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EMISSIONS INVESTIGATION OF SYNTHETIC BIOGAS IN A SPARK IGNITION ENGINE

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Abstract. *The use of biogas as a renewable energy source has been widely applied to generation and cogeneration systems as an alternative to the fossil fuels. Hence, technical contributions in terms of performance are always important to enhance the employed technologies, especially when they have to deal with a fuel of variable chemical composition. In this context, this paper presents experimental data about electric generation system, constituted of a locally built power generator coupled to a spark ignition engine (SIE) burning biogas as the main fuel, performed in a test bed for SIE. The test bed employed in this study allows the variation of composition of biogas and measure the pollutant emissions produced by the combustion process. The results obtained with this study shows that there is a trade off between NOx emissions and CO/HC emissions, with the decrease of* NO_x *with the addition of* CO_2 *in the biogas. These observations allow the conclusions that even if the combustion stability is penalized with the use of biogas, emissions are lower with this renewable fuel when compared to fossil fuels, such as gasoline and CNG.*

Keywords: *Biogas, Spark ignition engine, Emissions, Power generation.*

1. INTRODUCTION

The spark ignition (SI) reciprocating internal combustion engines are devices widely used to produce power from energy stored in a fuel. However, the hydrocarbons, which are used to feed the SIE, are expensive fuels, at some point must run out and contribute significantly to the problem of global warming. (Houdvka et al, 2008).

Using biogas as an alternative fuel to generate power contributes to mitigate global warming in two ways: (1) reduce fossil fuel consumption and (2) utilize methane that is regarded to increase the greenhouse effect to power generation. Furthermore, biogas is produced by anaerobic digestion from anaerobic organisms or biomass, what makes it sustainable. (Lim et al, 2015).

The industrial use of biogas as an alternative renewable resource to the fossil fuels applicable to electricity production is a reality in many countries, including Brazil. Thereby, not only Industry but also the Scientific Community has given special attention to the biomass study because of its physical and chemical properties and due to the fact of being found largely in urban centers, such as: liquids and shells of green coconut and of cashew nut; organic residues utilized in landfills sites; sewage; etc. (Olsson and Fallde, 2015).

Different from natural gas that presents a relatively regular chemical composition, the biogas composition may present high variations on composition, but typically CH_4 (60 – 65 mol%), CO_2 (35 – 40 mol%), H_2S (0.1 – 0.5 mol%) and traces of other gases, which reflects on a variation of Lower Heating Value (LHV) from $1{,}86 \times 10^4$ to $2{,}42 \times 10^4$ kJ/m^3 (Stern et al, 1998). This variation of the composition modifies the engine running, changing the combustion behavior and by consequence the levels of pollutant emissions. Since the biogas have an important content of CO_2 in its composition the quality of the ignition and the velocity of the flame are inferior compared to fossil fuels, which represents one of the main drawbacks of this renewable source (Zhang et al, 2018).

Although it has become cheaper and easier to reduce the CO_2 fraction of the biogas, following improvements in purification techniques such as membrane separation (Stern et al, 1998), typically much time (and hence expense) is required to obtain high purity methane, because it remains a challenge to eliminate CO_2 completely. Therefore, the combustion and emission characteristics of biogases with various compositions should be investigated (Kim et al, 2016).

In this regard, it is important to evaluate the impact of the changes in biogas on the emissions, in order to assure that power generation using this fuel is viable from an environmental point of view. In addition, the environmental legislation regarding combustion engines is becoming more severe in many developed countries, which demands solutions for using renewable energies like biogas, but with less pollutant emissions as possible.

2. EXPERIMENTAL APPARATUS AND METHODOLY

The tests have been conducted with a power generator set constituted of a spark-ignition engine (SIE) Volkswagen, naturally aspirated, with electronic injection system, connected to a Kohlbach three-phase synchronous generator with 50 Hz frequency and 30 KW output rated power. In order to maintain the output frequency at 50 Hz an electronic governor was integrated to the engine's throttle valve control. Therefore, the engine rotation speed was kept constant for all load conditions tested. The generator set was adapted with a conversion kit for Compressed Natural Gas (CNG) to enable the switching between gasoline and gaseous fuel. This equipment is composed of an electronic pressure regulator, which keeps the intake gas pressure at 1.6 bar. After the pressure regulator, the fuel injectors are responsible for sending the right amount of fuel to the cylinders; those injectors are controlled by an injection system, which allows a full configuration of the system specially the injection timing and frequency of the nozzle injector. The Tables 1 and 2 presents the tests conditions and technical information about the experimental apparatus.

Table 1: Engine specifications

Engine type	4-stroke, 4 cylinder
Combustion chamber	Bowl shape
Bore x Stroke	82,5 x 92,8 mm
Displacement	1984 cm^3
Compression ratio	10:1

Table 2: Experimental Conditions

Engine speed	3000 RPM
Coolant temperature	80 °C (353 K)
Ignition Timing	15° BTDC
Load Conditions (electric load)	9, 12, 15, 18, 21 and 24 kW
Equivalence ratio	Lean mixture (λ = 1,5)
Ambient temperature	35 °C (308 K)
Fuel temperature	30 °C (303 K)

The power generator is coupled with a 30 kW load bank, composed by an association of electric resistors, which allows the variation of the load in different values, simulating severe conditions of load changes. The results presented in this study were measured with a load variation from 9 kW to 24 kW. Considering that the objective of this study is to operate the engine with biogas as fuel, it was observed that the maximum load sustained with stability by the engine was 24 kW. For that reason, all tests were fixed at this maximum point for comparison of the results obtained.

To operate with biogas, the test bed was designed with a gas fuel mixer, which can synthetize the biogas from a mixture of Methane and Carbon Dioxide in different compositions. There is a direct link between the fuel injection system of the engine and the fuel mixer. With the mixing system, it is possible to change the composition of the biogas during the tests without turning the engine off allowing the simulation of severe changes in the fuel to observe the system behavior when such condition is imposed and the reflects in the emissions.

A 720-pulse-per-revolution encoder (AVL 365c) was attached to the crankshaft giving the rotation signal and a spark-plug-type pressure sensor (AVL, ZI33-A5S) was used in place of one of the spark plugs. With the In-cylinder pressure measures, it is possible to evaluate the combustion characteristics and observe the stability of the processes during a test cycle.

A gas analyzer (CO_2, CO, NO_x and UHC) was utilized to measure SIE engine's emission according to ISO 8178-1 (2012). Table 3 shows the specifications of the gas analyzer indicating the sample range of each emissions gas measured by the equipment. The acquired data from biogas combustion have been compared to data from reference fuel (Gasoline and CNG). Figure 1 shows the system diagram and the experimental apparatus utilized in the study.

Table 3: Gas Analyzer specifications

Carbon Monoxide (CO)	0 – 15 (% vol)
Carbon Dioxide (CO_2)	0 – 20 (% vol)
Unburnt Hydrocarbons (UHC)	0 – 2000 (ppm)
Nitric Oxides (NO_x)	0 – 5000 (ppm)

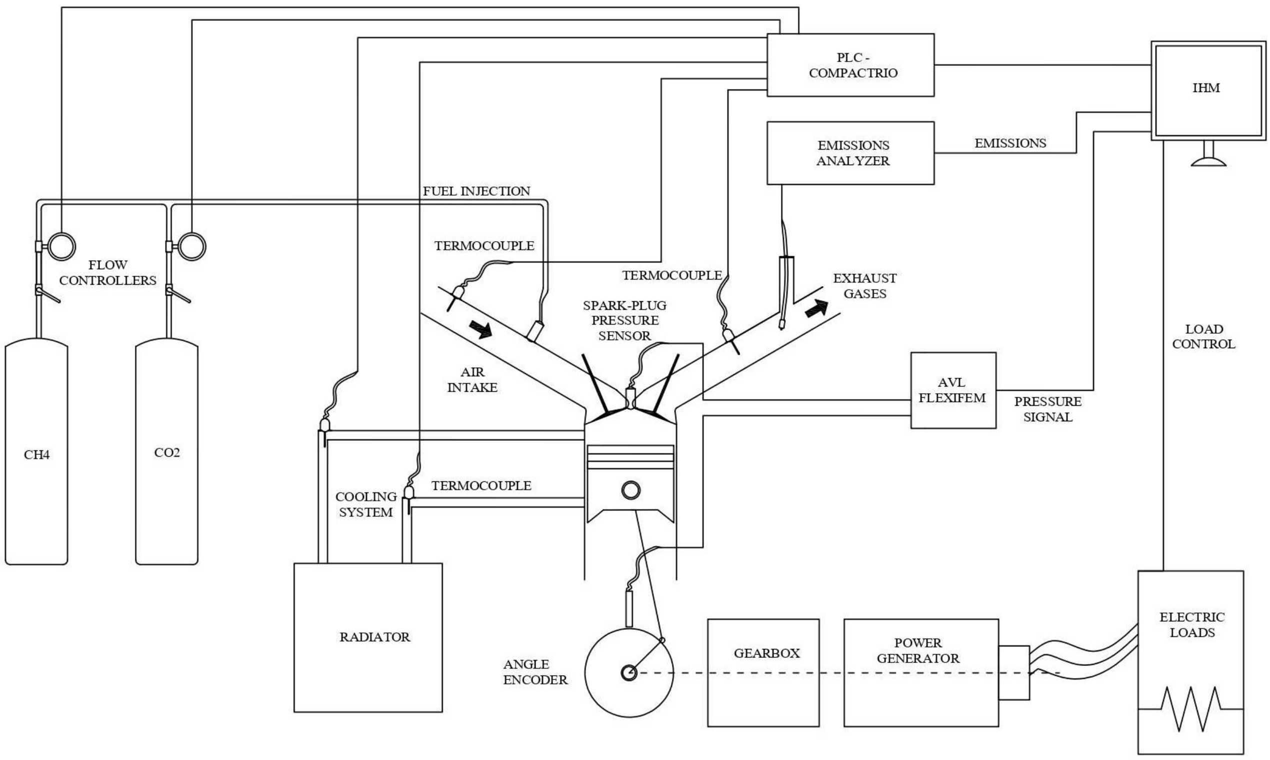

Figure 1: System diagram

Firstly, the ambient parameters were measured in order to maintain the same conditions in all testes performed, avoiding any modifications in the results due to different temperature or ambient pressure. Secondly, the engine was warmed up to a normal operation point with no load, using the reference fuel CNG. The operational temperature of the coolant fluid was kept at 80° C (353 K).

Once the generator set were in the desired operational conditions, the tests begun with the reference fuels. The first measures of emissions and In-cylinder pressure were made with the generator set in idle mode (without load) with a constant rotation of 3000 RPM. The emissions analyzer measured the combustion gases for a period of 5 min, in order to assure that any fluctuations in the emissions were accounted and the final values were averaged in this cycle of measurement. The In-cylinder pressure was measured over 1000 cycles, in order to measure the stability of the combustion by comparing results cycle by cycle.

After the first measures with the generator set in idle mode, the load is set to 9 kW and a new cycle of measurement took place identically to the first one. This procedure was repeated for load increases in steps of 3 kW until the system reached its maximum load capacity. As discussed before, for comparison reasons, the maximum load tested was 24 kW due to the instability conditions of biogas combustion with higher loads.

At the end of the cycle of emissions test for the reference fuels, the system was changed to operate with biogas and the same procedure presented before was implemented, this time for each concentration of biogas proposed. Table 4 presents the different types of fuels tested in the system.

Table 4: Fuels tested

Fuel	Chemical Composition (% of volume)	LHV (kJ/kg)
Gasoline	$C_nH_{1.87n}$ (Heywood, 1998)	42.500
CNG	91% CH_4 , 3,9% C_2H_6, 3,3% N_2 and traces of other gases	45.440
BIO10	90% CH_4 and 10% CO_2	37.560
BIO14	86% CH_4 and 14% CO_2	34.060

The composition of the gaseous fuels was defined by chromatographic analyses (Micro GC 490, Agilent). Samples of each gases used in the tests were analyzed in order to assure the volumetric percentage of the components of each fuel.

3. RESULTS AND DISCUSSION

3.1 Combustion analyses

In order to evaluate the emissions of the engine running with different fuels, combustion characteristics were studied, such as the Specific Fuel Consumption (SFC), Thermal Efficiency (TE), the Integral Heat Release, the Coefficient of Variance (COV) of Indicative Mean Effective Pressure (IMEP) and the In-cylinder temperature. These parameters help to understand the emissions results obtained by giving an idea of the combustion behavior in the engine.

Figures 2 presents the SFC. Firstly, it is possible to notice that the SFC for the CNG test is smaller than all other fuels tested. This behavior is because the engine was prepared with an ignition timing of 15° BTDC that is ideal for the combustion of CNG, penalizing the operation with other fuels. The levels of SFC for BIO10 and BIO14 were higher in almost all cases, mostly because of the presence of CO_2 in their composition. Due to the inert behavior of CO_2 in the combustion reaction, a higher volume of fuel is demanded to supply the same load when compared with other fuels. As the CO_2 content grows, the fuel volume increases to maintain the combustion reaction and deliver the load required.

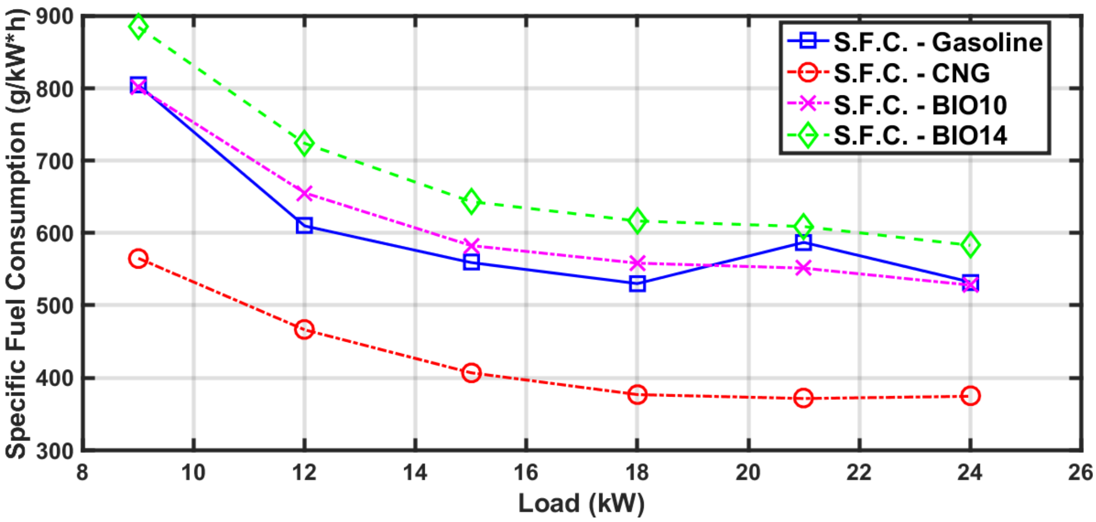

Figure 2: Specific Fuel Consumption with respect to the load.

Figures 3 shows the TE. As expected from Fig. 2, the TE of CNG is the highest due to the ignition timing that is optimal for the combustion of this gaseous fuel. For the biogas analyses, BIO10 and BIO14 presented a better thermal efficiency than Gasoline, even though the SFC of biogas is higher than Gasoline. This result is due to the inferior LHV of BIO10 and BIO14 when compared to Gasoline, which results in a better TE. In this case, the ignition timing benefits all gaseous fuels and results in an inefficient combustion for gasoline.

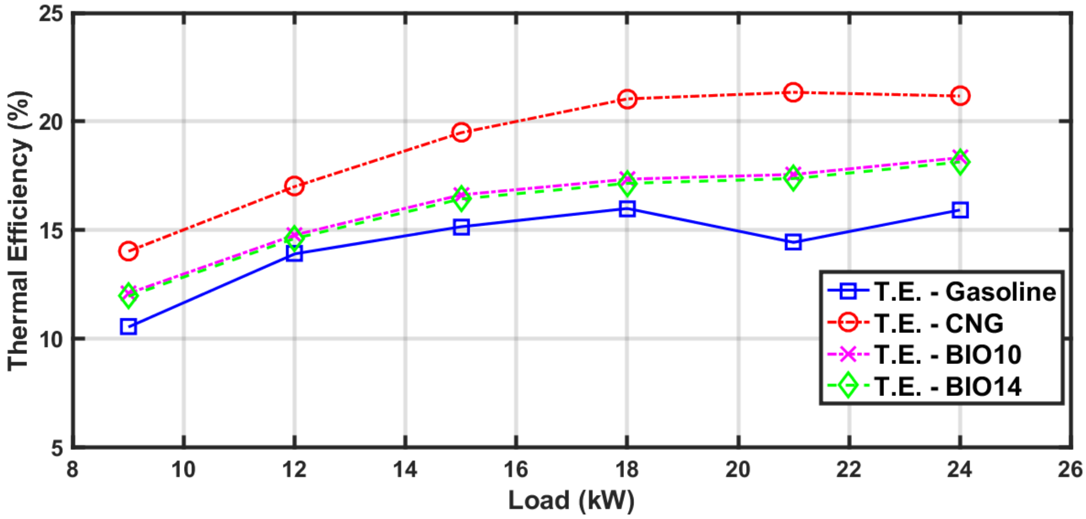

Figure 3: Thermal Efficiency with respect to the load.

Figure 4 indicates the Integral Heat Release (IHR) measured during the tests. This data was taken from the engine operating with a 9 kW load fixed for all fuels. The combustion of gasoline attained 10% of heat release at 9° Before Top-Dead Center (BTDC) and 90% of heat release was achieved at 59° After Top Dead Center (ATDC). In the case of the gaseous fuels, 10% of heat release were reach at 1° ATDC, 15° ATDC and 17° ATDC and to attain 90% of heat release 65° ATDC, 75° ATDC and 81° ATDC for CNG, BIO10 and BIO14 respectively. These results indicate that the combustion of gasoline initiates first than all the gaseous fuels and finishes early too. With the increase of the CO_2 content in Biogas the combustion tends to slow down in general, with a later start and ending. The slower combustion speed observed with the growth of CO_2 in the fuel was expected due to the lower energy density and weaker flame front propagation rate (Hotta et al., 2018). Hinton and Stone (2014) also reported this behavior when studding the laminar burning velocity of different biogas compositions, by varying the CO_2 content in the fuel.

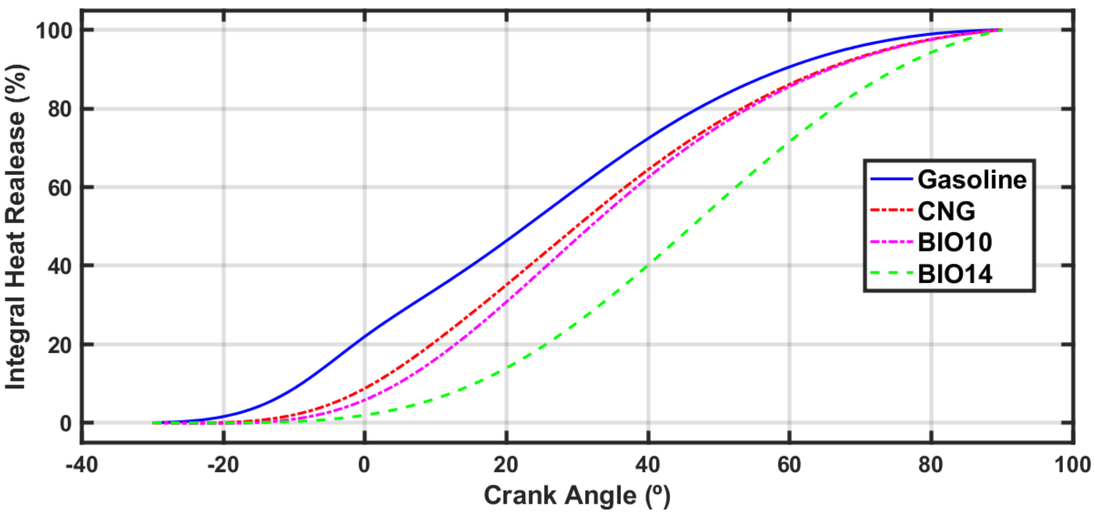

Figure 4: Variation of the Integral Heat Release with respect to crank angle.

Figure 5 shows that In-cylinder temperature tends to be lower with higher contents of CO_2 in the fuel. This result is very important to understand the NO_x emissions results due to the thermal mechanism of formation of this combustion product. In fact, the results presented in Fig. 5 shows that the gasoline have a higher In-cylinder temperature for all the load conditions observed. These results are due to the higher rate of heat released by gasoline, which have greater density of fuel being injected in the combustion chamber when compared to gaseous fuels. Furthermore, as the CO_2 content grows in biogas, the calorific power reduces and then the temperature decline because of the inert nature of CO_2 in the combustion reaction.

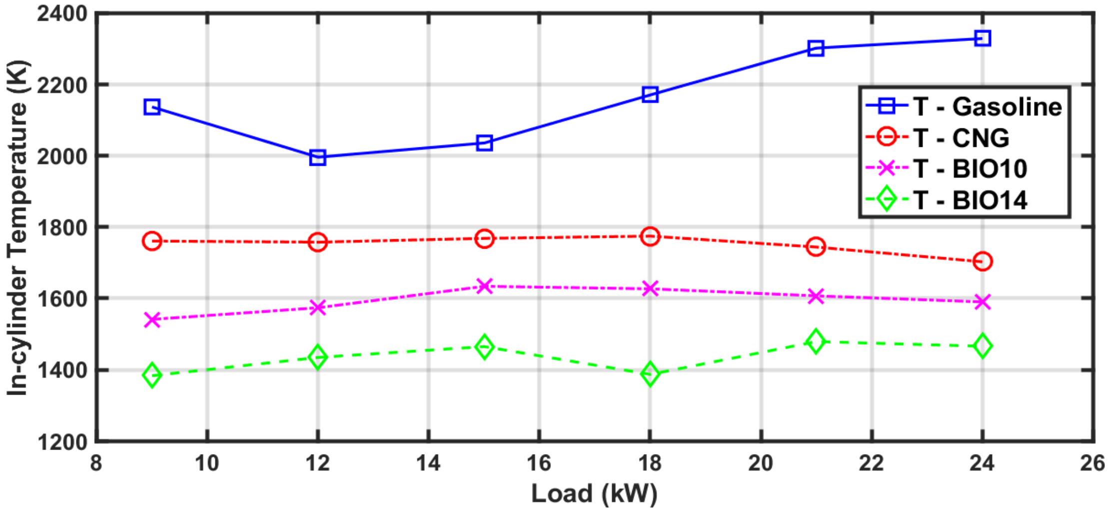

Figure 5: Variation of In-cylinder temperature with respect to the load.

Figure 6 presents the COV_{IMEP} results. This measure give an idea of the variation of IMEP cycle by cycle during an interval of measure. Higher values of COV indicates more variations between the cycles, which reveal the instability in the combustion reaction. From Fig. 6 it is possible to see that, as the load increases, the COV_{IMEP} tends to decrease, because the engine is more close to its maximum torque, which indicates more stable combustion behavior. However, if the load continues to increase, the engine will start to have a more instable combustion because it has attaint its limit of load and torque starts to decline. Furthermore, the increase of CO_2 in gaseous fuel tends to increase instability due to the inert nature of Carbon Dioxide. As the flame propagates inside the combustion chamber, the presence of CO_2 is responsible for quenching zones causing the instability in the combustion observed in the results obtained (Arroyo et al, 2014).

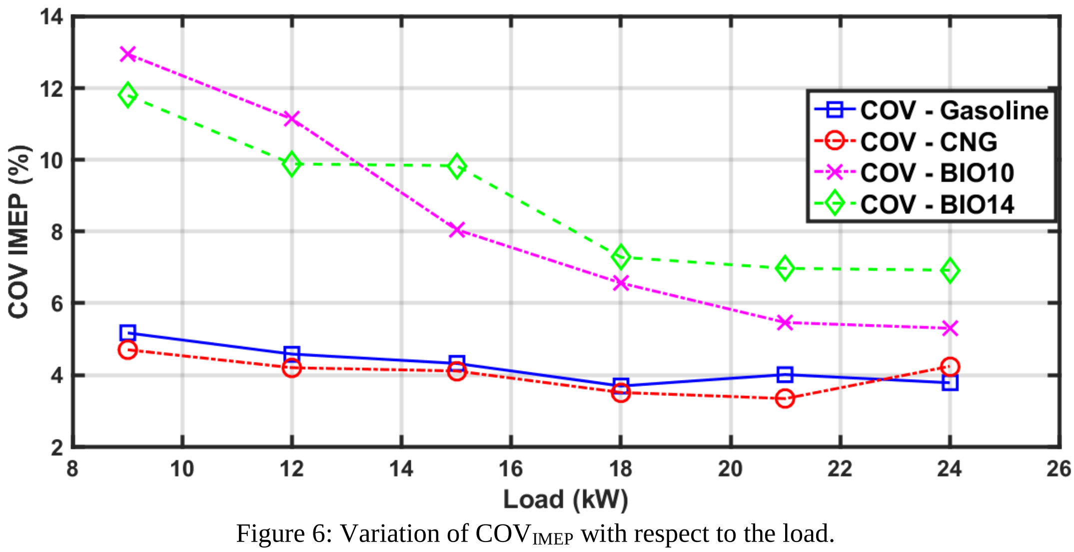

Figure 6: Variation of COV_{IMEP} with respect to the load.

3.2 Emissions

The first emissions results analyzed in this study are for CO emissions. Figure 7 indicates that CO emissions are lower for the gaseous fuels than gasoline. In fact, with the addition of CO_2 in the fuel, the CO emissions decreased 700% when compared to CNG and up to 800% when compared to gasoline. This fact can be explained by two different mechanisms. Firstly, the reaction of oxidation of the CO in CO_2 is slower than the formation of CO, therefore a slow combustion processes favors the consumption of CO. As discussed in Section 3.1, the combustion of biogas is slower (especially for the BIO14, which have higher CO_2 content) than the combustion of CNG and gasoline. Secondly, the concentration of CO tends to decrease with reduction of combustion temperature (Stone, 2012). As shown in Fig. 5, the biogas fuels (BIO10 and BIO14) have the lower combustion temperature between all the observed fuels.

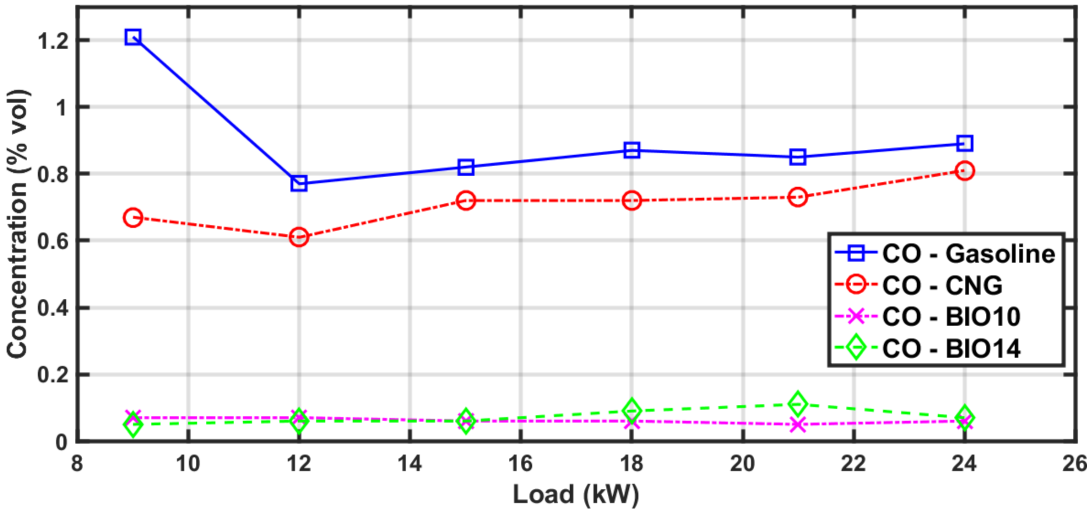

Figure 7: CO emissions evolution with load increase.

The next emissions analyses is for the Unburnt Hydrocarbons (UHC). Once more, the emissions from gasoline were higher than the gaseous fuels as shown in Fig. 8. However, the tendency observed from the UHC emissions is different from the other emissions discussed until now. In general, the increase of CO_2 content in biogas results in a growth of UHC emissions as the load increases. Firstly, the high UHC emissions from gasoline can be explained by the incomplete oxidation of the large carbon chains present in gasoline composition. As the load increases, the efficiency of the combustion rises and UHC emissions from gasoline tends to reduce, because with the rise of the load the engine is closer to its point of maximum torque, where the efficiency is optimal for the speed of 3000 RPM. In the case of gaseous fuels, as the CO_2 content rises the combustion reaction became more instable leading to flame quenching and incomplete combustion (Porpatham et al., 2008). As discussed in Section 3.1, the combustion of biogas with high contents of CO_2 is more instable as showed by Fig. 6 with the growth of COV_{IMEP}. Thus, UHC emissions are higher for BIO14 than CNG and BIO10.

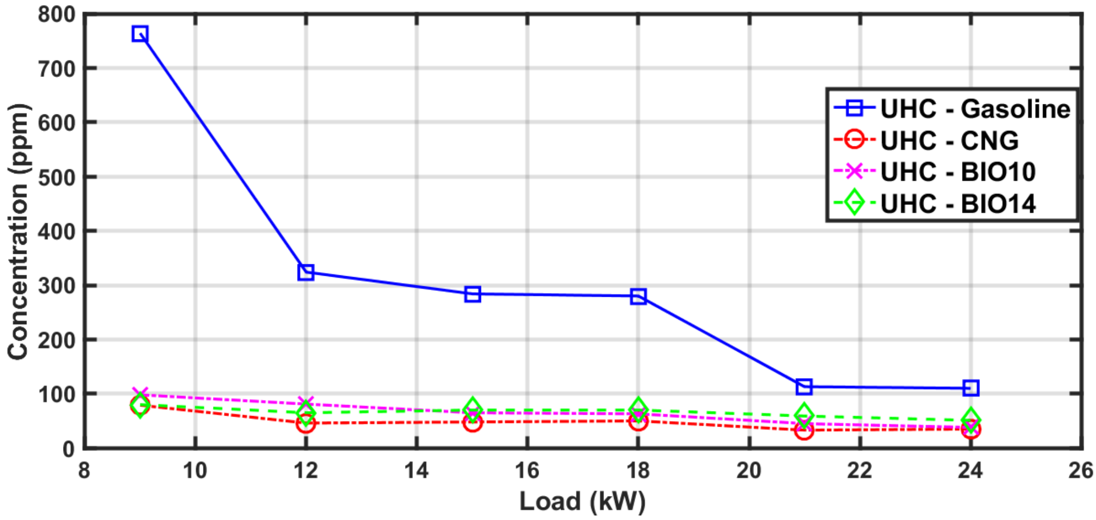

Figure 8: UHC emissions evolution with load increase.

Figure 9 presents the CO_2 emissions results for the fuels tested. Firstly, it can be noticed that results from gasoline are higher than all gaseous fuels. This observation is due to the amount of Carbon atoms that is consumed in the reaction of combustion when comparing the gasoline composition (mostly hydrocarbons with 8 or more Carbon atoms) with gaseous fuels (mostly composed of CH_4). Because of this visible difference, is natural that more molecules of CO_2 are formed in the combustion process. However, in the comparison between the gaseous fuels it is observable that by increasing the amount of CO_2 in the biogas composition, the emissions of CO_2 decrease. To analyze this behavior is important to notice the results showed in Figs. 7 and 8. In those cases, the amount of CO increased in BIO14 in relation to BIO10 and UHC emissions were higher for BIO14 than BIO10 and CNG. These results indicate that the combustion of BIO14 is incomplete and because of that fact, the formation of CO_2 in the combustion reaction is reduced. This behavior is more accentuate for higher loads (>15 kW). The tendency of the incomplete combustion is plausible in higher loads because of the flame quenching generated by the presence of an inert gas (the CO_2) injected with the fuel

(CH_4). As the amount of CO_2 increases, it is more likely to occur the formation of quenching zones inside the combustion chamber with high concentration of CO_2, which prevents the realization of a complete combustion in that zone. The result of this phenomenon is the increase of CO and UHC in the emissions and a decline of CO_2 emissions.

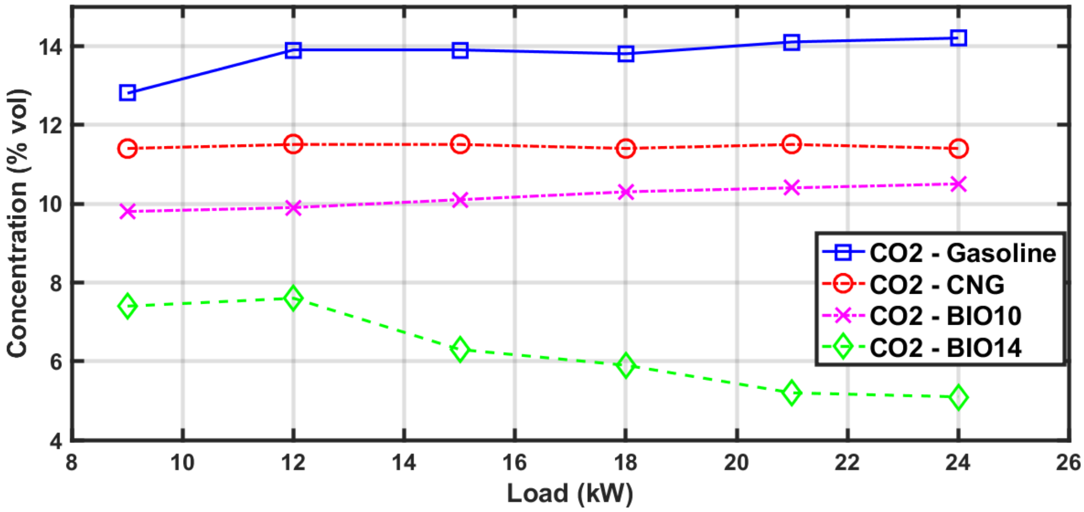

Figure 9: CO_2 emissions evolution with load increase.

Finally, the NO_x emissions are presented in Fig. 10. As expected, the NO_x emissions were lower in the case o BIO14 due to its higher CO_2 content (Kim et al., 2016). The strong relation between NO_x formation and the In-cylinder temperature, due to the thermal mechanism that produces the nitric oxides, explain the results obtained in the experimental tests. As discussed in Section 3.1, higher temperatures are attained in the combustion of gasoline and tends to decrease with the increase of CO_2 (Figure 5). Furthermore, the number of carbon atoms present per unit volume also favors the NO_x formation by the Prompt mechanism, which contributes for the rise in the Nitric Oxide emissions.

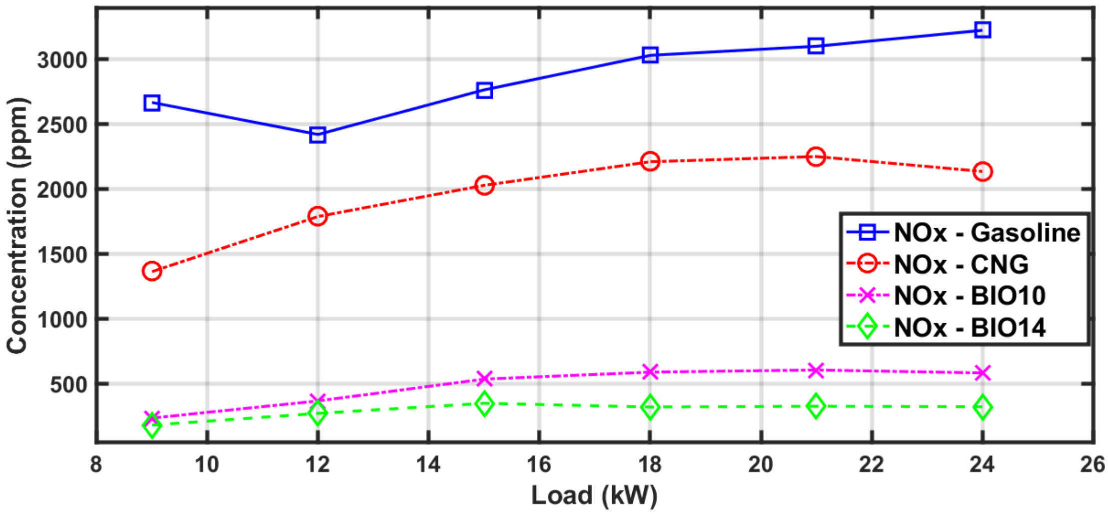

Figure 10: NO_x emissions evolution with load increase.

4. CONCLUSIONS

The combustion behavior and emissions of a spark-ignition engine were studied by varying the fuel and the load of the engine. It was observed that in general, biogas is a good substitute for fossil fuel in terms of power generation, showing lower emissions and a relatively stable combustion. The quality of the biogas plays an important role in the quality of the power generated due to its influence in combustion stability. While comparing the operation of the engine with the different fuels, the following inferences are drawn.

- The combustion process is faster for gasoline and tends to be slower with the increase of CO_2 in biogas;
- In-cylinder temperature decreases with the increase of CO_2 content in biogas. The combustion temperatures for gasoline are from 38% to 62% higher than BIO14;

- The combustion of biogas with the presence of an inert gas (CO_2) tends to be more instable than the reference fuels (gasoline and CNG). However, in all cases studied the stability was increased with the rise of the electric load applied;
- For the emissions results, CO, CO_2 and NO_x emissions were, in general, lower for BIO14 showing that the use of biogas as mains fuel could help to decrease the pollution in power plants. Only UHC results were against this tendency, but they still below the gasoline results.

This work showed that further analyses are required in order to enhance the capacity of the SIE to operate with biogas in higher loads and with lower concentrations of Methane in its composition.

5. REFERENCES

Arroyo, J., Moreno, F., Muñoz, M., Monné, C., Bernal, N., 2014. "Combustion behavior of a spark ignition engine fueled with synthetic gases derived from biogas". *Fuel*, Vol. 117, pp. 50 – 58.

ABNT NBR ISO 8178-1:2012. "Reciprocating internal combustion engines -- Exhaust emission measurement -- Part 1: Test-bed measurement systems of gaseous and particulate emissions".

Heywood, J. B., 1998. "Internal Combustion Engine Fundamentals", *McGraw-Hill*, New York.

Hinton, N., Stone, R., 2014. "Laminar burning velocity measurements of methane and carbon dioxide mixtures (biogas) over wide ranging temperatures and pressures". *Fuel*, Vol 116, pp. 743 – 750.

Hotta, S. K., Sahoo, N., Mohanty, K., 2018. "Comparative assessment of a spark ignition engine fueled with gasoline and raw biogas". *Renewable Energy*, Vol 134, pp. 1307 – 1319.

Houdkova, L., et al., 2008. "Biogas – A Renewable Source of Energy". *Thermal Science*, Vol. 12, No.4, pp. 27-33.

Kim, Y., Kawahara, N., Tsuboi, K., Tomita, E., 2016. "Combustion characteristics and NOX emissions of biogas fuels with various CO2 contents in a micro co-generation spark-ignition engine". *Applied Energy*, Vol. 182, pp. 539 – 547.

Lim, C. Kim, D. Song, C. Kim, J. Han, J. Cha, JS, 2015. "Perfomance and emission characteritics of a vehicle fueled with eriched biogas and natural gases". *Applied Energy*, Vol. 139, pp 17-29.

Olsson, L. Fallde, M., 2015. "Waste(d) potential: a socio-technical analysis of biogas production and use in Sweden." *Journal of cleaner production*, Vol. 98, pp. 107 – 115.

Porpatham, E., Ramesh, A., Nagalingam, B., 2008. "Investigation on the effect of concentration of methane in biogas when used as a fuel for a spark ignition engine". *Fuel*, Vol. 87, pp. 1651 – 1659.

Stern, S. A. Krishnakumar, B. Charati, S. G. Amato, W. S. Friedman, A. A. Fuess, D. J., 1998. "Performance of a bench-scale membrane pilot plant for the upgrading of biogas in a wastewater treatment plant." *J. Membr. Sci*., Vol. 151, pp. 63 – 74

Stone, R., 2012. "Introduction to Internal Combustion Engines". Palgrave Macmillan.

Zhang, Y. Zhu, M. Zhang, Z. Chan, Y. L. Zhang, D., 2018. "Combustion and emission characteristics of simulated biogas from Two-Phase Anaerobic Digestion (T-PAD) in a spark ignition engine." *Applied Thermal Engineering*, Vol. 129, pp. 927 – 933.

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