Experimental Analysis of a Small Generator set Operating on Dual Fuel Diesel-Ethanol

Marcel Alex Vailatti*, Carlos Roberto Altafini*, Giovani Dambros Telli*, Josimar Souza Rosa**

Abstract

This work aims to analyze the operation of a generator set on single fuel mode with diesel oil, and on dual fuel mode using diesel–ethanol blends. The engine used to realize the experimental analysis was a diesel cycle model, single cylinder, direct injection, air refrigerated and coupled to a three-phase electric generator, whose set capacity was 8.0 kVA. The generated electric energy was dissipated in electrical resistances inside a reservoir with running water. Fuels were blended in different volumetric ratios, using a small portion of vegetable castor oil to promote the homogenization. The percentages of substitutions of diesel oil were from 10% to 50%, increasing by 10% the replacement for each sample. Also, the engine was operated with 100% substitution of diesel oil, i.e., for this condition, the samples were composed of ethanol/castor oil 90/10 (volume/volume), 80/20 and 75/25. The blends of diesel and ethanol did not obtain good performance, mainly in taxes of substitution above 40%, causing combustion failures, operational instability, and increase of fuel consumption, although it has achieved a greatly reduction on opacity percentages. The blends with 100% of substitution of diesel oil obtained good performance except to blend with 90% ethanol, where occurred combustion failures, which caused operational instability. To these conditions, the results achieved are increase of consumption by 17%, decrease of opacity by 79%, decrease of exhaust gas temperature by 3.5% and increase of engine thermal efficiency by 1.3%. At the ethanol – castor oil blends there was a decrease in the percentage of opacity by 96%, decrease of exhaust gas temperature by 17.6%, with a minimum of operational irregularities, although fuel consumption has increased by 52.4% and the engine thermal efficiency has decreased almost 1.7%.

I. INTRODUCTION

Reducing dependence on fossil fuels in recent decades has stimulated a great effort throughout the world, both in the academic area and in the industrial area, for solutions that meet this objective, as well as reducing gaseous emissions in the atmosphere in the combustion of these fuels. In this sense, special attention has been addressed to the study of the operation of internal combustion engines (ICE) Otto cycle and Diesel cycle, with alternative fuels in flex mode (as in Brazil is known), or in dual fuel mode, respectively. The difference between the two modes of operation is in the mode as fuels are used in the engine. Flex mode, fuels (liquid or gas) are used alternately, while in dual fuel mode, fuels are used simultaneously [homogeneous mixtures of diesel oil (DO) and biodiesel and diesel and straight vegetable oil, and mixtures of DO and natural gas (NG)]. Although in flex fuel engines, two liquid fuels are also used, as is the case with the standard gasoline sold today in Brazil (with 27% ethanol diluted in gasoline), and other proportions of gasoline and hydrated ethanol (HET) that are possible to use, characterizing the dual fuel mode operation. In the dual fuel mode design, NG becomes the primary fuel, while the DO becomes the secondary fuel, being gradually replaced by the gaseous fuel.

Due to the large amount of petroleum fuels, mainly gasoline and diesel, the performance of the ICE is given by the manufacturers based on these fuels. However, there has always been an interest by the governments in reducing the dependence of the energy matrix based on fossil fuels. Incentives vary according to the availability of alternative sources in each region. In Brazil, the focus is to use alcohol derived from sugarcane, either in the anhydrous form or hydrated. The hydrated alcohol is distributed directly from fuel stations, since the anhydrous alcohol is mixed in the gasoline. Pauferro [1] defends the use of mixed alcohol to the DO due to the potential reduction of emissions of oxides of nitrogen (NO_x) and particulate matter. Another advantage highlighted by [1] is that the alcohol is practically free of sulfur. This element, besides being harmful to the environment, compromises the useful life of the engines, especially in the post-treatment devices like catalysts and exhaust gas recirculation (EGR) system. The author [1] further explains that the EGR is a device that promotes the recirculation of the exhaust gases to the intake manifold, being diluted with the admitted air load, reducing the possibility of NO_x formation.

According to [2], an increase in the demand for oil and other energy sources is forecast around 30% from 2010 to 2040, given the growth of the economy. This demand may

increase the price of liquid fuels, opening up space for competition with biofuels, which contribute to reducing gaseous emissions. This aspect, according to Caro et al. [3], justifies in itself the use of ethanol mixed with other fuels. However, meticulous studies are needed to allow the restrictions on pollution to be obeyed. The use of ethanol generates changes in the physicochemical properties of fossil fuels, such as reduction of cetane number, viscosity and calorific value. Pauferro [1] states that the cetane number of ethanol assumes very low values due to its high self-ignition temperature when compared to the DO, increasing the ignition delay of the air-fuel mixture, requiring the use of a fuel-promoting additive ignition. According to the same author [1], the lower calorific value of ethanol, around 27 MJ/kg, compared to that of the DO, around 42 MJ/kg, represents another property that needs to be compensated and can partially, be achieved by increasing the engine compression ratio.

Normally, ethanol application in ICE operating in Diesel cycle follows two techniques: by DO-ethanol blends and by atomizing (fumigating) ethanol. There are variations of the fumigation technique as a function of the place where the ethanol is sprayed in the engine. With the partial substitution of the DO by mixing with ethanol, it is necessary to include some additive to improve the cetane number of the blend, because this parameter, as already mentioned, is low for alcohol, causing significant delays on ignition of ICE-CI. However, the inclusion of the additives should be done with caution, because depending on their nature, there may be formation of products harmful to the environment and health. Ethanol, like other light alcohols, is characterized by having a polar molecular structure, unlike DO, which is characterized by having an apolar structure, rendering the total solubility of ethanol in the DO impossible for mixtures above 5% of this alcohol. Therefore, it is indispensable the application of homogenization promoters in these mixtures, which are called cosolvents. These substances, in general, are long molecules and have chemical affinities both with the polar molecules and with those apolar [1] - [4]

The performance of a CI engine operating with a ternary fuel mixture (diesel - alcohol anhydrous - castor oil) was evaluated in [5], where the castor oil was used as a phase activator to the mixture and alcohol additive. The authors used the mixtures without the need of specific processes to adapt them to the engine and without making changes in their original injection parameters. The blends were obtained by a simple process in which known amounts of each component were mixed in a container. In a first phase, emulsions with variable contents of castor oil in the alcohol were prepared to determine the viscosity and calorific value of the mixture. In a second step, for each ratio of castor oil-alcohol blend, an amount of DO was added that would provide complete solubility of the blend. The ternary mixtures were characterized for viscosity, calorific value, specific mass and surface tension, and compared to DO. Only a ternary mixture did not show phase separation (90% DO, 9% alcohol and 1% castor oil), which was tested in a ICE of two cylinders, four-stroke, and direct injection, and its performance characteristics was determined on dynamometer. The results of the tests showed that several performance characteristics are comparable to those using conventional diesel, with small losses in power and efficiency, which demonstrates that it is technically feasible

to apply this mixture as an alternative fuel without the need of modifications in the engine. Regarding the environmental effects, the authors observed less intensity in the level of soot.

In [3], two organic additives were selected for their different physico-chemical parameters to study the behavior of a mixture of diesel and ethanol. These compounds have the molecular structure of glycerol bound to certain functional groups. The authors investigated properties directly related to engine parameters (viscosity, cetane number, calorific value and volatility) and characterize fuel quality (homogeneity, cold properties, anti-corrosive quality and volatility). The fuel formulations were prepared with 2% additive and ethanol content between 10 and 20% by volume relative to the DO. Mixtures with and without additives were compared in two diesel engines, one with direct injection and the other with indirect injection. The authors mention that the behavior of the engines seemed to be improved in the presence of additives in the DO-alcohol mixture, with reduction of pollutants in the gaseous emissions, but there were cyclical irregularities and delay of ignition. However, detonation problems were not observed in the study.

Can, Çelikten e Usta [6] investigated the effects of adding ethanol (10% and 15%, by volume) in DO on the performance and emissions of a four-cylinder, turbocharged, indirect injection, four-stroke engine at different injection pressures (150, 200 and 250 bar) of the fuel blend and at full load. 1% isopropanol was added to the mixtures to satisfy homogeneity and avoid phase separation. Experimental results showed that the addition of ethanol reduced CO, soot and SO_2 emissions, although it caused an increase in NO_x emissions and a power reduction of 12.5% for addition of 10% ethanol, and 20% for addition of 15% ethanol. The authors also identified that with the increase of the injection pressure of the engine operating on dual fuel mode, there was a decrease in CO and smoke emissions, especially between 1500 and 2500 RPM, in relation to single fuel mode operation with DO, although there was some power reduction.

Estrada [7] assessed the performance and emissions of a diesel engine of an agricultural tractor using blends of DO (with 5% of biodiesel) and hydrated ethanol (HET), using mixtures with 3%, 6%, 9%, 12% and 15% of this alcohol. The results indicated that as the percentage of HET increased, the mean values of torque and power decreased. With the mixture of 3% of HET, these parameters did not differ statistically, obtaining the lowest fuel consumption. At 12% of HET on the blend the engine performance had reductions of torque and power in relation to the DO100 operation of 2.97% and 2.95%, respectively, while the fuel consumption did not present statistical difference. While mixtures of 12% and 15% of HET, the reductions of opacity, CO_2 and NO_x in relation to DO100 were of 22.22 and 24.44%, 5.2 and 5.6%, and 6.65 and 10.48%; respectively. The author considered that the engine operating in dual fuel mode DO-HET12, emissions of pollutants have been significantly reduced, without a considerable loss of performance.

Kumar et al. [8] do an extensive review of the properties of the main alcohols (methanol, ethanol and butanol) compared to those of gasoline and DO. In the author's comparison, butanol has the potential to overcome the problems associated with the use of methanol and ethanol.

This review discusses the progress in the production of these alcohols from different primary sources, in addition to the use of mixtures, especially DO-methanol and DO-ethanol in ICE-CI. For such blends the combustion, performance and emissions in ICE are analyzed, including the use of additives to improve the cetane number of the same. The author's study revealed that butanol would be the best alternative in mixtures with DO because of its properties and miscibility being better than those of methanol and ethanol.

In relation to the partial substitution of DO by atomization (fumigation) of ethanol, [1] and [4] describe the following ethanol injection strategies in the engine: intake manifold fumigation; double injection with glow plugs in the combustion chamber; and direct injection at the beginning of the compression time. Glow plugs have the function of increasing the temperature of the combustion chamber, compensating the lower cetane number of ethanol. The authors highlight the particularities of each system.

Imran et al. [9] also addressed to alcohol fumigation systems in diesel engines, identifying the potentials of using this process. It is a review article in which the authors make a critical analysis of the effect of fumigation of methanol and ethanol on diesel engine performance and emissions, emphasizing that a variety of fumigation ratios from 5% to 40% have been applied in different types of engines with different forms of operation. They also point out that the application of the alcohol fumigation technique has led to a significant reduction of emissions: CO_2 up to 7.2%; NO_x up to 20%; and particulate matter up to 57%; although there has been an increase in the percentages of CO and hydrocarbons (HC) emissions. It was also observed an increase in the specific fuel consumption caused by the higher latent heat of alcohol vaporization compared to those of DO. Finally, the authors highlight the decrease in thermal efficiency of the engine at high loads.

Pedrozo et al. [2] claim that the use of ethanol, a fuel with presence of oxygen in its molecule, with high resistance to detonation (high octane) and high latent heat of vaporization, enhances the reactivity power. Associated with this, renewable biofuels can provide a sustainable alternative to replace petroleum-based fuels, as well as reduce gaseous emissions that cause the greenhouse effect. However, combustion of the DO-ethanol mixture leads to low engine efficiency at low loads due to incomplete combustion. In this way, the authors carried out an experimental study on a 2.03 L single-cylinder diesel engine with a common rail DO injection system, operating at low loads (1200 rpm and effective mean pressure of 0.615 MPa). The ethanol fumigation strategy was applied directly to the engine intake manifold, and the EGR effects, inlet air pressure and the diesel injection pressure in the rail were also evaluated. The best results were obtained for 54% ethanol in the mixture, 25% EGR, 125 kPa of the intake air pressure and 90 MPa common rail pressure, leading to the following values: 45.5% of thermal engine efficiency; combustion efficiency of 96.7%; reduction of 65% in NO_x emissions and 29% in particulate matter.

Abu-Qudais, Haddad and Qudaisat [10] studied the effects of the ethanol fumigation technique on the air intake manifold and DO-ethanol blends on the performance and emissions of a single-cylinder diesel engine of 0.582 L. The results showed that both applied techniques presented the same behavior on performance and emissions. However, the best results were obtained with the fumigation method at the rate of 20% of ethanol, which led to increases of 7.5% in thermal efficiency, 55% in CO and 36% in HC emissions; and a decrease of 51% in particulate matter. The best results for DO-ethanol blends were obtained for the mixture of 15% of ethanol: increase of 3.6% in thermal efficiency, increases of 43.3% in CO and 34% in HC; and a reduction of 32% in particulate matter.

In [11], a 2.06 L single-cylinder diesel engine with variable compression ratio was analyzed, operating in a dual fuel mode DO-ethanol (ethanol injection in the air intake manifold), 100% electronically controlled. Once the engine was adjusted to the maximum torque in each load condition, the DO was gradually replaced by ethanol according to the established requirements. The authors made comparisons between different operating conditions considering the DO replacement rate and the indicated thermal efficiency. In the work were still considered gases flows in the combustion chamber in quiescent and swirl mode, compression ratios of 14:1, 16:1 and 17:1, being tested two DO injectors (one with 35 g/s and another with 45 g/s) plus 4 DO injection pressure levels (800, 1000, 1200 and 1400 bar). The highest DO replacement rates occurred at the 16:1 compression ratio, reaching more than 50%.

Chauhan et al. [12] assessed a small single-cylinder diesel engine of 0.9 L, with compression ratio of 17:1, power of 7.5 kW, operating on diesel-ethanol dual fuel mode by fumigation. An electric generator was coupled to engine. Fumigation was carried out using a kind of carburetor at constant volume. The authors stated that the atomization of ethanol resulted in a lower temperature combustion. The percentage of fumigation of ethanol that yielded the best emissive results was 15%: lower concentrations of NO_x, CO, CO_2 and exhaust gas temperature, although emissions of non-combusted HC increased in all load ranges.

Ingle and Nandedkar [13] analyzed the specific consumption and thermal efficiency of a four-cycle, single-cylinder ICE-CI, operating on dual fuel mode DO-biodiesel of castor vegetable oil (CVO) up to the total DO substitution, i.e., in B100 mode. As a result, the authors obtained a small increase in the value of the thermal efficiency according to the increase of the percentage of substitution of DO for biodiesel of CVO; except in the replacement rate of 40%, where there was a great reduction of the thermal efficiency. On the specific fuel consumption analysis, the best values were obtained in the replacement rates of 60% and 80%, and the highest was obtained in the replacement rate of 40%.

Sattanathan [14] studied the effects of the use of biodiesel of CVO on different percentages of DO substitution in emissions, thermal efficiency and specific fuel consumption in an ICE-CI. The author observed that how higher is the percentage of substitution of DO by biodiesel up to B100, lower is the amount of noncombustible hydrocarbons and the opacity of the gases. On the other hand, increasing the rate of substitution of DO by biodiesel also increased CO and NO_x emissions. The performance results showed that the thermal efficiency decreases with the increase of the percentage of substitution, and the specific fuel consumption increases how bigger is the percentage of substitution.

Finally, one of the few studies involving the use of ethanol-CVO blended fuels in small ICE-CI was performed

in the early 80's [15]. As a main result of the study it was identified that the emissions with minimum opacity and NO$_x$ production at satisfactory thermal efficiency values of the engines were obtained with a mixture of 60% of ethanol and 40% of CVO. In addition, it was found that at light loads and low engine speeds studied, the combustion variation was closely related to the ignition delay, being controlled by an increase in the intake air temperature or in the increase of the CVO content in the mixture.

In this article is studied the use of hydrated ethanol (HET), in the form available at the fuel stations, mixed with diesel oil (DO) in a small 8 kVA genset. The engine used is unmodified and despite of many studies already developed, there is a lot to understand about the functionality of the compression ignition engines in dual fuel mode. Although the simplest process is the mixing of the alcohol with the oil, the solubility is difficult. Therefore, a small amount of castor vegetable oil (CVO) was used to produce a greater homogenization of the mixtures. In the study the thermomechanical performance of the genset and the opacity characteristics of the emissions produced by the motor are evaluated.

II. MATERIALS AND METHODS

In order to compare the performance parameters of the system studied, some features of the main components used in the development of this work: generator set, instrumentation, properties of the fuel blends; are presented. Also, the methodology followed on the experiments is shown.

The engine used in the tests is Agrale brand, model M90, single cylinder, and has the following constructive, operating and setting features: 668 cm^3 of displacement; direct injection (DI); fuel supply system by gravity; injection pump unit embedded in the block; fuel filter cartridge type (plastic) of 20 μm mesh; forced air cooling by fan built into the flywheel; crankcase lubricating oil incorporated into the engine block, with capacity of 2.5 liters; speed control by acceleration lever and fuel oil rate adjustment by an eccentric mechanism acting on the injection pump; injection angle of 21° BTDC; injection opening pressure of 180 bar; and electric starter. It is noted that the fuel consumption of this engine was adjusted by the manufacturer to engine-generator (genset) version according to NBR ISO 3046/1/1995 standard.

The engine is coupled by belts and pulleys to an electric generator (alternator) three-phase Kolbach brand, model 46530/05, 8 kVA of apparent power, 60 Hz and 220 Volts, with star connection. The generator operates at 1800 rpm and the electric energy produced is dissipated on electric resistances immersed in running water inside a reservoir.

The engine was tested with DO substitution rates from 10% to 100% by volume, whose proportion of fuels are reported in Table 1. As seen in this table, the experiments were done with DO-HET-CVO blends with up to 50% of DO. It is important to mention that in all these blends the miscibility of HET-CVO (which was complete) in the DO, not occurred completely.

For the determination of the properties of the DO-HET-CVO blends, samples of the miscible part of the mixtures were collected. The measured properties were: absolute viscosity (μ), specific mass (ρ) and higher heating value

(*HHV*). The viscosity measurement (cP) was done at 25 °C through an Anton Paar rheometer, model physic mcr 301, with cone-plate geometry. For the measurement of the specific mass, made at 20 °C, a 25 mL pycnometer was used, along with a precision digital balance of the Marte brand, model AL500, with a maximum load of 500 g and a resolution of 0.001 g. The pycnometer was initially calibrated with deionized water to determine its exact volume. The equipment used in the heating value analyses was a constant volume calorimetric pump of the VEB brand, number 08, model 1031, and using benzoic acid as reference substance. Table 2 presents the average values of two measures of the properties of the mixtures used, including pure fuels (DO100, HET100 and CVO100). It is noted that the DO60-HET36-CVO4 sample did not follow the tendency of the other samples and the same behavior is observed for *HHV* for the DO70-HET27-CVO3 sample.

Table 1– Fuel contents in the samples (% Vol.)

Sample number	DO (%)	DO Substitution (%)	HET (%)	CVO (%)
1	100	0	0	0
2	90	10	9	1
3	80	20	18	2
4	70	30	27	3
5	60	40	36	4
6	50	50	45	5
7	0	100	90	10
8	0	100	80	20
9	0	100	75	25

Table 2 – Fuel properties

Mistura comb.	μ (cP)	ρ (g/cm^3)	*HHV* (MJ/kg)
DO100	3.52	0.843	46.78
HET100	0.50	0.806	30.49
CVO100	577.7	0.945	Nm*
DO90 HET9 CVO1	3.41	0.842	43.94
DO80 HET18 CVO2	2.96	0.840	42.71
DO70 HET27 CVO3	2.86	0.835	42.76
DO60 HET36 CVO4	3.36	0.833	38.23
DO50 HET45 CVO5	2.60	0.831	36.21
HET90 CVO10	Nm*	0.830	Nm*
HET80 CVO20	1.75	0.838	37.13
HET75 CVO25	Nm*	0.845	Nm*

*Nm: Not measured

DO used was the S500 (up to 500 ppm of sulfur) with 7% of biodiesel, which is commonly found at fuel stations, as well as HET. Castor vegetable oil (CVO) used as a cosolvent is found in commercial establishments. In order to determine the alcoholic level of HET, an Incoterm Gay-Lussac alcoholometer was used, with a scale ranging from 0 to 100% (V/V) and resolution of 1 °GL. Measurements were made with two HET samples, with the average percentage of alcohol in volume at 20 °C, 95.5% (95.5 °GL), that is, there is, on average, 4.5% in volume of water present.

The engine was submitted to HET in partial substitution to the DO, together with CVO cosolvent, to improve the HET miscibility in the DO and to maintain the lubricity. This

prevented any modification in the engine's power system, causing it to operate in the same way as in a DO100 single fuel mode. Figure 1 shows a schematic of the experimental workbench with its main components.
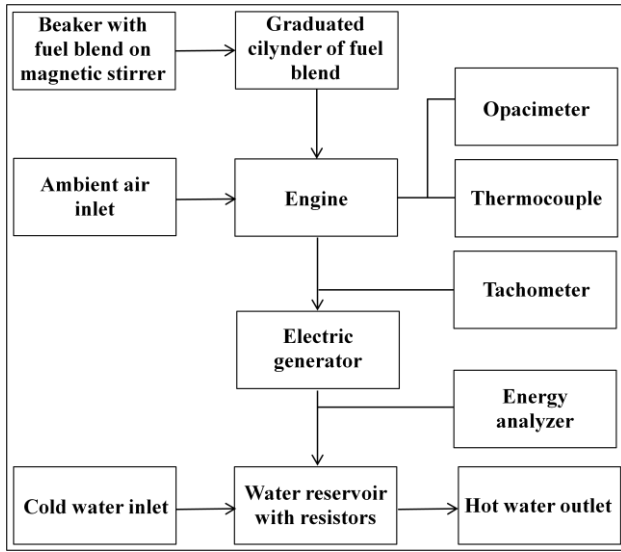

Figure 1 – Experimental scheme

According to the scheme of Figure 1, the equipment/instruments used to monitor the global operation of the system are described below.

Fuel supply to the engine - by means of a magnetic stirrer Velp Scientifica, AER model, the mixture prepared in a 1.8 L beaker was maintained shaken, with which the fuel mixture was manually supplied in a graduated measuring cylinder with a capacity of 100 mL and resolution of 1 mL. The fuel supply hoses for the engine and the return hose were mounted on the cylinder, in such a way that the fuel supply and return is made fully by gravity.

Engine exhaust gaseous - the exhaust gas temperature measurement was done with a K-type thermocouple connected to a reader Novus brand, 305 model. The thermocouple was installed in contact with the combustion gases in the engine exhaust manifold in one point closest to the outlet of the combustion chamber. The equipment has a measuring range between -50 °C and 1300 °C, with resolution of 0.1 °C and recording of 5 measurements every 2 seconds. For diesel engines, it is common to use an opacimeter to assess the pollution generated by the engine. The method is applied even by regulatory agencies as a tool for control and vehicular inspection of trucks and buses. The opacimeter used in the experiments is of Napro brand, NA9000 model and the values are obtained through software installed in computer. The opacimeter has opacity measurement range from 0 to 99%, light absorption coefficient measurement range from 0 to 9.99 m^{-1}, accuracy of ± 2%, resolution of 0.1, camera temperature of 75 °C, beam length of 430 mm, response time from 0.9 to 1.1 s, ambient temperature from 5 to 40 °C and ambient humidity from 0 to 85%.

Speed of the electric generator – the adjustment of the speed on the generator shaft was performed with an Extech Instruments 461920 laser reflective tachometer. Its range is from 2 to 99999 RPM, with resolution of 0.1 RPM below 1000 RPM, or 1 RPM above this value.

Energy analyzer - voltage, current, frequency and power of the generator were monitored by an Embrasul RE6000 energy analyzer. This analyzer has measurement resolutions of 0.01 V and 0.01 A for voltage and current, respectively. For both voltage and current, the accuracy is 0.2%. The operating range is from 50 to 500 V for AC voltage, and from 0.2 to 1000 A for AC current.

Air conditions in the test environment – local atmospheric pressure, dry bulb temperature and relative air humidity were measured by specific transducers available on the dynamometric system installed in the same test environment.

To perform the experiments, the following procedures were followed: - initial heating of the engine on DO100 mode for 20 minutes, with the engine unloaded, and with speed set to around 1800 RPM, throttled by an acceleration lever, measured with tachometer on the generator pulley; - after the engine warm-up period, the generator was activated by setting the circuit-breaker switch connected to the electrical resistors; - due to the load, it was necessary to adjust the generator speed to 1800 RPM; - the test time of each fuel sample was set at 30 minutes, or the necessary time for the total consumption of the quantity of mixture prepared; - the fuel consumption was obtained by timing the time to consume 50 mL in the graduated cylinder; - after the total consumption of a given fuel mixture, the subsequent mixture was carried out only by supplying it to the graduated cylinder, without interrupting the operation of the engine, but the measure of consumption was made after having consumed the volume relative to two graduate cylinders, i.e., almost 200 ml; due to the low miscibility of HET in the DO, while the engine was in operation with the amount of fuel present in the beaker, the remainder of the mixture remained in the beaker on the magnetic stirrer, as mentioned before; - during the consumption of each 50 mL of fuel present in the cylinder were measured the exhaust gas temperature, rotation, active power, atmospheric pressure, dry bulb temperature, relative air humidity, opacity and light absorption coefficient; - data collection was repeated at least 10 times for each sample/fuel mixture; the correction of the experimental values for the standard reference condition (barometric pressure of 100 kPa, air temperature of 298 K and relative air humidity of 30%) was made based on the standard NBR ISO 3046/1, whose correction method is summarized in the determination of power and specific fuel consumption adjustment factors.

The specific fuel consumption (*SFC*) of DO100 and of the mixtures was performed from Equation (1).

$$SFC = \frac{\dot{m}_{fuel}}{P} = \frac{\rho \cdot \dot{V}}{P} \qquad (1)$$

where *SFC* is expressed in g/kWh, $\dot{m}_{fuel}$ is fuel consumption in g/h, *P* is the corrected active power in kW, ρ is fuel specific mass in g/cm^3, and $\dot{V}$ is volumetric flow rate in cm^3/h.

The engine thermal efficiency (η_t) was calculated from Equation (2).

$$\eta_t = \frac{3,6 \cdot 10^6}{SFC \cdot HHV} \qquad (2)$$

where *HHV* represent higher heating value of fuels in kJ/kg.

III. RESULTS AND DISCUSSION

From NBR ISO 3046/1 standard already mentioned were calculated the correction factors of power (α) and of specific fuel consumption (β) on the basis of the environmental parameters measured during the experiments. Values of these factors are reported in Table 3 for each of the experiments.

Table 3 – Correction factors of *P* and *SFC*

Fuel blends	α	β
DO100	0.918	1.013
DO90 HET9 CVO1	0.916	1.014
DO80 HET18 CVO2	0.914	1.014
DO70 HET27 CVO3	0.912	1.014
DO60 HET36 CVO4	0.912	1.014
DO50 HET45 CVO5	0.918	1.013
HET90 CVO10	0.930	1.011
HET80 CVO20	0.925	1.012
HET75 CVO25	0.927	1.012

As mentioned in the previous section, the experiments with each fuel mixture occurred for an average of 30 minutes, being taken 10 measurements on average. Table 4 presents the mean results for the experiments performed.

Table 4 – Experiment average results

Fuel blends	$T_{exhaust}$ (°C)	P_{c*} (kW)	SFC_{c*} (g/kWh)	η_t (%)	Opac. (%)
DO100	465	5.6	338.8	22.7	43.7
DO90 HET9 CVO1	486	5.6	353.0	23.2	48.2
DO80 HET18 CVO2	506	5.6	371.2	22.7	39.7
DO70 HET27 CVO3	498	5.6	373.6	22.5	18.5
DO60 HET36 CVO4	492	5.6	399.3	23.6	15.7
DO50 HET 45 CVO5	449	5.6	397.3	25.0	9.2
HET90 CVO10	437	5.5	516.2	-	1.9
HET80 CVO20	396	5.5	459.9	21.1	2.6
HET75 CVO15	403	5.5	449.8	-	2.7

*Corrected parameters

By observing the results obtained from exhaust gas temperature, can be verified that the temperature increases in the bands of lower DO substitution, but reducing thereafter. Peralta and Barbosa [5] obtained a reduction of the discharge gases temperature in the order of 7.2%, mixing DO, ethanol and castor oil. Using the fumigation method, Chauhan et al. [12] observed a 35 °C reduction in exhaust gas temperature, using ethanol fumigation of 20% at full load.

In this work, using only HET and CVO mixtures, the exhaust gas temperature has decreased reasonably, which is attributed, according to [8], to the higher latent heat of vaporization of ethanol (0.92 MJ/kg) compared to DO (0.23-0.60 MJ/kg).

In Figure 2, the results obtained to the exhaust gas temperature with the standard deviations are illustrated.
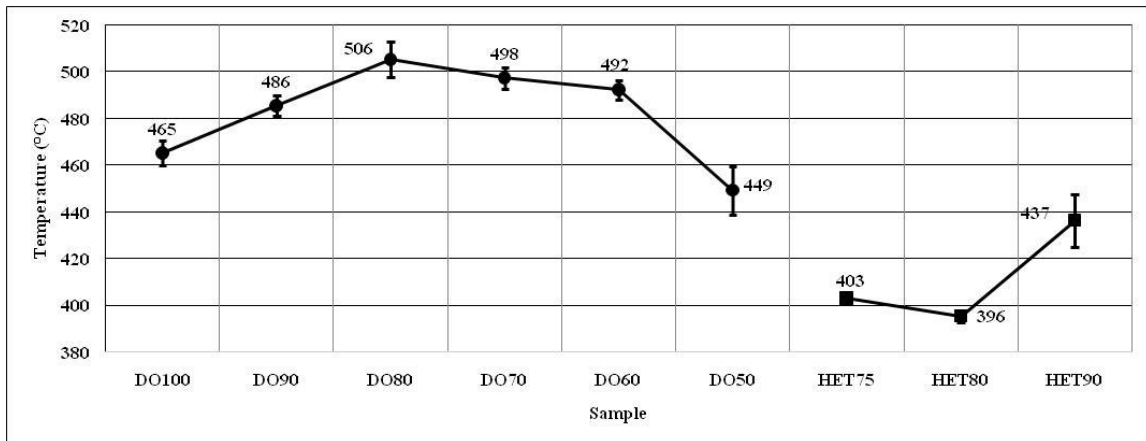

Figure 2 – Exhaust gas temperature

HET90-CVO10 sample showed many failures during the combustion, which caused the increase and oscillation of the exhaust gas temperature.

As the electric generator coupled to the engine was coupled to a constant resistive load, the active power did not get much variation. The values that obtained the greatest divergence from the average power generated around 5.6 kW were caused by combustion failures, especially for blends with higher HET content, being necessary to adjust the engine speed through the throttle lever to maintain the generator speed at 1800 RPM.

Corrected specific fuel consumption was calculated by Equation (1) using the corrected active power and dividing by factor β. Figure 3 shows the specific consumption corrected with the standard deviation for each mixture.
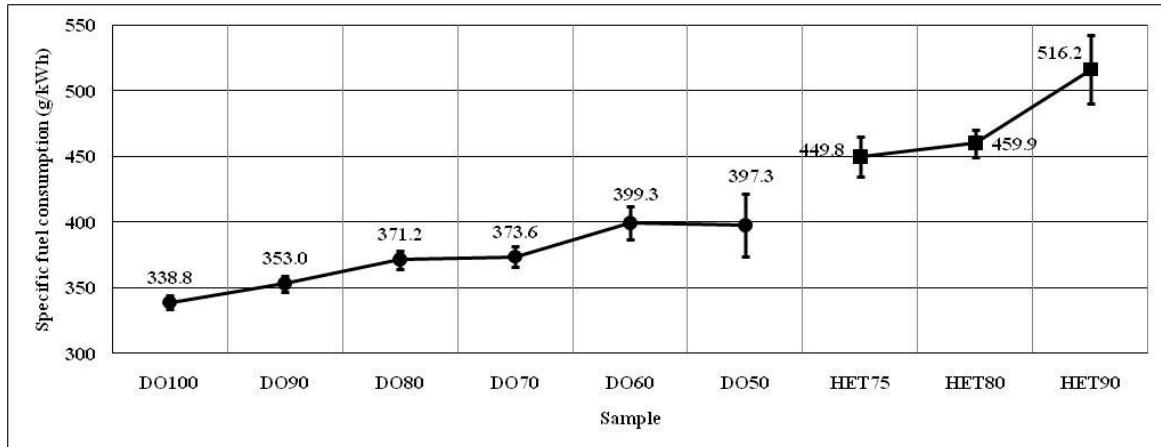
Figure 3 – Corrected specific fuel consumption

The specific fuel consumption increases as the substitution rate of DO by HET increases, except for 50% of replacement. This is due to the irregular operation of the engine at this replacement rate, causing its rotation to decrease during the test, even by adjusting the acceleration lever of the engine. In general, the standard deviation represents the measurement of uncertainty, which means that higher the standard deviation more failures occurred in the combustion. Imran et al. [9] observed the same behavior operating with the fumigation method. Peralta and Barbosa [5], working with non-fumigated ternary mix, found a 4.8% increase in specific fuel consumption for a 10% of replacement rate of DO. For the same replacement rate, an increase of 4.1% in specific consumption was observed in this study. Already Estrada [7] obtained a 3.8% increase in specific fuel consumption for a substitution rate of 15% of DO per HET.

When operating the engine with total DO suppression and working only with the HET-CVO blended fuel, an increase in specific fuel consumption is observed. In general, it can be stated that the specific fuel consumption increases as the substitution rate of DO by HET increases because the calorific value is lower than those of DO. Even the samples with total DO substitution having higher *HHV* than the 50% substitution sample (Table 2, 37.13 MJ/kg against 36.23 MJ/kg) and very close to the 40% substitution (38.23 MJ/kg), their specific fuel consumption were higher. This fact can be explained by the viscosity of the fluid being smaller (1.75 cP vs. 2.60 cP), causing greater fuel flow to the engine for the same injection time.

The genset thermal efficiency was calculated from Equation (2) using the corrected specific fuel consumption and the fuel higher heating value. In Figure 4, the genset thermal efficiencies operating with each blend and the respective standard deviations are shown.
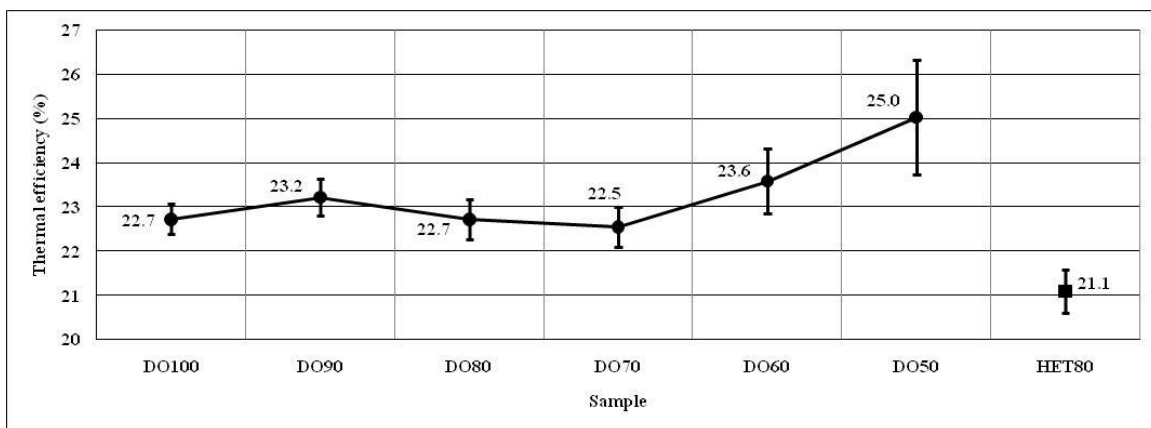

Figure 4 – Genset thermal efficiency

For samples HET90-CVO10 and HET75-CVO25 the genset thermal efficiency was not determined because the calorific value of the samples was not measured. In general, up to 30% DO substitution, the efficiency oscillated slightly, as observed in the standard deviations identified in the figure. So, as in the specific fuel consumption measurements, the standard deviation is proportional to the engine's combustion failures during the experiments. In the work of Abu-Qudais, Haddad and Qudaisat [10] the thermal efficiency increased by 7.5% for the fumigation method and

5.4% by using the mixture. In this work, for the percentage of 20% DO substitution, the same thermal efficiency of the DO100 operation was obtained. On the other hand, Peralta and Barbosa [5] obtained a decrease of 6.9% on engine efficiency, operating with a DO90-HET9-CVO1 blend. Also according to [5], this is due to the lower cetane number caused by the addition of HET.

Imran et al. [9] obtained yield drop at low load and increase at medium and high loads. The authors explain that because the HET has high latent heat of vaporization,

causing a decrease in the exhaust gas temperature, the efficiency at low loads becomes smaller. For medium and high loads, HET increases the ignition delay resulting in a lower temperature loss for the combustion chamber and cylinder walls.

Analyzing the thermal efficiency of the HET80-CVO20 blended fuel, the same case of specific fuel consumption occurs. A greater amount of fuel injected into the engine and the heating value not so below for that of the DO100, caused a drop in efficiency.

In Figure 5, the results of exhaust gas opacity as well as the results of standard deviation are presented.
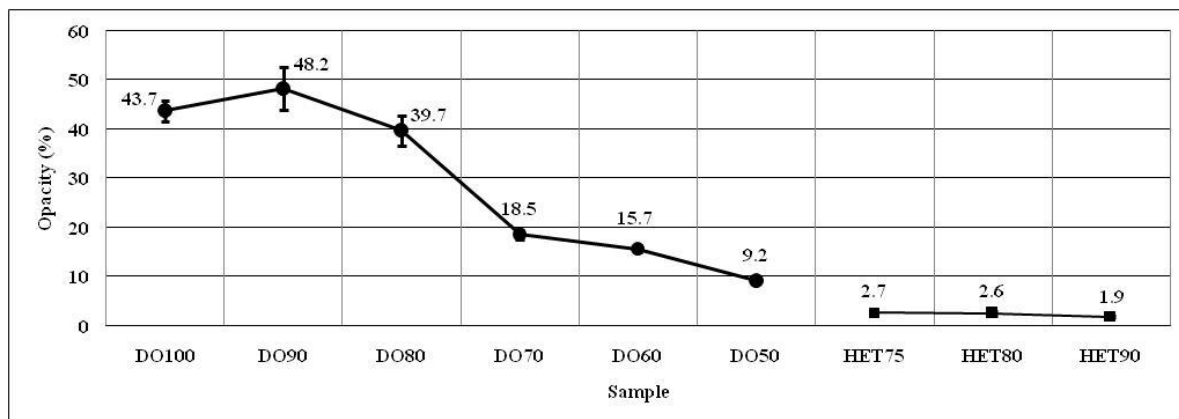

Figure 5 – Exhaust gas opacity

It is found that the percentage of exhaust gas opacity tends to decrease with the substitution of DO by HET. Chauhan et al [12] obtained a similar curve of decreasing of the exhaust gas opacity as the percentage of substitution of DO for ethanol at various load levels increased. Similarly, Imran et al [9] observed the same behavior in the experiments performed. This is due to the fact that the oxygen present in HET improves combustion, reducing gas opacity. Another factor to consider is that HET has a lower amount of carbon in its chemical composition, resulting in a lower emission of particulate matter. For the opacity measurements, it was found that the combustion failures did not influence its value, as observed by the low value of the standard deviation, as the alcohol content in the mixture increases.

By completely eliminating the DO from the blend, the opacity percentage reduces to almost zero. As shown in Figure 5, the high percentage of HET used in these samples contributed to this large reduction.

In general, in the use of ternary biofuel mixtures, as performed in this work, one of the substances acts as cosolvent to improve the miscibility. The CVO here, that besides acting as a cosolvent, acts as a lubricity improver in the mixture, since ethanol reduces this characteristic of the binary mixture DO-HET. However, it was observed that in all the ternary mixtures used in the work, the phases were separated. In particular, it was noted that in the DO70-HET27-CVO3 mixture compared to the DO70-HET30 mixture in separate and similar containers, the phase separation occurs at approximately the same level, indicating that the presence of CVO on mixture it is justified only by the increase in lubricity.

Certainly, by the current liter prices of the three substances used in this work (DO, HET and CVO), the use in ICE neither of the biofuel ternary mixtures based on them, nor of the HET-CVO binary mixtures, is economically justified. In Brazil, the HET liter price at gas stations is around 17% higher than the DO. Moreover, the price of the CVO liter (not bulk) in commercial establishments is about

6 times greater than the DO liter price. Therefore, the justification for the use of HET-CVO binary mixtures in partial or total substitution of DO in the ICE is ecological, which can have an economic repercussion as well. In other words, the production and use of biofuels, in addition to bringing less environmental problems resulting from the gaseous emissions of the equipments (greenhouse effect, acid rain, etc.), can benefit the national economy by reducing energy dependence based on fossil fuels.

IV. CONCLUSIONS

In this work were presented experimental data of a small generator set, being the engine originally of the diesel cycle, operating in tri and dual fuel modes: diesel-ethanol-castor oil and ethanol-castor oil.

The characterization analyzes of the fuel mixtures were satisfactory within the results expected and found in the bibliography. Only two samples did not meet the expected standards. The viscosity analysis of the DO60-HET36-CVO4 sample was higher than expected, not following the trend of the other samples. The higher heating value of the DO70-HET27-CVO3 sample also did not follow the trend of the others, getting higher than expected.

As for the performance analysis of the generator set on dual fuel mode, the results obtained were interesting, being able to totally substitute the DO for mixtures of HET with CVO without any failures in the combustion. In operation with DO-HET-CVO blends, the engine presented regular operation up to 30% DO replacement, showing some irregularities at higher percentage of replacement. This fact could be observed from the values of standard deviation in the results. Certainly, for the engine to operate on dual fuel mode as performed here, the engine must be properly heated and prior operation with pure diesel oil is required. In addition, it is recommended that the final operation of the engine be with diesel oil to avoid that the presence of the ethanol next to its components not to promote the corrosion of the same.

The specific fuel consumption increased as the substitution rate increased, which was already expected because the HET had a lower heating value than the DO.

A 15% reduction in exhaust gas temperature was achieved with total DO replacement. Already at the 50% replacement rate, the percentage of reduction of the exhaust gas temperature was of 4%, demonstrating that the HET positively influences to decrease this temperature, avoiding excessive thermal losses.

The results of the genset thermal efficiency were satisfactory, showing an increases with the addition of HET in the mixture, although the increase of the standard deviation (more functional instability of the engine). Only at 30% DO substitution the efficiency was lower, but not very significant. Up to 2.3% increased the genset thermal efficiency, except when DO use was completely suppressed, having a decrease of almost 1.7%, which may have occurred because of the lower viscosity and heating value of the binary blend.

The opacity analysis and, consequently, the light absorption coefficient of the exhaust gas showed a very significant improvement for all substitution range except for 10%. A decrease of 41.8% in the opacity index was achieved, representing a 96% variation in relation to DO100 use. The light absorption coefficient followed the same trend, decreasing by 97%.

In general, the study of engines operating in dual fuel mode using HET and CVO was satisfactory in the opacity levels, mainly at high replacement rates. As regard efficiency, studies should be deepened for best results.

While the price of the liter of ethanol applied at Brazilian gas stations is linked to the price of gasoline, it is not economically attractive to use it in ICE. However, for the rural producer who plants different crops, he can produce biofuels (ethanol and vegetable oils) to move the engines he owns.

For further work, more in-depth studies on DO injection and ETH blend methods are suggested, and the fumigation method can be used. Experiments with different injection points of the fuel mixtures are also interesting from the point of view to avoid the irregular operation of the engine with the addition of HET.

Long-term experiments can be performed enabling results closer to the actual engine operating conditions, including exhaust gas analysis such as CO, CO_2, NO_x, SO_x, particulate matter and hydrocarbons unburned. These data would give a better understanding of the combustion of fuel mixtures at different substitution rates and injection points.

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