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## EXPERIMENTAL ANALYSIS OF A SMALL ENGINE-GENERATOR GROUP OPERATING ON DIESEL-ETHANOL BY FUMIGATION METHOD

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**Abstract.** *The aim of this article is to investigate the effects of a small engine-generator group operating on diesel-ethanol by fumigation method. The experiments were conducted in a single-cylinder diesel engine coupled to a generator. Ethanol was atomized at the engine intake manifold by a port fuel injector. The diesel oil substitution rates were 12.8% to 70% in energy. The experiments resulted in a decrease in the opacity and a reduction up to 18% in temperature of the engine exhaust gases. On the other hand, an increase in specific fuel consumption and up to 5.5% in genset thermal efficiency have been noted. The results were satisfactory, showing that ethanol can be used as an alternative fuel for diesel engines.*

**Keywords:** *internal combustion engine, compression ignition, diesel-ethanol, mono fuel operation, dual fuel operation.*

### 1. INTRODUCTION

Nowadays the primary energy of the world is based on fossil resources. The data from International Energy Agency (2016), mention that 83% of the primary energy supply came from fossil fuels and 31% about the total primary energy value came from oil. The dependency from fossil fuel is not expected to reduce, according to U.S. Energy Information Administration (2014), analyzing the projections for world economic growth, an increase in demand for oil and other energy sources is expected to increase by more than 30% from 2010 to 2040.

Transport sector is responsible for the consumption of 64.5% of all oil produced in 2014, about 2425.8 Mtoe, resulting in 23% in all CO<sub>2</sub> emission emitted at atmosphere (IEA, 2016). These data concern a lot the governments around the globe and show our dependency from fossil fuels. Our fossil resources are being reduced in a fast way. Imran et al (2013) discuss some statistics that we just have oil reserves for more about 50 years. On the other hand, the governments are encouraging people to use renewable energy, to save fossil fuel and reduce emissions. For example, Labecka, Slavinskas e Mažeika (2014) report that until 2020 in all European Union, the transport sector should use at least 20% of renewable energy.

The most part of the internal combustion engines (ICE) today are in the transport sector and the most part of them are operating with diesel oil (DO) only. The reason of it is that they have more efficiency and lower consumption compared with spark ignition engine (SI). To achieve some tasks and legislations proposed by the governments, it is necessary to substitute all the diesel or part of it, for renewable fuels.

Many researchers are being conducted to replace some part of diesel oil by hydrated ethanol (HET). The advantage to replace diesel to ethanol, is the use of a renewable fuel, reducing the fossil dependency and emission of pollutants. According to Renewable Fuels Association (2015) the largest producers of ethanol in the world are United States and Brazil with 57% and 28% of all ethanol produced, respectively.

Egúsqüiza (2011) describe the main alcohol injection strategies in the engine: atomization alcohol at the intake manifold, fumigation method, double injection with glow plugs in the combustion chamber; and direct injection with diesel-ethanol blends. The author highlighted the particularities of each method. Boretti (2012) quotes that fumigation method allows high percentages of substitutions rates and it is the best available solution to operate an ICE with alcohol. The great advantage of fumigation method is due ease assembly when compared to the other methods. In

addition, the method of the mixtures does not allow high substitution rate because the OD and HET are not miscible and when using co-solvents the method is not invoked by operation cost. Finally, the double injection method is difficult to perform due to high level of changes required in the engine system, especially the necessary physical space in the cylinder head for installation and correct orientation of the second injector in the combustion chamber.

Abu-Qudais, Haddad and Qudaisat (2000) studied the effects of the ethanol fumigation technique on the air intake manifold and DO-ethanol blends on performance and emissions of a single-cylinder diesel engine. The results showed that both applied techniques presented same behavior on performance and emissions. However, fumigation method at rate of 20% of ethanol were the best results, 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 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.

Chauhan *et al.* (2011) evaluated experiments in 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, which 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<sub>x</sub>, CO, CO<sub>2</sub> and exhaust gas temperature, although emissions of unburned HC increased in all load ranges.

Imran *et al.* (2013) 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 of 5% to 40% have been applied in different types of engines with different forms of operation. They also pointed out that the application of the alcohol fumigation technique has led to a significant reduction of emissions: CO<sub>2</sub> up to 7.2%; NO<sub>x</sub> up to 20%; and particulate matter up to 57%; although there has been an increase in the percentages of CO and hydrocarbons emissions. It was also observed an increase in the specific fuel consumption caused by alcohol lower heating value compared to those of DO. Finally, the authors highlighted the decrease in thermal efficiency of the engine at high loads.

In Britto Júnior and Martins (2014), 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). 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 gas 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%.

In another paper, Britto Júnior and Martins (2015) analyzed the engine emissions with the best configuration tested in their previous work. The configuration of the engine tested was with a 45 g/s injector, 17:1 compression ratio and combustion chamber in "swirl" mode. The tests were performed at 1800 rpm, with four load variations. The authors achieved a maximum rate of 65% diesel replacement and 49% efficiency. They also obtained a reduction of NO<sub>x</sub> emissions by 60%, in contrast the emissions of HC and CO and aldehydes increased.

Pedrozo *et al.* (2016) 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 exhaust gaseous recirculation (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<sub>x</sub> emissions and 29% in particulate matter.

Jamuwa, Sharma and Soni (2016) evaluate experimental tests using a stationary compression ignition engine with a power of 3.7 kW at 1500 rpm, compression ratio of 16.5:1, single cylinder coupled to an alternator. Resistor bank composed of lamps was used to vary the engine load in nine different loads. Ethanol was injected at engine intake manifold at flow rates of 0.1, 0.2, 0.3, 0.4 and 0.5 kg/h. The results showed that thermal efficiency decreased by around 11.2% at low loads. However, at high loads the thermal efficiency increased by around 6% compared to diesel. The authors report a maximum reduction of 22%, 41% and 27% in NO, smoke index and CO<sub>2</sub>, respectively. They observed a simultaneous increase of 144% in HC concentration and 139% in CO concentration when compared to the engine running on diesel. The authors believe is due to the change in the physicochemical properties of the mixture of air and fuel, combustion temperature, oxygen concentration, number of cetanes and ignition delay that occurred with the addition of ethanol in the combustion.

Due to the expressive production of ethanol in Brazil and the concerns about the utilization of fossil fuels and the emissions of warming gases, this article studied the effects of utilization of hydrated ethanol (HET) on performance of small engine generator set operating with diesel-ethanol by fumigation method.

## 2. EXPERIMENTAL PROCEDURE

In this section are presented some constructive features of the engine used in the development of the work, the main characteristic fuels used and the methodology used for the experiments.

The engine used in the tests is Agrale brand, model M90 and has the following constructive features: single cylinder, 668 cm<sup>3</sup> of displacement, direct injection (DI), forced air cooling by fan built into the flywheel, speed control by acceleration lever, injection angle of 21° before top dead center (BTDC); injection opening pressure of 180 bar and electric starter. The engine is coupled by belts and pulleys to an electric generator. An electric generator with three-phase, Kolbach brand, 8 kVA of apparent power and voltage of 220 Volts with star connection was used. The generator operates at 1800 rpm and can receive resistive or inductive loads.

The engine has been operated with pure diesel and different ethanol fumigation rates (0.117, 0.214, 0.337, 0.468 and 0.694 g/s). Fuel samples and ethanol mass flow are reported in Table 1.

Table 1 - Fuel samples and ethanol mass flow.

Sample Number	Sample designation	Ethanol mass flow (g/s)
0	DO100	0.000
1	HET1	0.117
2	HET2	0.214
3	HET3	0.337
4	HET4	0.468
5	HET5	0.694

The performance characteristics, exhaust emissions have been recorded and analyzed at a single resistor load. Furthermore, these parameters have been compared with those of pure diesel case (DO100).

The main characteristics of the fuels used in this work are presented in the sequence. DO used was the S500 (up to 500 ppm of sulfur) with 8% of biodiesel, which is commonly found at fuel stations, as well as HET. For the determination of the properties of the DO and HET, samples of the fuels were collected. The measured properties were: absolute viscosity ( $\mu$ ), specific mass ( $\rho$ ) and higher heating value (HHV).

The viscosity measurement (cP) was done at 25 °C through an Anton Paar rheometer, physic mcr 301 model, 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, AL500 model, 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, 1031 model, and using benzoic acid as reference substance. Table 2 presents the average values of two measures of the properties of fuels (DO and HET).

Table 2 - Fuel properties.

Properties	DO	HET
Absolute Viscosity (cP)	3.52	0.5
Specific Mass (g/cm <sup>3</sup> )	0.843	0.806
Higher Heating Value (MJ/kg)	46.78	30.49

The engine was submitted to HET in partial substitution to the DO with fumigation method, which atomization of ethanol was made at intake manifold. This prevented a few modifications in the engine's power system, causing it to operate in a different way as in a DO100 single fuel mode. Figure 1 shows a schematic of the experimental workbench with its main components.

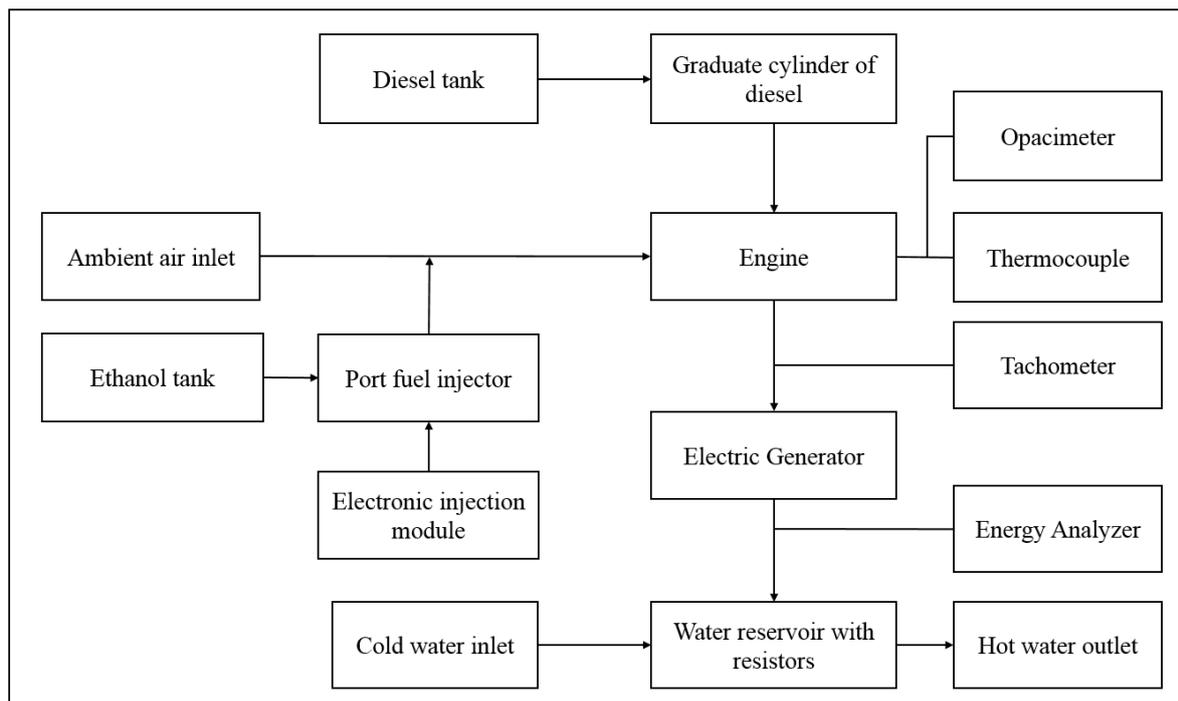


Figure 1 - Experimental Scheme

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

Port fuel injector system are composed by: automotive injector, 18 to 21 mL/min, fixed at the intake manifold; fuel pump, VTO brand; pressure regulate valve adjusted to 4.5 bar; automotive rotation sensor to start the injection BTDC of engine; and injection electronic module FuelTech brand, FT300 model, to control the opening injection time of the valve.

Engine exhaust gaseous 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.

The opacimeter used in the experiments is of Napro brand, NA9000 model and the values were 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<sup>-1</sup>, 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%.

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.

Embrasul RE6000 energy analyzer monitored the voltage, current, frequency and power of the generator. 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.

Specific transducers installed in the test room measured local atmospheric pressure, dry bulb temperature and relative air humidity.

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, and due to the load, it was necessary to adjust the engine speed to 1800 RPM.

The test time of each ethanol mass flow sample and pure diesel were set of 30 minutes, the fuel consumption of diesel was obtained by timing the time to consume 50 mL in the graduated cylinder. After the total consumption of diesel in the graduated cylinder, the refill 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.

During the consumption of each 50 mL of diesel present in the graduate cylinder, the others parameters were measured: exhaust gas temperature, rotation, active power, atmospheric pressure, dry bulb air temperature, relative air humidity, opacity and light absorption coefficient. Data collection was repeated at least 5 times for each experiment.

Ethanol consumption was determined by the opening injection time adjusted in FuelTech apparatus. An experimental realized before, showed how many grams per second was injected to a determined time. To perform the ethanol consumed was used 1.76, 2.52, 3.76, 5 and 7 ms of injector opening time.

After collect all the data for one ethanol mass flow sample, the opening time of the port fuel injector was changed without turning off the engine. Due to changing the opening injection time, the ethanol mass flow was changed and it was necessary to readjust the engine speed to 1800 RPM moving the acceleration lever of the engine. This procedure was repeated for each new injector opening time.

The correction of the experimental values to 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 HET samples was performed from Equation (1).

$$SFC = \frac{\dot{m}}{P} = \frac{\rho \dot{V}}{P} \quad (1)$$

where  $SFC$  is expressed in g/kWh,  $\dot{m}$  is fuel consumption in g/h,  $P$  is the corrected active power in kW,  $\rho$  is fuel specific mass in g/cm<sup>3</sup>, and  $\dot{V}$  is volumetric flow rate in cm<sup>3</sup>/h. DO substitution rate in energy was performed from equation (2), where  $HHV$  represent higher heating value of DO and HET in kJ/kg.

$$\%S = \frac{\dot{m}_{HET} HHV_{HET}}{\dot{m}_{HET} HHV_{HET} + \dot{m}_{DO} HHV_{DO}} \cdot 100 \quad (2)$$

The genset thermal efficiencies ( $\eta_t$ ) operating on mono and dual fuel modes were determined from the corrected specific fuel consumption and from the  $HHV$  of the fuels using Equation (3) and (4), respectively.

$$\eta_t = \frac{3.6 \cdot 10^6}{SFC_{DO} HHV_{DO}} \cdot 100 \quad (3)$$

$$\eta_t = \frac{3.6 \cdot 10^6}{SFC_{DO} HHV_{DO} + SFC_{HET} HHV_{HET}} \cdot 100 \quad (4)$$

### 3. RESULTS AND DISCUSSION

As mentioned before, the experiments was conducted at speed of 1800 RPM for the electric generator, for each sample the test took 30 minutes long and 5 measurements was collected. The Table 3 presents the mean results for the experiments performed. The values are already correct by NBR ISO 3046/1 standards.

Table 3 - Mean results.

Samples	DO substitution rate (%)	$P$ (kW)	$\eta_t$ (%)	$SFC$ DO (g/kWh)	$SFC$ HET (g/kWh)	Exhaust gas temperature (°C)	Opacity (%)
DO100	0.0	6.6	22.8	338.2	0.0	602.1	65.0
HET1	12.8	6.6	23.8	283.0	62.4	572.8	50.6
HET2	23.5	6.5	23.7	249.5	115.3	550.2	38.7
HET3	37.8	6.5	24.0	200.9	183.4	518.0	26.4
HET4	52.3	6.5	24.0	154.6	254.7	494.2	20.1
HET5	70.9	6.5	22.0	103.3	377.4	506.8	8.8

As we can observe in Table 3, the power produced of the generator set not changed significantly, because the load condition on the electric generator was constant during all tests, with the resistors always on, i.e., not changing the load in the genset.

DO substitution rate was performed by equation (2) at different ethanol fumigation rates (0.117, 0.214, 0.337, 0.468 and 0.694 g/s), representing DO substitution rates from 12.8% to 70.9% by energy, and hence, a wide range of diesel replacement was achieved, as we can observe in Table 3.

We can observe in Table 3, when DO substitution rate increases, the *SFC* of DO was reduced, as expected. The opposite occurs for the *SFC* of HET that starts from zero when the engine was operating only with DO and increased as HET is added into the system. It is also noted that the growth of the *SFC* of HET does not follow in the same proportion of DO reduction. When comparing the total specific fuel consumption for 70.9% of DO substitution rate with DO100 sample (only diesel operation), it is noted an *SFC* increase about 42%. The amount of HET consumed is greater than that of reduced OD. This is due to the lower ethanol *HHV* (30.49 MJ/kg) compared to those of DO *HHV* (46.78 MJ/kg). As consequence, it is necessary more ethanol to deliver the same amount of energy when operating only with DO. The *SFC* trends converge to the results found by Imran *et al.* (2013).

The genset thermal efficiency was calculated using the equations (3) and (4). Figure 2 illustrates the thermal efficiency results. It can be noticed in figure 2, that when increasing DO substitution rate, the thermal efficiency was increasing until 24.0% and after it, starts to decrease. The highest thermal efficiency was found by HET3 and HET4 samples, representing 37.8 and 52.3% of DO replacement, resulting in 24.0% of thermal efficiency, i.e., about 5.5% higher than the DO100 mode operation. This improvement in thermal efficiency is attributed to high oxygen content in ethanol that enriches the mixture improving the combustion process.

The substitution of DO for ethanol results in better values of thermal efficiency excepted for the HET5, with 70% of DO substitution that decreased to 22.0%, a reduction about 3.2%. It can be explained due the higher latent heat of vaporization of ethanol. According to Kumar *et al.* (2013), 0.92 MJ/kg to HET and 0.23-0.60 MJ/kg to DO. In consequence of this difference, results in a low combustion temperature that may not be able to ignite all ethanol injected which leads to a reduction in thermal efficiency and some failures during the combustion.

Jamuwa, Sharma and Soni (2016) found similar results, i.e., at high loads, a maximum increase of 6% of thermal efficiency was obtained. They explain that ethanol has a lower cetane number, causing ignition delay, resulting in higher rates of heat released and reduction of thermal loss with the cylinder wall, increasing thermal efficiency.

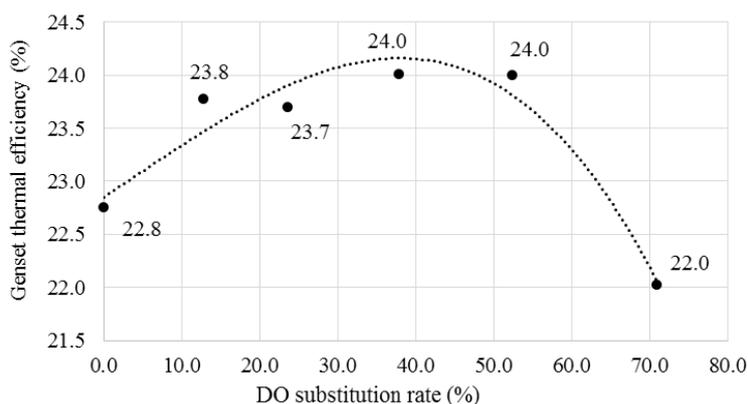


Figure 2 - Genset thermal efficiency

Figure 3 illustrates the exhaust gas temperature in function of DO substitution rate. Adding ethanol in the diesel combustion tends to reduce the exhaust gas temperature reasonably, which is attributed to the higher latent heat of vaporization of ethanol that in addition of reducing the combustion temperature, can decrease the temperature of intake air, resulting in lower exhaust gas temperature. The greater reduction happened in HET4 sample, about 18% of reduction in exhaust gas temperature compared with pure diesel (DO100). HET5 sample showed many failures during the combustion, which caused the increase the exhaust temperature and did not follow the other samples.

The experimental tests of Chauhan *et al.* (2011) result in a reduction in exhaust gas temperatures, at full and 70% of load, i.e., the exhaust gas temperature reduced about 12% as DO substitution increases. They attributed due to low cetane number of the ethanol and lower heat losses.

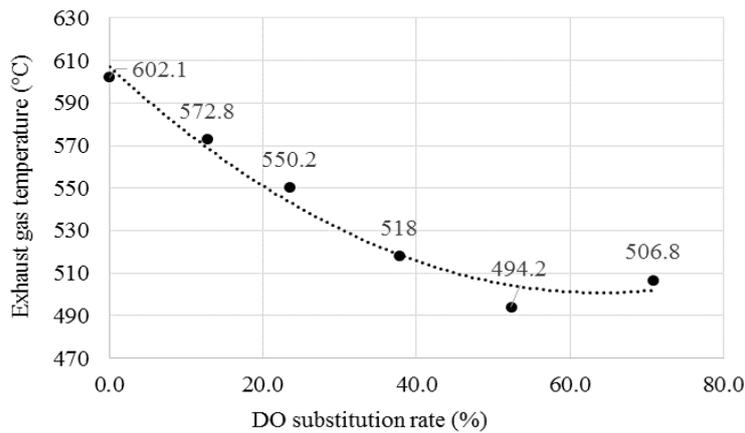


Figure 3 - Exhaust gas temperature

Figure 4 shows the exhaust gases opacity. It was found that the percentage of exhaust gas opacity tends to decrease with the substitution of DO by HET. At mono fuel operation showed 65.0% of opacity and at 70.9% of DO substitution rate the opacity was reduced to 8.8%. It could be a possible reduction of particulate matter in exhaust gases. Chauhan *et al.* (2011) obtained a similar curve of decreasing of the exhaust gas opacity as the percentage of substitution of DO for ethanol increased at various load levels of engine operation. Similarly, Imran *et al.* (2013) observed the same behavior in the experiments performed. This is because 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.

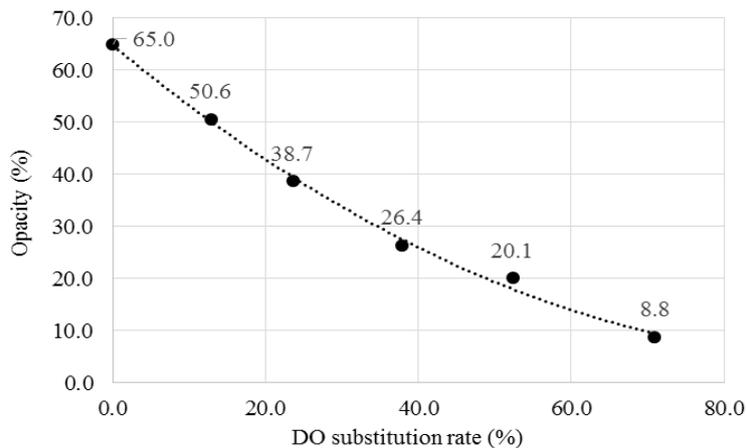


Figure 4 - Gas opacity

#### 4. CONCLUSION

In this paper were presented the results of tests carried out with a small engine-generator group (genset) operating on mono fuel mode with diesel oil (DO100) and with diesel-ethanol on dual fuel mode by fumigation method. The study was intended to compare the results of specific consumption, thermal efficiency, exhaust gas temperature and opacity of the genset operating on the modes mentioned. The performance analysis of the generator set on dual fuel mode showed interesting results, being able to partial substitute the DO for HET operating on fumigation method.

Results of genset thermal efficiency were satisfactory, showing an increase with the addition of HET, up to 5.5%. Only at 70.9 of substitution rate, the efficiency was 3.2% lower than DO operation only, which may have occurred because of the higher latent heat of vaporization of ethanol causing the reduction of combustion temperatures.

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

It is noted in the results that the internal combustion engine working with diesel-ethanol decreased the temperature of the exhaust gases. Up to 18% reduction in exhaust gas temperatures was achieved with 70.9% of DO replacement, demonstrating that the higher latent heat of vaporization of ethanol positively influences to decrease this temperature, avoiding excessive thermal losses.

The opacity of the exhaust gases trend to reduce when adding ethanol. At mono fuel operation, opacity was 65% and with HET5 sample achieved 8.8% of opacity, demonstrating an expressive reduction and possible a decreased in particulate matter.

In general, the results were satisfactory, showing that the use of ethanol is viable and can be used as an alternative fuel for diesel engines, thereby reducing dependence on fossil fuels and reducing the emission of pollutant gases. In the study herein presented, the gas emissions were not assessed, but would be interesting to analyze exhaust gases, such as CO, CO<sub>2</sub>, NO<sub>x</sub>, SO<sub>x</sub>, 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.

## 5. ACKNOWLEDGEMENTS

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