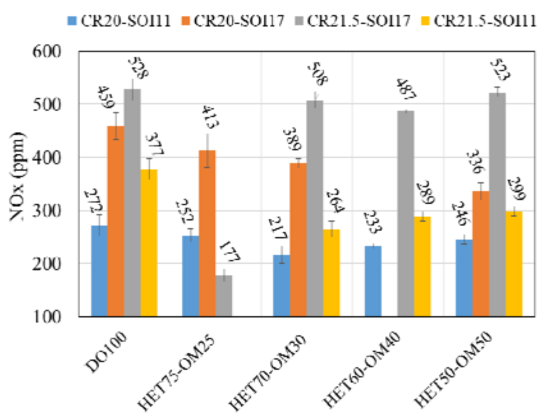


Figure 11. $NO_x$ emissions.

## CONCLUSIONS

In this work, experimental data of an engine-generator set were presented. The engine used was a single cylinder internal combustion engine diesel cycle operating in mono-fuel and dual-fuel mode with specific mixtures of hydrous ethanol (HET) and castor oil (OM). In all mixtures of HET and OM, there was apparently complete miscibility between the two substances.

Based on the experiments reported, it was observed that the power measurements with the use of DO showed higher values in relation to the mixtures, remaining stable. The mechanical changes made (CR and SOI) to the engine were beneficial to the results, demonstrating that the performance is comparable to the performance of the DO, especially when the concentration of OM in the mixture was increased. Specific fuel consumption increased in tests with ETH-OM mixtures, which was expected due to the lower LHV, with the ETH50-OM50 sample being the one with the lowest consumption. The fuel conversion efficiency found was higher for the HET-OM samples than with the DO and the higher the HET percentage, the greater was the efficiency obtained.

Regarding to the exhaust gas temperature, the use of HET contributes positively, thus avoiding greater thermal losses resulting from combustion. The tests with the higher compression ratio caused the temperature values to rise, there was also an increase in temperature in the mixtures with greater presence of OM. In terms of emissions, it can be noted from the experiments carried out that the engine operating in dual-fuel mode with HET-OM, promotes a significant reduction in emissions of carbon monoxide, $CO_2$ and $NO_x$ and also an improvement in the levels of smoke opacity and efficiency.

In economical terms, the use of the HET-OM mixture in diesel engines is not justified by the prices paid per liter of HET and, especially, by OM, compared to the DO price. However, it was justified for the rural producer to plant vegetable crops for the production of the fuels treated here. In addition, the use of so-called biofuels in engines contributes greatly to reducing dependency based on fossil fuels.

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