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ENGINE BEHAVIOR ANALYSIS USING BIOGAS

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Abstract. *The situation of energy around the world indicates that even the most common fuels like coal, petrol, natural gas and even nuclear power have a dead sentence. So renewable energies like hydropower, wind power, biomass solar power are having more importance in terms of researches and development, as well installed systems. One characteristic in common of the renewable energies is the decentralized approach, sometimes even individual. In this line the "biogas" should start adverse reactions, since the blind enthusiasm until believe of a critic open mind or full rejection. The technology on biogas have been develop in the last 50 years with small units, being largely expanding to production of biogas and the treatment of anaerobic waste. The utilization of biogas has received attention with systems more sophisticated to production and conversion of energy available on biogas in mechanic power, always when have this possibility. This way, the knowledge about the behavior of technology on biogas is important to choose the better apply. Among the technologies available to generate electrical energy using biogas, the featured is the internal combustion engine because it is a strong machine and have thermal efficiency higher than gas turbines operating in the same conditions and it is possible the utilization of thermal energy on systems like Organic Rankine. The engines of combustion that use biogas can even utilize biomethane (biogas purified with high rates of methane) that changes the operation of the engine. This way was performed the analysis of behavior from internal combustion engine with biogas of landfills, with different compositions of methane, the objective is inquiring the influence of composition on gas and generate of electrical and thermal energy from an engine.*

Keywords: *Biogas, Engine, Energy efficiency.*

1 INTRODUCTION

The search for new possibilities of renewable energy is one subject in discuss at the moment, the missing of rains on southeast of Brazil, which is dependent of hydropower together to need of increasing the demand for energy linked to the low cost of this energy makes of the Biogas from solids urban and industrial wastes one alternative for trade a part of fossils fuels like petrol and diesel.

There is a lot of technologies to transform the gas of landfills in energy power, some technologies that deserve high top are the internal combustion engine, gas turbine, vapor systems and fuel cells. A great part of systems that provides electrical power from gases uses internal combustion engines or turbines. For example, in the United States of America the great majority of installed systems or in development uses the internal combustion engine, as seen on figure 1. Where the EPA (2013) show the technologies to electrical power generator in landfills of USA, which can be measured the installed capacity of these engines represents 65,8%, gas turbine 12,1%, vapor turbines 8% and micro turbines only 1%.

Another observation that must be make is the cogeneration and the combined cycles have the same order of importance in relation to installed systems and on operation. On the figure still can be perceived that the internal combustion engine is the most used, being followed with a high advanced by the gas turbines, the cogeneration and the cycles systems. Technologies like Stirling engines, Organic Rankine cycles and fuels cells are in phase of development.

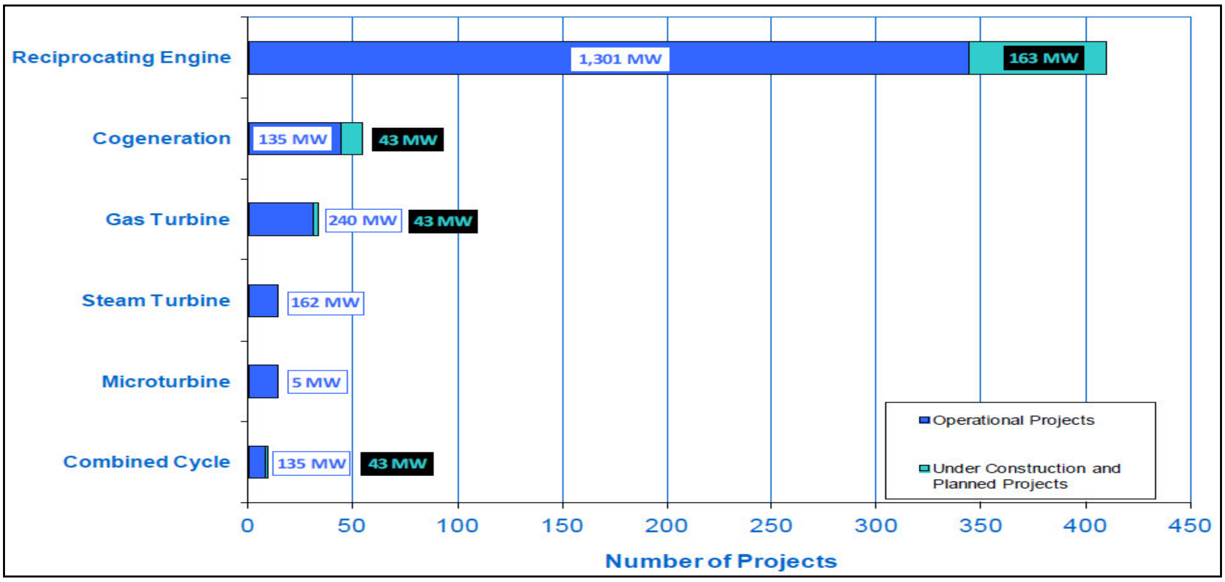

Figure 1 – Distribution of Technologies for electrical power generator in relation to installed systems and systems on phase of building and development.

So at the moment, internal combustion engine is the technology most used to electrical power generator from biogas. This occur because the relations of power, strength and low cost. The interval of advisable power is between 1 to 3 MW. In addition, the technologies to make these machines are already consolidated and the economic risks are smaller than other technologies. Another characteristic is the facility to move away the machine, this allow the engine may be transferred to another place in case to few biogas inside the landfill. The levels about emission of NOx and CO are higher than showed by others technologies, as seen in the table 1 (BOVE& LUNGHI, 2006; HAO, YANG, ZHANG, 2008).

Table 1- The technologies most used with gas.

Technology	Power (kW)	efficiency (%)	Maintenance cost (US$/kWh)	Emissions of NOx (ppm)
Gas Engine	30 – 5000	30– 40	0,007 – 0,015	250 – 3.000
Gas turbine	500 – 150000	20 - 30	0,002 – 0,008	35 – 50
Small gas turbine	30 – 1000	28		< 9
Organic Rankine	100 – 2000 (1)	18	0,004	16

The internal combustion engines allow the use on automotive vehicles and equipment to electrical power generator. Basically these engines can be classified by the type of ignition, they can follow two cycles: Otto Cycle (This represent the ignition by spark); Diesel Cycle (that means the ignition is spontaneous or by compression). The engines working with biogas and natural gas can operate following the both cycles. But, there is the necessity to modify some parts: on store, injection, ignition and compression rate. The release of energy present on the fuel occurs with the chemistry reaction of the fuel on a thermal energy, increasing the temperature and the pressure inside the cylinder of combustion, doing mechanical work. The chemistry composition of the fuel represents one important base to analysis the potential of available energy on the process of conversion. Thus, in this work is realized the analysis of influence on the composition of biogas inside the engine, related with the power generator, thermal efficiency, temperature of gases escapes and the amount of refuse thermal energy available. To do this analysis was made a connection on manufacture catalogs, available on open literature.

2 BIOGAS

The biogas is made from degradation of organic material under anaerobic form, it is constituted in more part of methane and carbonic gas, and can present few parts of H_2, H_2S, N_2, CO e O_2, however, what makes the biogas more energetic is only function of methane, because this is the only gas present in biogas that can enter in combustion, so when the biogas has more methane present, more noble will be and higher will be your calorific capacity. Mitzlaff et al. (1988)

According with Mitzlaff et al. (1988) the biogas only will be considered a fuel when it has more than 50% of methane in the blend, as seen on the table 2, the biogas present volume percentage between 50 to 80 %, CCE et al. (2000), in average, this value can be upper with the purification of biogas removing part of the CO_2.

Table 2. The constitution of the Biogas

Gas	Nomenclature	% (Vol/Vol)
Methane	CH4	50 - 80
Carbon Dioxide	CO2	20 - 40
Hydrogen	H2	1 - 3
Nitrogen	N2	0,5 - 3
Others	H2S, CO, NH3,)2	1 - 5

Because the biogas characteristics on landfills and your availability, Stachowitz (2003) and Tsatsarelis et. al. (2013) claim that is possible generate power with gas that has 35% of methane, but this kind of limit must be avoid to not damage the engine. These authors suggested that few landfills (lower than 0.5 millions of tons) and old landfills, usually are not good to realize projects to generator power from biogas, and middle landfills are capable to support projects between 500 to 2000kW.

2.1 Proprieties of do biogas

Following the main properties observed, when choose a gas fuel or a mixture of gas fuels are present. But, it is necessary to set some parameters such as standard conditions are reference, it means 101.31 kPa (14.696 psia) and 15.55°C (60°F). When a gaseous fuel flow is stated in standard cubic feet (SCF) or standard cubic meters (SCM) and it is reference to a gas at standard conditions. In some places, Europe for example, gas is referenced to 101.31 kPa (14.696 psia) and 0°C (32°F). When gases referenced to 0°C (32°F), the units are called normal cubic meters (NM^3) or normal cubic feet (NF^3).

Composition: Fractions or percentages of mass, volume or molar by the main components, the features and other components determined by the analysis of gas. To ideals gases the volumetric fraction is equal to molar fraction.

Calorific Value (CV): Quantifying the energy released on heat form, on the complete combustion of a fuel with air, at constant pressure and with all products of combustion remain to the initial temperature of the reagents. The gross calorific value (GCV), is when the water formed on the combustion is in liquid state and the net calorific value (NCV) is when the water formed on the combustion is in the vapor state. The gross calorific value of biogas from landfills can be determined by the equation 1 and the equation 2 show the way to convert the GCV to NCV.

$$GCV = \frac{y_{CH4} \times GCV_{CH4}}{MW} \tag{1}$$

$$NCV = NCV\left(h_{lv}\left(0{,}09H\right)\right) \tag{2}$$

Where: molar fraction of methane (y_{CH4}); gross calorific value of methane (GCV_{CH4}) is equal to 800 MJ/kmol; molecule mass of gases mixture (MW) kg/kmol; h_{lv} is the enthalpy of change phases (2,31 MJ/kg a 25˚C); H is the mass fraction of hydrogen.

Stachowitz (2013) report that the knowledge of the composition of the gas fuel and the calorific power is important to indicate what type of thermal process is more suitable to use with biogas, so in the figure 2 it shows the technology to conversion more suitable in function of the quality of methane and the calorific value of the blend. So, as shown in figure 2 the use of engines is more advisable to gas mixture with volume of methane higher than 45 %.

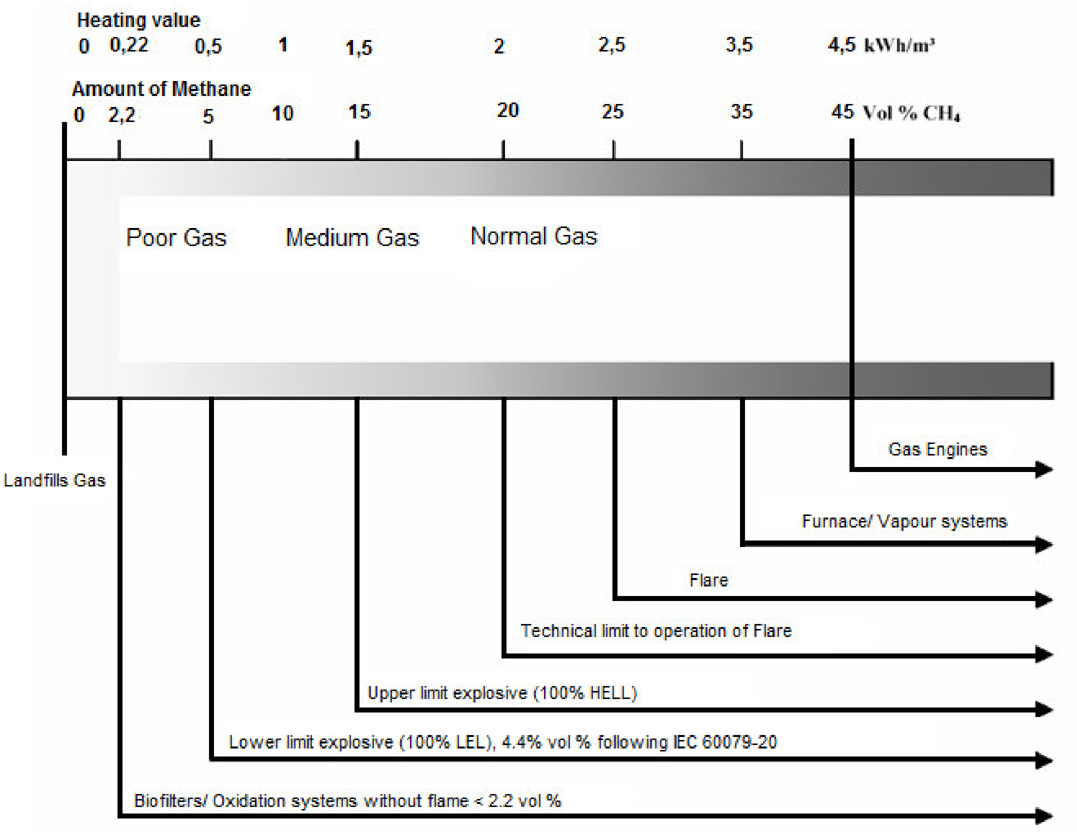

Figure 2 – Better ways to operation in a plant in function to quantity of biogas (Stachowitz, 2013).

Relative Density (rd): It is the division between the mass of gas (m_{gas}) in any volume and the mass of dry air ($m_{gas,ref}$) with the composition standardized by ISO 6976, which must occup the same volume under normal conditions of temperature and pressure. Equation 3.

$$rd = \frac{m_{gas}/V}{m_{gas,ref}/V} = \frac{\rho_{gas}}{\rho_{gas,ref}} \tag{3}$$

Where: ρ is the mass specific.

Wobbe Index: It is the quantity of energy available in a system of combustion through a hole injector. Two gases that have different compositions, but with the same Wobbe index, will show the same quantity of energy through a hole injector. The quantity between the gross calorific value (GCV) and the square of the relative density (rd) under the same conditions of temperature and pressure on reference (Equation 4).

$$WI = \frac{GCV}{\sqrt{r_d}} \tag{4}$$

Sulphur: It is the sum of all components which content sulphur in the gas. Some components of sulphur in the water can create the corrosion of steel and aluminum.

Point of drew: It is the temperature which occurs the formation of the first drop of liquid when the gas is cold or compressed. The liquids most probable to be found it is water, hydrocarbons, or glycol which have different points of dew.

Methane Number: It shows the capacity of the fuel do not explode, when it is under highs levels of temperature and pressure inside the cylinder of combustion. The knock resistance of a fuel is determined by comparing the compression ratio at which the fuel knocks to a reference fuel blend that knocks at the same compression ratio. Different scales have been used to rate the knock resistance of CNG including the engine octane number (EON) and the methane number (MN).

The differences in these ratings are the reference fuel blends used for comparison to the natural gas. The reference fuel blend used for comparison to the natural gas for the MON is composed of iso-octane, with an octane number of 100, and n- heptane with an octane number of 0. However, since natural gas has a higher knock resistance than iso-octane, tetraethyl lead (TEL) must be blended with the reference fuel to increase the reference MON. The MON for CNG fuels range from approximately 115 to over 130.

Methane number uses a reference fuel blend of methane, with a methane number of 100, and hydrogen, with a methane number of 0. Follow present methane numbers of some individual component gases are: methane (100); ethane (44); propane (32); butane (15); n-butane (10); hydrogen (0).

Normal MN values of natural gas from the grid have between e.g. 75 and 100. Many natural gas engines manufacturers, both for stationary applications as used in HD or HD NGV's have a minimum methane number specification of e.g. 70. A mixture of methane and CO_2 can have a higher methane number than 100, due to thermodynamic effects of CO_2 during the combustion. As an example: the biogas calculator calculates a MN of approx. 130 in case of a mixture of 70% methane and 30 % CO_2. However, H_2S has a very strong negative influence on the methane number. Mixing 1% (10.000 ppm) H_2S with methane results in a MN of approx. 85. Since biogas does not contain ethane, propane, butane or other higher hydrocarbons, the methane number is usually higher than shown, so it will have a low probability of detonation.

Inert: The main inert in the gas are the dioxide of carbon and the nitrogen. Your presence in the gas reduces the calorific power, besides of increase the resistance to detonation.

Inflammability Resistance: This is the limit of gas concentration, where the concentration upper the higher limit or above the down limit to propagation of spark do not occur without a source of ignition. In case of a mixture that have methane is important know for example the limits to flammability of the mix methane-air at 25ºC and between 5- 15 vol %, so blends with less than 5 vol. % and with more than 15 vol.% of CH4 are flammable by spark.

The proprieties showed are relevant to operation on adequate systems of generation, it is necessary considerer the specifications of quality in the fuel gas that will be used inside the engine have the same specifications shown by the manufactures, so as seen in the table 3 the abstract of specifications recommended by Environment Agency (2004) with relation to quality of the biogas by greats providers of poor gas that is used in European United and in USA.

Table 3. Biogas characteristics of landfills

Manufacture	Jenbacher (General Eletric)	Deutz	Caterpillar	Waukesha
Calorific value (MJ/Nm^3)	Max variation: <0,5% CH4 (V/V) for 30 s	14,4	15,7 - 23,6 recommended	> 15,73
Gas temperature	< 40ºC	10 - 50 ºC	-----	> -29ºC - < 60ºC
CH4 (% V/V)	-----	> 40%	CH_4/CO_2: 1,1 a 1,2	-----
Methane	-----	140 gas of landfill	----	----
Sulphur	2,000 mg/Nm3 CH4 (with catalyst); 1,150 mg/Nm3 CH4 (without catalyst) (total S e H2S)	< 2200 mg/Nm3 CH4	< 2,140 mg H2S per Nm3 CH4 (Total S and H2S)	< 715 mg/Nm3 CH4 (total S
Hydrogen (%v/v)	-----	-----	-----	< 12%
Relative humid	< 980% with zero of condensed	< 60 - 80%	< 80% the smaller temperature of fuel.	Zero of liquid water. Recommend chill the gas at 4ºC and then filters coalescent
Total of Clorine and Fluor	**Without catalyst:** < 100 mg/Nm3 CH4 (mass base: one part of Chlorine by two of F) without guarantee of restriction; 100-400 mg/Nm3 CH4 with guarantee of restriction; >400 mg Nm3 CH4 without guarantee **With catalyst:** 0 mg/Nm3 CH4	< 100 mg/Nm3 CH4	< 713 mg Cl per Nm3 CH4 (total of compounds halogenated like chlorine)	300 mg/Nm3 CH4 (total of organics halogenated like chlorine)
Silicon (Si)	**Without catalyst:** < 20 mg/Nm3 CH4 without guarantee of restriction; > 20 mg/Nm3 CH4 with guarantee of restriction **With catalyst**: 0 mg/Nm3 CH4	< 10 mg/Nm3 CH4	< 21 mg/Nm3 CH4	< 50 mg/Nm3 CH4
Dust	< 50 mg/Nm3 CH4 (particles < 3 µm)	< 10 mg/Nm3 CH4 (particles < 3 -10 µm)	< 30 mg/Nm3 CH4 (particles < 1 µm)	Removal of particles > 3 µm
Flotation of gas pressure	< 10 mbar/second	< +- 10% of value reference with frequency < 10 per hour	-----	-----

The manufactures showed in table 3 are two North-Americans (Caterpillar and Waukesha), one manufactory Austrian (Jenbacher) and one German (Deutz). Those specifications of quality on fuels could allow the possibility of a treatment. The specifications showed on table 3 are provided only for informative use, that way the specifications could have variations with the type of the engine. The relative humidity < 0.02 was calculated from: UR = [(mg/kg in oil of the engine in Si) x (quantify of total de oil in liters)]/[(power of engine in kW) x (time of service of petrol in hours)]; The specifications showed by the manufactures in mg/MJ were converted in mg/Nm³ CH4 with the calorific value of methane equal to 37,5 MJ/Nm³; those specifications declared by the manufactures in mg/liter of landfill gas were converted in mg/Nm³ CH4 take on 50 per cent CH4 (v/v).

3 Engines of internal combustion with biogas

Working with biogas like the active fluid there is at the moment two cycles to be followed: Otto cycle, with combustion due to ignition; Diesel cycle, combustion due to high compression of air that when enter in contact with the fuel starts the combustion.

On the Otto cycle, are few the changes in relation with the original cycle, like the injection of air and biogas, the mix chamber must be adapted to work with gases, it is necessary to a complete and more efficiency combustion have excess of air, assuming value of equivalency section (λ) closer to 1.2 (Mitzlaff et al., 1988), however, there is no difference when it is compared with the common cycle, this means, the process will continue without changes, only changes the fact of the compression could be higher than like the active fluid.

On the Diesel cycle, the air and the biogas are compressed together and then the diesel is injected only to start the ignition. For dual engine work must have a relation between the quantity of diesel and biogas inside the cylinder of compression. Mitzlaff et al. (1988) show that rates above 10% of diesel is improper has not spontaneous ignition, this value is relative it depends of the Project and the capacity of power. This percentage can vary between 10 % and 20 % of diesel. Besides the diesel function like a cooler.

The relation of biogas and air can suffer variations, although it expects excess of air in the blend, these are mix by chamber, the air is not limited at the start, but it is admitted the relation of 4 to 1, it means 4 parts of air to 1 part of biogas, to occur complete combustion. If the quantity of air is scarce, it could have fall in the pressure of compressive, so there is fall in the power and efficiency, with sudden falls the blend can be inactive to suffer auto ignition. The composition of biogas commits loss of ignition, if the methane has rates above 15 % of methane on the mix with air, this means, when the air has more than 85 % of volume, so do not occur the combustion.

The biogas can suffer high rates of compression, poor fuels cannot be sized to the same rates of compression that a high energy fuel, according with (Huang and Crookes et al., 1998) the best rate is 13:1 for any biogas, on the other hand rates of 15:1 there is the phenomenon of knock. According with Cañavate et al. (1998) the rate must not exceed 12:1, because the composition of biogas is not constant, due your stability and do not start spontaneous combustion in high rates of temperature and pressure. How the efficiency of the cycles is linked with the rates of compression, the work realized will have great increase compared with fuels that cannot suffer equal rates.

On continuous operation of internal combustion engine, there is a lot of variables that determine work like: Temperature, pressure of air in the inlet of machine, the concentration of methane in the fuel. Caterpillar (2010) manufacture of engines working with natural gas and biogas, the factors of correction are shown: In figure 3 is about ambient temperature; in the figure 4 in relation to altitude, and the figure 5 in relation to composition of fuel, all refers to engine G12CM34.

Looking with attention it is possible to see that in the figure 4 until 38ºC the power of the engine is not affect, this means, the ambient where the engines is installed must be ventilated to have heat trades with the ambient. In the figure 5 the atmospheric pressure or the altitude only affects the power when it is higher than 700 meters, after this altitude the derate factor grow 0.02 every 250 meters. However, to happen this the engine must be aspirate, because in a turbo compressor this factor does not apply. According with the figure 6 the number of methane present in the fuel must be higher than 55% of the blend, besides to obtain the perfect derate factor it is necessary have more than 70% of methane in the mixture.

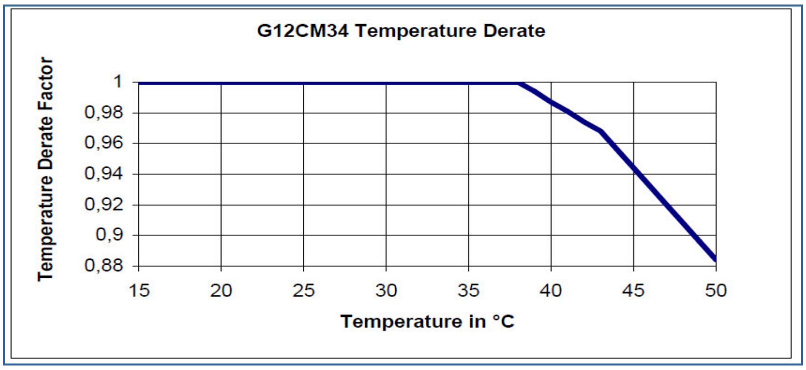

Figure 3. Derate Factor x Temperature (ºC)

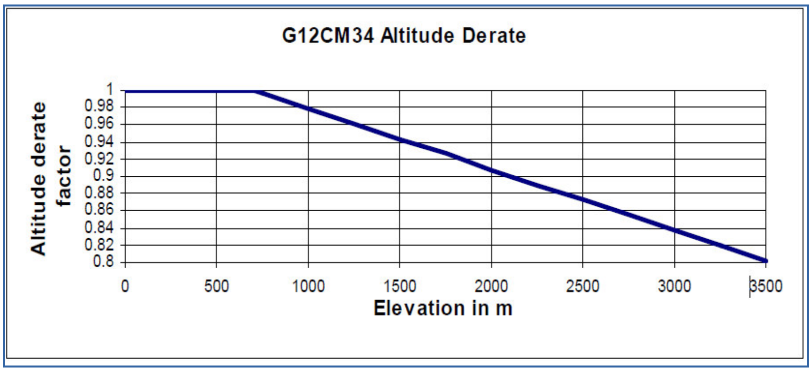

Figure 4. Altitude derate factor x Elevation (m)

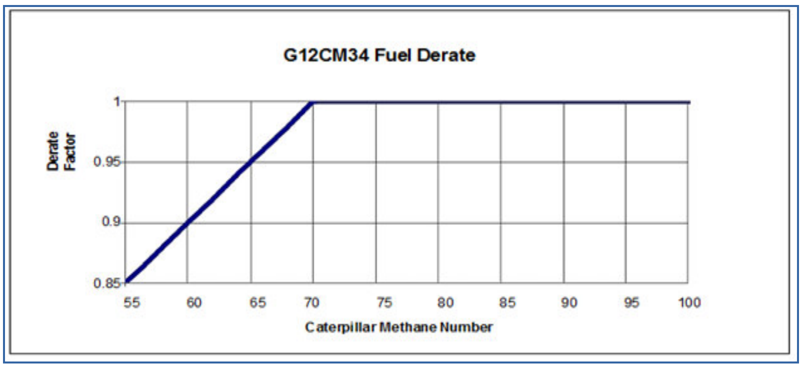

Figure 5. Derate factor x Caterpillar methane number

4 Evaluation of engines using biogas

The internal combustion engines with the objective to generate electrical power can be used in systems of cogeneration or even in systems of combined cycles with vapor water or Organic Rankine cycles. In both systems it is important know the behavior on project conditions (design point) and on partial load or even out of project conditions (off-design point). The operation out of the project conditions can be assigned to atmospherics conditions like pressure, temperature of air, fuel composition and load operation.

There are researchers of parameterization that feature dimensionless variables relations of operations in diesel engines overload (Cruz, 2004) and on internal combustion engine (ICE) aspirated working with liquid fuels (He and Cai, 2009), but the relations of this authors are apply in engines that operate with value of equivalency section closes to stoichiometric conditions (0.9 until 1.1). Gas and biogas engines which have "learn burn" technology, operating with excess of air with value of equivalency section (1.3 until 1.7), allowing the reduction of NOx, with lower probability of detonation and increasing the gas mass of combustion which can be used in heat production systems (Meggyes and Nagy, 2009).

The information from operation conditions of an engine at rated load and partial load, like present on table 4 referent to technical information engine G3520C for company Caterpillar operating with natural gas (Caterpillar, 2015) are very important and useful on behavioral analysis of combined cycles of cogeneration.

Table 4. Gas engine site specifications technical data - G3512 LE (Caterpillar, 2015)

Rating and efficiency	Units	Load 100%	Load 75%	Load 50%
Engine power	kW	2154	1616	1077
Engine efficiency	%	38,5	37,0	35,1
Exhaust stack temperature	˚C	487	511	527
Exhaust mass flow	kg/kW-hr	5,90	6,02	6,30
Exhaust mass flow	kg/h	3,53	2,70	1,88

The information on table 4 usually are not showed on manufacturer catalog, it is common be only available the rated condition. It is interesting have relations that allow rated condition link the behavior on partial load, allowing analysis to system out of conditions to rated load and with the variation of fuel composition.

This way was realized the collect of data bases on catalog of gas and biogas (60% of methane and 40% of carbon dioxide) from manufactures like Caterpillar, Cenergy and General Electric.

From the data, with a total of 15 engines, using the resource "data analysis" of Excel's software, was elaborated dimensionless relations to: Power on function of load (f_p) equation 5; efficiency in function of load (f_e) equation 6; temperature of combustion gases in function of load (f_{Text}) equation 7; dimensionless gas mass flow in function of load ($f_{madm,g}$) equation 8; dimensionless factor of ambient temperature influence (f_{Tamb}) based in figure 3 (equation 9); dimensionless factor of atmospheric pressure (f_{Pamb}) based on figure 4 (equation 10); dimensionless factor of methane number (f_{MN}) based on figure 5(equation 11).

$$f_p = -0{,}001857 + 0{,}010058 L_{load} - 3{,}714\times10^{-7} L_{load}^2 \quad (5)$$

$$f_e = 0{,}6866 + 5{,}100\times10^{-3} L_{load} - 2{,}194\times10^{-5} L_{load}^2 + 1{,}361\times10^{-16} L_{load}^3 - 5{,}4210\times10^{-19} L_{load}^4 \quad (6)$$

$$f_{Text} = 1{,}1214 - 8{,}4824\times10^{-4} L_{load} - 3{,}6596\times10^{-6} L_{load}^2 + 2{,}2898\times10^{-16} L_{load}^3 - 8{,}6736\times10^{-19} L_{load}^4 \quad (7)$$

$$f_{m,adm,g} = 1{,}2649 - 4{,}831\times10^{-3} L_{load} - 2{,}1945\times10^{-5} L_{load}^2 + 7{,}11224\times10^{-17} L_{load}^3 - 2{,}1684\times10^{-19} L_{load}^4 \quad (8)$$

$$f_{Tamb} = 0{,}6371 + 0{,}0243 T_{amb} - 0{,}0004 T_{amb}^2 \quad (9)$$

$$f_{alt} = 1{,}0492 - 7\times10^{-5} alt - 8\times10^{-11} alt^2 \quad (10)$$

$$f_{MN} = 0{,}31 + 0{,}01 MN \quad (11)$$

And: L_{load} = actual load [%]; T_{amb} = ambient temperature [C]; alt = elevation [m]; MN = methane number.

To determine the behavior of engines in partial load was realized the relations (equation 12 to 1) that linked the dimensionless relations (equations 5 to 11) with the proprieties of full load (100%) on engine.

$$W_{PL} = W_{ref} \times f_p \times f_{Tamb} \times f_{alt} \times f_{MN} \quad (12)$$

$$T_{g,ext} = T_{g,ext,REF} \times f_{Text} \quad (13)$$

$$\eta_{eng} = \eta_{eng,ref} \times f_e \quad (14)$$

$$m_{exhaust,\text{dimen},actual} = m_{exhaust,\text{dimen},ref} \times f_{m,g} \times f_{Tamb} \times f_{alt} \quad (15)$$

And: W_{PL} = actual engine power [kW]; W_{ref} = reference engine power [kW]; $T_{g,ext}$ = Exhaust stack temperature actual [C]; $T_{g,ext,Ref}$ = Exhaust stack temperature reference [C]; η_{eng} = Engine efficiency actual [%]; $\eta_{eng,ref}$ = Engine efficiency reference [%]; $m_{exhaust,dimen,actual}$ = Exhaust mass flow dimensionless actual [kg/kW-hr]; $m_{exhaust,dimen,ref}$ = Exhaust mass flow dimensionless reference [kg/kW-hr].

The others proprieties are obtained in equations submitted belong follow next.

From thermal efficiency equation (equation 16) the amount of consumed energy is determined by the cycle (Q_{input}). The low heating value of fuel determines the mass flow of fuel (equation 17). The balance of mass (equation 18) determines the amount of air consumed

(m_{air}) in kg/s. From the relation air fuel real and the relation air fuel stoichiometric (equation 19) is determined the value of equivalency section (λ). From the equation 20 is determined the electrical power available.

$$Q_{input} = \frac{W_{PL}}{\eta_{eng}} \tag{16}$$

$$m_{comb} = \frac{Q_{input}}{LHV} \tag{17}$$

$$m_{air} = m_{g,ext} - m_{comb} \quad \Rightarrow \quad m_{g,ext} = m_{exhaust,\mathrm{dimen},actual} \times W_{PL} \tag{18}$$

$$\lambda = \frac{(A/F)_{actual}}{(A/F)_{\mathrm{Stoichiometry}}} \tag{19}$$

$$W_{el} = \eta_{ger} \times W_{TM} \tag{20}$$

Making the analysis showed and the behavior of an engine that can operate with natural gas and biogas, was elaborated the table 4. This table basically is formed of inlet variables: variation of load on engine (50 to 100%); Methane index (100 = low index of detonation; 55 = moderate index of detonation and application limit for apply on gas engines), molar fraction of methane (0,8 CH_4 = indicates the typically composition of natural gas; 0,4 CH_4 = indicates the typically composition of biogas).

Variables calculated: Electrical power available (W_{te}) calculated from equation 20, the efficiency of generator is considered 97%; mechanical power of generator (W_m) calculated from equation 12; power produced by an Organic Rankine cycle (W_{ORC}) with efficiency of 15% and effectiveness 0,7 to heat exchangers between exhaust gases and the fluid work of Organic Rankine cycle (Schuster, et al, 2009); Full power of cycle (W_{tm}) which is the sum of generator power and Organic Rankine power; Consumption of energy by the cycle (Q_{in}) calculate from the equation 16; Available energy on the combustion gases (Q_{exaust}) considering the inlet temperature T_{ex} with the outlet temperature like 180ºC and the flow gases mass of combustion (m_{gas}); Energy available (Q_{TC}) for Organic Rankine; Thermal efficiency of generator (η_{eng}) calculated from equation 14; Global efficiency of combined cycle (η_{cycle}); Temperature of gases out of the engine (T_{ex}) obtained from equation 13; Mass flow of fuel (m_{FUEL}) obtained from equation 17; Mass flow of gases from combustion (m_{gas}) obtained from equation 15; Value of equivalency section (λ) obtained from equation 19.

Must be highlighted to realize the simulations on table 5 was elaborated a program developed in EES, which has procedures to calculate the process of combustion, the blend of gases and balance of mass and energy.

Table 5. Results of simulation of combined cycle (Engine cycle and Organic Rankine)

Load [%]	NM	y_{CH4}	W_{te} [kW]	W_{tm} [kW]	W_m [kW]	W_{ORC} [kW]	Q_{in} [kW]	Q_{exaust} [kJ/s]	Q_{TC} [kJ/s]	η_{eng} [%]	η_{cycle} [%]	T_{ex} [C]	m_{FUEL} [kg/s]	m_{Gas} [kg/s]	λ
50	100	0,90	1124	1159	1077	82	3123	778	544	34,49	35,99	521	0,08	1,90	1,70
60	100	0,90	1345	1387	1293	94	3628	895	627	35,63	37,07	515	0,09	2,23	1,71
70	100	0,90	1565	1614	1508	105	4121	1004	703	36,60	37,98	509	0,11	2,55	1,73
75	100	0,90	1675	1727	1616	111	4365	1055	739	37,02	38,37	505	0,11	2,71	1,73
80	100	0,90	1784	1840	1724	116	4609	1105	773	37,40	38,72	502	0,12	2,87	1,74
90	100	0,90	2003	2065	1939	126	5098	1200	840	38,04	39,29	495	0,13	3,19	1,75
100	100	0,90	2221	2289	2154	135	5595	1290	903	38,50	39,69	487	0,15	3,52	1,76
50	100	0,65	1123	1158	1077	81	3123	773	541	34,49	35,98	521	0,15	1,90	1,63
60	100	0,65	1345	1386	1293	93	3628	890	623	35,63	37,06	515	0,18	2,23	1,65
70	100	0,65	1565	1613	1508	105	4121	998	698	36,60	37,97	509	0,20	2,55	1,66
75	100	0,65	1674	1726	1616	110	4365	1049	734	37,02	38,36	505	0,22	2,71	1,66
80	100	0,65	1784	1839	1724	115	4609	1098	769	37,40	38,71	502	0,23	2,87	1,67
90	100	0,65	2002	2064	1939	125	5098	1193	835	38,04	39,28	495	0,25	3,19	1,68
100	100	0,65	2220	2289	2154	135	5595	1283	898	38,50	39,68	487	0,28	3,52	1,69
50	100	0,45	1123	1158	1077	81	3123	767	537	34,49	35,96	521	0,27	1,90	1,52
60	100	0,45	1344	1385	1293	93	3628	883	618	35,63	37,04	515	0,32	2,23	1,54
70	100	0,45	1564	1612	1508	104	4121	990	693	36,60	37,95	509	0,36	2,55	1,55
75	100	0,45	1673	1725	1616	109	4365	1040	728	37,02	38,34	505	0,38	2,71	1,56
80	100	0,45	1783	1838	1724	114	4609	1090	763	37,40	38,69	502	0,40	2,87	1,56
90	100	0,45	2001	2063	1939	124	5098	1183	828	38,04	39,26	495	0,44	3,19	1,57
100	100	0,45	2219	2288	2154	134	5595	1272	891	38,50	39,66	487	0,49	3,52	1,58
50	55	0,90	967	996	926	70	2686	669	468	34,49	35,99	521	0,07	1,64	1,70
60	55	0,90	1157	1193	1112	81	3120	770	539	35,63	37,07	515	0,08	1,92	1,71
70	55	0,90	1346	1388	1297	91	3544	863	604	36,60	37,98	509	0,09	2,19	1,73
75	55	0,90	1440	1485	1390	95	3754	907	635	37,02	38,37	505	0,10	2,33	1,73
80	55	0,90	1535	1582	1482	100	3963	950	665	37,40	38,72	502	0,10	2,47	1,74
90	55	0,90	1723	1776	1667	108	4384	1032	722	38,04	39,29	495	0,11	2,75	1,75
100	55	0,90	1910	1969	1852	117	4812	1110	777	38,50	39,69	487	0,13	3,03	1,76
50	55	0,65	966	996	926	70	2686	665	466	34,49	35,98	521	0,13	1,64	1,63
60	55	0,65	1156	1192	1112	80	3120	765	536	35,63	37,06	515	0,15	1,92	1,65
70	55	0,65	1346	1387	1297	90	3544	858	601	36,60	37,97	509	0,18	2,19	1,66
75	55	0,65	1440	1484	1390	95	3754	902	631	37,02	38,36	505	0,19	2,33	1,66
80	55	0,65	1534	1582	1482	99	3963	945	661	37,40	38,71	502	0,20	2,47	1,67
90	55	0,65	1722	1775	1667	108	4384	1026	718	38,04	39,28	495	0,22	2,75	1,68
100	55	0,65	1909	1968	1852	116	4812	1103	772	38,50	39,68	487	0,24	3,03	1,69
50	55	0,45	966	996	926	69	2686	660	462	34,49	35,96	521	0,23	1,64	1,52
60	55	0,45	1156	1191	1112	80	3120	759	532	35,63	37,04	515	0,27	1,92	1,54
70	55	0,45	1345	1387	1297	89	3544	851	596	36,60	37,95	509	0,31	2,19	1,55
75	55	0,45	1439	1484	1390	94	3754	895	626	37,02	38,34	505	0,33	2,33	1,56
80	55	0,45	1533	1581	1482	98	3963	937	656	37,40	38,69	502	0,34	2,47	1,56
90	55	0,45	1721	1774	1667	107	4384	1018	712	38,04	39,26	495	0,38	2,75	1,57
100	55	0,45	1908	1967	1852	115	4812	1094	766	38,50	39,66	487	0,42	3,03	1,58

Comparing the results showed in table 5(in yellow) with references values of table 3, it is checked the percentage errors to load of 50%, error of -1,75 % on efficiency, error of -1,14 % on the exhaust gases temperature, error of 1,12 on exhaust gases; to load of 75%, error of -0,05 % on efficiency, error of -1,15% on the exhaust gases temperature, error of 0,41 on exhaust gases; to load of 100%, error of 0,0 % on efficiency, error of 0,0% on the exhaust gases temperature, error of -0,28 on exhaust gases. Stand out that this errors obtained because the dimensionless equations obtained from the average values of the curves analyzed, and not all engines have curves with the same comportment.

It is checked on table 5 the influence of methane number on the reduction of engine power, and the influence from the concentration of methane on energy value and the fuel mass which contributed on the lower efficiency of combined cycle when the methane number decrease.

It is checked the decrease of fuel-air equivalence ratio when the concentration of methane decrease, this occurs because the heat power decrease, in this way it is necessary more mass of fuel to have the wished power. This information is important to the function of biogas engines; however, the landfill's life can reduce the content of methane so the engine must be prepared to make changes in fuel flow.

The generate power by the Organic Rankine system represents closer to 5,8% of total power when the engine was operating with full load and approximately 7,0% of total power when the engine was operating with 50% of load. Should be highlighted that this values could be expanded, for example the utilization of technologies of Organic Rankine which can operate with efficiencies closer to 25%, use Organic Rankine systems with can operate with more elevate temperatures (closer to 450ºC) and this way operate with heat exchangers with more efficiency or even work without this equipment.

5 Conclusion

In this article is shown the methodology to realize the analyses of gas and biogas engines working with rated load and with partial load. Due to the difficulty to found curves of operation on engines, usually the gas engine technical data present information at rated load and some at partial load. From the methodology introduce was possible realize the study of behavior on gas with high content of methane and gas with the content like in biogas on internal combustion engines.

Also checked that the high excess of air, demand by technology "lean burn", there is a potential of energetic utilization to generate additional power (Organic Rankine) , to refrigeration systems and production of vapor (boiler with heat recovery). The choice of the best alternative must be followed by the economic analysis that will indicates the viability of implementation of a project on the moment of analyze, but must be highlighted that thermodynamic analyses does not depend of time.

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