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**PARAMETRICAL AND ANALYTICAL ANALYSIS OF BIOGAS
PRODUCTION AND ITS USE AS AN ALTERNATIVE FUEL IN A GAS
TURBINE CYCLE**

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***Abstract:** Due to a growing concern for the environment, it is increasingly sought out to replace traditional fossil fuels for ecological alternatives, trying to minimize possible environmental impacts in search of a more sustainable economy. That way, biogas has been shown as a less polluting way to generate energy, mainly in rural environments. That is why this article aimed to estimate the biogas production and apply it in a simple thermodynamical process. At first, a parametrical study on the biogas production was made, changing the feed origin (difference between cattle and pig slurry), the number of individual animals used, the time of hydraulic retention and the biodigester's temperature. This first step showed that the increase of all the individual parameters resulted in a significant rise in the final volume of biogas produced. It is noted that, while utilizing data of a diverse catalog of similar studies, cattle slurry has shown more promising results, since a single ox can produce almost 10 times more cubic meters of biogas compared to a pig. Then, in a thermal analysis, the type of slurry, the numbers of animals, the fuel/air ratio and the biodigester operational temperature were varied to observe the difference of energy produced and the Thermodynamical System's thermal efficiency. Like the biogas production, the cattle slurry showed more promising results, producing more energy; however, there was no difference between the thermal efficiency, which presented values around 41.13%. Despite the efficiency's values, the system can be further optimized using a cogeneration process after the biofuel's burn. The temperature's alteration showed minimal results, its increment resulted in only a 0.6% increase in the efficiency. Lastly, the variation in the fuel/air ratio presented a curve in a parabolic shape. Despite the format of the resulting graphics, lower values of the fuel/air ratio were more favorable, presenting higher values of thermal efficiency and energy produced. In short, ~~the~~ biogas production, together with its use as an energy generator, can be a promising step in trying to minimize environmental impacts, reduce waste and, consequently, increase profit in a rural environment.*

Keywords: Biogas, Biogas production, Thermodynamical analysis, Parametrical analysis

1. INTRODUCTION

Despite the damage made to the environment and the increasing social and governmental pressure for its reduction, fossil fuel is still responsible for more than half of the total electrical energy used in the world (INTERNATIONAL ENERGY AGENCY, 2021; TOWARDS, 2017). For this reason, the irreversible damage made to planet Earth (MAHLIA et al., 2014; OMER, 2008) together with international treaties, such as the Paris Agreement (DELBEKE et al., 2019) resulted in a search for ways of replacing this kind of fuel. Between the available options, biogas is gaining attention as an ecologically friendly and cheap alternative.

Even with its relative low thermal performance (DE FARIA et al., 2017), biogas is gaining recognition as one of the main forms of fuel used in the generation of energy in a diversity of countries (BLÁZQUEZ et al., 2021; INTERNATIONAL ENERGY AGENCY, 2021). This is happening in a variety of sectors, for instance the use of biogas in systems of cogeneration (BLÁZQUEZ et al., 2021), in the replacement of traditional thermal systems for cheaper and more efficient models (WU; MA, 2016) and the reuse of waste as a way to produce biogas (SCHROEDER; SCHALAU; MOLNARNE, 2014). In more extreme cases, biogas plays a key role in fully sustainable communities, where all electrical energy used is produced domestically (known as net Zero-Energy Communities - nZEC) (AMARAL et al., 2018;

HAHNEL et al., 2020). All of this is possible because biogas can be produced both from animal and vegetable remains, as well as from common waste. (PRODRONIDIS; COUTELIERIS, 2017).

On the other hand, the implementation of systems with a this new form of fuel can be difficult in urban environments, therefore, biogas has been predominantly used in rural areas, where all waste produced locally can be transformed into biogas (DEMIRBAS, 2007; GHOLIZADEH; VAJDI; MOHAMMADKHANI, 2019).

Currently in Brazil, the main sources of waste that can be used for the production of biogas are linked to the sugar-energy, agricultural and sanitation sector (ABIOGAS, 2018). In an ideal context, if all this biomass was processed, Brazil would be able to produce almost 82 billion cubic meters of biogas per year, which would make it possible to supply 36% of all national energy demand (ABIOGAS, 2018).

Simply put, biogas is produced through anaerobic digestion of biodegradable materials; this biomass can originate from different sources (RODIONOVA et al., 2017), such as crop residues (SUN et al., 2015), grass, straw (WANG; LV; WENG, 2020), food remains (KOWTHAMAN; ARUL MOZHI SELVAN; SENTHIL KUMAR, 2021; VIJIN PRABHU et al., 2021), waste resulting from industrial processes (DE CLERCQ et al., 2019), different forms of sewage (GULSEN AKBAY; DIZGE; KUMBUR, 2021; LIN et al., 2017) and, perhaps most importantly, from animal waste (CECK; APARECIDA ROMAN, 1983; JUNIOR, 2019; MITO et al., 2018).

This last point is key for the use of biogas as a substitute for other forms of fuel, as this anaerobic digestion process usually takes place in a biodigester that can be easily built, even without much technical knowledge (CECK; APARECIDA ROMAN, 1983). It should be noted that biogas production is continuous, which makes it possible for a small biodigester to generate enough gas for common domestic and rural needs, such as: cooking gas, water heating, fuel for some engines and heating for survival and comfort of some animals (CECK; APARECIDA ROMAN, 1983). Another fundamental characteristic of the biodigester is that, in addition to producing biogas, it also generates a residue that can be used directly as fertilizer, further facilitating some rural activities (CECK; APARECIDA ROMAN, 1983).

However, despite this great applicability of biogas (mainly in rural environments), the mechanisms that produce biogas have been understudied. Many biogas studies and calculators are usually only concerned with the origin of the biomass (generally the amount and type of animal that will produce the waste used) and almost never with other operational parameters, such as the temperature or even the pH of the mixture that will be submitted to the biogas generation process. In addition, studies that address the generation and direct application of biogas simultaneously are rare, even in an extremely basic thermal cycle.

Thus, the main objective of this study is to perform a parametric analysis on the potential of biogas generation, estimating the amount produced and, consequently, submitting this biofuel to a simple thermal cycle (Gas Turbine), with the aid of computer simulations and in the light of different studies carried out previously on the subject. The representative scheme that shows the entire analysis cycle is shown in Figure 01.

2. LITERATURE REVIEW

2.1. Biogas Definition

From a chemical point of view, biogases are mixtures of CH_4 and CO_2 , with small percentages of N_2 , O_2 , H_2 , H_2S , H_2O , CO , NH_3 , siloxanes, aromatics, and dust particles (GAO et al., 2018). It should be noted that the exact proportions of each component depend directly on the generation of the raw material used and the mode of production of the biogas, in addition to the variation in the time of bacterial activity (ESCUADERO; SERRANO, 2019). Despite this chemical complexity involving biogas, it is possible to obtain satisfactory approximate results when considering that the biofuel is composed only of a basic mixture of 60% CH_4 and 40% CO_2 (GARCÍA et al., 2021; GHOLIZADEH; VAJDI; MOHAMMADKHANI, 2019).

Because methane has a much higher thermal potential than carbon dioxide, the presence of CH_4 in large amounts is advantageous. However, as previously mentioned, controlling the percentage variation of these compounds is extremely difficult. The most determining factors for the composition of biogas are: its origin and the pH of the biomass. The origin can be easily identified, but pH is an inconsistent and complex variable to control (JUNG et al., 2021; VIJIN PRABHU et al., 2021; WU et al., 2016). In the case of small and medium-sized farmers who generally operate biodigesters independently, pH is often ignored. Due to this lack of applicability of pH control, there are few models that estimate the true impact of this variable on the resulting biogas. There are some studies that empirically analyze this variation (VIJIN PRABHU et al., 2021), but without providing a theoretical calculation that can be applied in other cases.

2.2. Cycle in analysis

Through the material collected in a Literature Review, a thermal system was theorized that begins in the production of biogas and goes to its use as a fuel in a simple thermal process through a Gas Turbine cycle. This process is outlined in Figure 01.

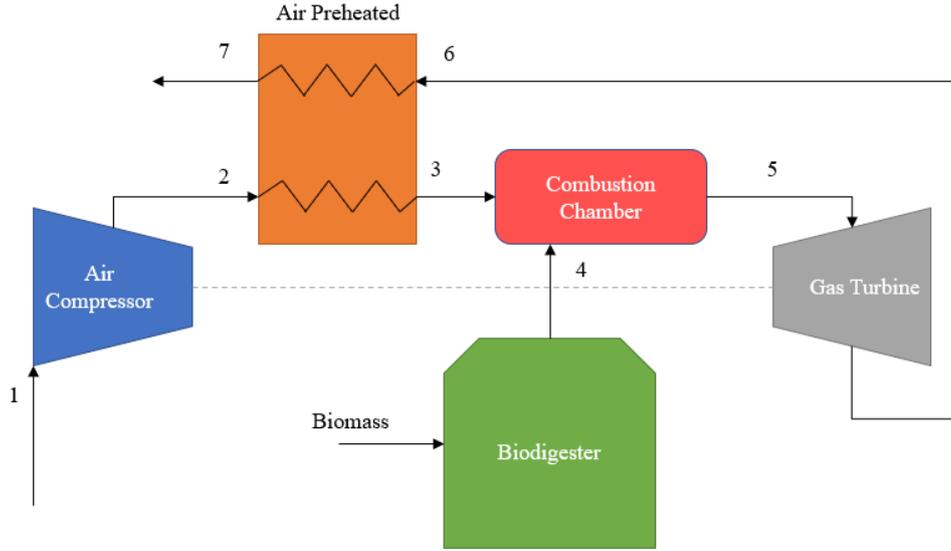


Figure 1. Representative Scheme of the Technical Process.

2.3. Mathematical Modeling of Biogas Production

Among the models available in the literature that estimate biogas production, this study chose to use a method developed by British researchers (WU et al., 2016). This methodology uses a biogas calculation table that takes into account the origin of the biomass, the temperature of the mixture and the time that the waste remains inside the biodigester (called hydraulic retention time).

Two cases were compared: a farm with a pig slurry and another with a cattle slurry. In both, all animals would have their waste constantly used in biodigesters to produce biogas.

2.3.1. Method used for Estimating the Biogas Production

The method applied was created by British researchers (WU et al., 2016) joining two other existing methods (BOLZONELLA et al., 2005; TCHOBANOGLOUS; BURTON; STENSEL, 2003) in order to formulate a table to calculate the production of biogas using data collected experimentally in the UK.

This method follows an extensive step-by-step process that aims to find the amount of biogas produced daily, as expressed by Eq. (01).

$$\dot{V}_{BG,i} = \dot{m}_{VS,i} \cdot Y_{BG,i}^P \cdot VSD_i \quad (01)$$

where: \dot{V}_{BG} [$\text{m}^3_{\text{biogas}} \text{day}^{-1}$] represents the estimated daily production of biogas associated with a biomass “i”; $\dot{m}_{SV,i}$ [$\text{kg}_{VS} \text{day}^{-1}$] denotes the daily mass flow rate of volatile solids contained in biomass “i”; $Y_{BG,i}^P$ [$\text{m}^3_{\text{biogas}} \text{kg}_{VS}^{-1}$] corresponds to the potential biogas production of material “i” and VSD_i [%] represents the volatile solids destruction.

Initially, the retention time adopted in the biodigester is defined, which can be calculated according to Eq. (02).

$$RT = \frac{V_{Dig}}{\dot{V}_{feed}} \quad (02)$$

where: RT [days] is the hydraulic retention time; V_{Dig} [m^3] corresponds to the active volume of the digester used and the \dot{V}_{feed} [$\text{m}^3 \text{day}^{-1}$] means the volumetric flow of the feed inserted in the digester daily.

Then, the authors (WU et al., 2016) explain that the method used arose from the combination of two different ways of calculating the volatile solids destruction by material. Therefore, Eqs. (03) and (04) explain these different forms.

$$VSD_{i,B1}^{RT} = \frac{B \cdot k_1 \cdot RT}{1 + B \cdot k_1 \cdot RT} \cdot 100\% \quad (03)$$

$$VSD_{i,B2}^{RT} = k_3 + k_2 \ln(B \cdot RT) \quad (04)$$

where: VSD_i^{RT} [%] represents the estimated volatile solids destruction at a specific hydraulic retention time; B [dimensionless] is the relative bacterial activity factor and k_{1-3} [dimensionless] are treated as model parameters.

All values of the constants used are shown in Table 1. However, factor “B” must be calculated separately, as it varies according to temperature. In addition, Eq. (05) does not vary continuously, since this method considers that the production of biogas can occur with the help of two different forms of microorganisms, the mesophilic (which develop better at moderate temperatures, usually between 20 and 45°C) and the thermophilic (which develop better at high temperatures) (ABIOGAS, 2018). Each stage is only valid for a specific temperature range. The mesophilic analysis is only valid between 30 and 40°C, while the thermophilic one operates between 50 and 60°C. The behavior of factor B can be seen in Figure 2.

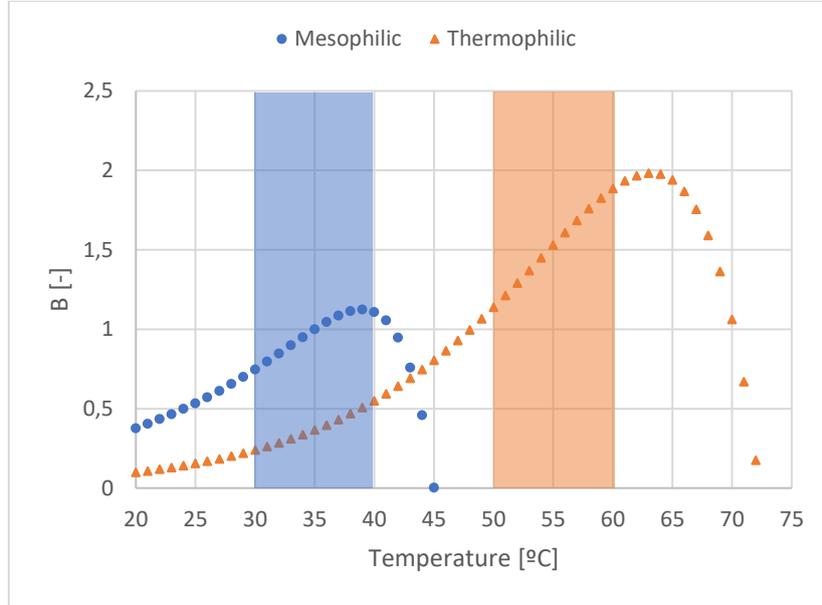


Figure 2. Relationship between temperature and bacterial activity factor.

$$B = k_4 \exp(k_5(T - k_6)) - k_7 \exp(k_8(T - k_6)) \quad (05)$$

where: T [°C] is the temperature at which the process takes place and k_{4-8} [dimensionless] are taken as model parameters.

Despite being easily calculated, the hydraulic retention time is an extremely difficult factor to be empirically determined. This occurs because the mixture present inside the biodigester is not homogeneous. Previous studies conclude that a considerable part of the biomass remains only half of the predicted time, while another portion stays twice as long (WU et al., 2016). Therefore, the volatile solids destruction factor is corrected by Eq. (06), which already considers that a portion of the biomass will stay for half the retention time (0.5RT), another for twice as long (2RT) and a last one that will stay for the foreseen time (RT).

$$VSD_{i,(B_1 \text{ ou } B_2)} = k_9 VSD_i^{0.5 \cdot RT, T} + k_{10} VSD_i^{2 \cdot RT, T} + (1 - k_9 - k_{10}) VSD_i^{RT, T} \quad (06)$$

where: $VSD_i^{0.5 \cdot RT, T}$ [%] is the volatile solids destruction that occurs at half the predicted hydraulic retention time (0.5RT) and at an operating temperature (T); $VSD_i^{2 \cdot RT, T}$ [%] is the volatile solids destruction that occurs at twice the predicted hydraulic retention time (2RT) and at an operating temperature (T); $VSD_i^{RT, T}$ [%] corresponds to the volatile solids destruction that occurs at the predicted hydraulic retention time (RT) and at an operating temperature (T); and, finally k_{9-10} [dimensionless] are the averaging weights, considering that $0 \leq k_9 + k_{10} \leq 1$.

After carrying out all the previous calculations for the two different forms (B_1 and B_2), the amount of biogas produced is taken as a weighted average between these two results, as explained by Eq. (07).

$$DSV_i = k_{11} DSV_{i, B_1} + (1 - k_{11}) VSD_{i, B_2} \quad (07)$$

where: k_{11} is the weighted average factor, noting that $0 \leq k_{11} \leq 1$.

Table 1. Fixed values for the parameters used in the biogas production estimation calculations, where (m) refers to the mesophilic analysis while (t) refers to the thermophilic.

Parameters	Value	References
k ₁	0.2	(APPELS et al., 2008)
k ₂	13.7	(BOLZONELLA et al., 2005)
k ₃	18.9	(TCHOBANOGLIOUS; BURTON; STENSEL, 2003)
k ₄	(m) 0.494; (t) 22.8	(LIER; MARTIN; LETTINGA, 1996; WU et al., 2016)
k ₅	(m) 0.0704; (t) 0.107	(LIER; MARTIN; LETTINGA, 1996; WU et al., 2016)
k ₆	(m) 23.8; (t) 58.6	(LIER; MARTIN; LETTINGA, 1996; WU et al., 2016)
k ₇	(m) 0.00233; (t) 21.0	(LIER; MARTIN; LETTINGA, 1996; WU et al., 2016)
k ₈	(m) 0.323; (t) 0.113	(LIER; MARTIN; LETTINGA, 1996; WU et al., 2016)
k ₉	0.39	(WU et al., 2016)
k ₁₀	0.13	(WU et al., 2016)
k ₁₁	0.8	(WU et al., 2016)

Finally, the methodology was slightly modified, adding the number of animals involved in the process.

Considering Eq. (01), it can be seen that this method only takes into account the mass flow of manure that enters the biodigester per day. In this way, using the data collected by Embrapa (MITO et al., 2018) in Table 2, it is possible to know how many liters of effluents (feces and urine) a single animal produces per day. Adding this information to the effluent density presented in Table 3, Equation (01) was modified, which results in the equation described by Eq. (08).

Table 2. Values referring to the production of daily effluents per animal.

Type of Slurry	Effluent Production [L animal ⁻¹ day ⁻¹]
Pigs	10.28
Cattle	93.70

Reference: MITO et al., 2018.

$$\dot{V}_{BG,i} = \left(\frac{N \cdot \dot{V}_{deg} \cdot \rho_{deg}}{1000} \right) \cdot Y_{BG,i}^P \cdot VSD_i \quad (08)$$

where: N [dimensionless] represents the number of animals used; \dot{V}_{deg} [L animal⁻¹ day⁻¹] denotes the volumetric flow of manure production per animal in one day and ρ_{deg} [kg m⁻³] corresponds to the density of the effluent in question.

Table 3. Parameters associated with different kinds of feed.

Feed material	Volatile Solids [%]	Biogas Yield $Y_{bio,i}^P$ [m ³ _{bio} /kg _{sv}]	CH ₄ percentage [%]	Density [kg/m ³]
Pig slurry	7.5%	0.340	55.0%	986
Cattle slurry	6.0%	0.400	58.0%	1026

Reference: TEODORITA AL SEADI, DOMIJK RUTZ, HEINZ PRASSL, MICHAEL KOTTNER, TOBIAS FINSTERWALDER, SILKE VOLK, 2008; WU et al., 2016.

2.4. Transformation of Biogas Volumetric Flow to Mass and Molar Flow

As previously presented, the methodology used estimates the volumetric flow of biogas, which results from a variety of operating parameters. However, calculations involving thermal cycling generally involve mass or molar flow, thus requiring a parameter transformation.

Considering that the biogas creation process takes place at the pressure established by Table 4, which can be found in page 9 (equivalent to 1062 kPa), and that the biogas formed is at the same temperature used previously in Eq. (05), it is possible to use the Clapeyron equation to estimate the molar flow rate of the mixture. Such modification results in Eq. (09).

$$\dot{n}_{biogas} = \frac{p \cdot \dot{V}_{BG,i}}{\bar{R} \cdot T} \quad (09)$$

where: \dot{n}_{biogas} [kmol s⁻¹] is the biogas molar flow; p [kPa] represents the pressure at the exit of the biodigester and at the entrance of the combustion chamber (considered equivalent to 1062 kPa); \dot{V}_{BG} [m³ s⁻¹] is the volumetric flow of biogas resulting from the biogas estimation methodology; \bar{R} [kJ kg⁻¹ kmol⁻¹] denotes the universal gas constant (considered equivalent to 8.314 kJ kg⁻¹ kmol⁻¹) and T [K] is the operating temperature used to estimate biogas production.

Knowing the molar flow rate, the mass flow rate can be determined through the relationship between mole and molar mass. As explained above, the biogas used was considered as a simple mixture, containing 60% CH₄ and 40% CO₂ (both in molar percentage). So, the molar mass of the mixture used is 27.2 kg kmol⁻¹. With these data, the mass flow of biogas can be calculated according to Eq. (10) or by Eq. (11).

$$\dot{m}_{biogas} = \dot{n}_{biogas} \cdot Mm_{biogas} \quad (10)$$

$$\dot{m}_{biogas} = 27.2 \cdot \dot{n}_{biogas} \quad (11)$$

where: \dot{m}_{biogas} [kg s⁻¹] is the mass flow rate of biogas; \dot{n}_{biogas} [kmol s⁻¹] represents the molar flow of biogas and Mm_{biogas} [kg kmol⁻¹] means the molar mass of the biogas used.

2.5. Mathematical Modeling of the Thermal Cycle

With the calculation completed, it was considered that the amount of biogas produced was directly sent to be mixed with air in a combustion chamber. After the burning process, the resulting gases passed through a Gas Turbine to produce electricity, as shown in Figure 01.

2.5.1. Air Compressor

Even before being mixed with biogas, the air passes through a compressor, which results in the following equation for this Thermal Process:

$$\eta_{AC} = \frac{\bar{h}_{in} - \bar{h}_{out,is}}{\bar{h}_{in} - \bar{h}_{out}} \quad (12)$$

$$\dot{W}_{AC} = \dot{m}_{air} \frac{\bar{h}_{out} - \bar{h}_{in}}{M_{air}} \quad (13)$$

where: η_{AC} [dimensionless] is the thermal efficiency of the air compressor; \bar{h}_{in} [kJ kg⁻¹ mol⁻¹] corresponds to the molar enthalpy of the compressor inlet; $\bar{h}_{out,is}$ [kJ kg⁻¹ mol⁻¹] represents the molar enthalpy considering a process as isentropic at the compressor outlet; \bar{h}_{out} [kJ kg⁻¹ mol⁻¹] denotes the real molar enthalpy at the compressor outlet; \dot{m}_{air} [kg s⁻¹] corresponds to the mass flow of air; M_{air} [kg mol⁻¹] is the molar mass of air and \dot{W}_{AC} [kW] represents the power consumed by the air compressor.

2.5.2. Air Preheater

Before entering the combustion chamber, the air passes through a preheater, which exchanges heat with the product resulted from the thermal process. The process that takes place in the preheater was calculated according to Eq. (14).

$$\dot{n}_{air}(\bar{h}_{air,out} - \bar{h}_{air,in}) = \dot{n}_{prod}(\bar{h}_{prod,in} - \bar{h}_{prod,out}) \quad (14)$$

where: \bar{h}_{in} [kJ kg⁻¹ mol⁻¹] are the preheater inlet enthalpies of both the air and the gas resulting from the process; \bar{h}_{out} [kJ kg⁻¹ mol⁻¹] corresponds to the preheater outlet enthalpies of both the air and the gas resulting from the process; \dot{n}_{air} [kmol s⁻¹] denotes the mass flow rate of air and \dot{n}_{prod} [kmol s⁻¹] represents the mass flow rate of the gas resulting from combustion.

2.5.3. Combustion Chamber

Inside the combustion chamber, it was necessary to balance the chemical equation. For this, it is necessary to define the concept of the Fuel-Air ratio (FAR or $\bar{\lambda}$), according to Eq. (15).

$$\bar{\lambda} = \frac{\dot{n}_{fuel}}{\dot{n}_{air}} \text{ or } \frac{\dot{n}_{prod}}{\dot{n}_{air}} = 1 + \bar{\lambda} \quad (15)$$

where: $\bar{\lambda}$ [mol mol⁻¹] is the fuel-air ratio of the mixture; \dot{n}_{fuel} [mol s⁻¹] denotes the molar flow of the fuel used (in this case, biogas); \dot{n}_{air} [mol s⁻¹] means the molar flow rate of air and \dot{n}_{prod} [mol s⁻¹] corresponds to the molar flow rate of the product resulted from the combustion process.

To vary the amount of air present during the process, the chemical balance of combustion was written as a function of FAR. It should be noted that, as previously mentioned, the biogas used contains 60% CH₄ and 40% CO₂. It was also considered that atmospheric air is composed of N₂ and O₂, in addition to small portions of CO₂ and H₂O (GHOLIZADEH; VAJDI; MOHAMMADKHANI, 2019). In this way, the resulting chemical balance was written according to and Eq. (16).

$$\begin{aligned} & \bar{\lambda}[0.6CH_4 + 0.4CO_2] + [0.7748N_2 + 0.2059O_2 + 0.0003CO_2 + 0.019H_2O] \\ & \rightarrow [1 + \bar{\lambda}][Y_{N_2}N_2 + Y_{O_2}O_2 + Y_{CO_2}CO_2 + Y_{H_2O}H_2O] \end{aligned} \quad (16)$$

where: Y_i [mol mol⁻¹] is the mole fraction of a chemical component “i”.

With the balance defined, the molar fraction of each resulting component was determined using Eq. (17) to (20).

$$Y_{N_2} = \frac{0.7748}{1 + \bar{\lambda}} \quad (17)$$

$$Y_{O_2} = \frac{0.2059 - 1.2\bar{\lambda}}{1 + \bar{\lambda}} \quad (18)$$

$$Y_{CO_2} = \frac{0.0003 + \bar{\lambda}}{1 + \bar{\lambda}} \quad (19)$$

$$Y_{H_2O} = \frac{0.019 + 1.2\bar{\lambda}}{1 + \bar{\lambda}} \quad (20)$$

The combustion chamber was considered an open system. Then, performing the thermal and mass balance, it was possible to obtain Eq. (21).

$$\dot{Q}_{c,v} + \dot{n}_{fuel}\bar{h}_{fuel} - \dot{n}_{prod}\bar{h}_{prod} + \dot{n}_{air}\bar{h}_{air} = 0 \quad (21)$$

where: $\dot{Q}_{c,v}$ [kW] is the power associated with the combustion chamber.

The values of molar enthalpies used were calculated considering that all chemical components involved are ideal gases. Therefore, the molar enthalpy of the air at the inlet and the product at the outlet were calculated according to Eq. (22) and (23).

$$\bar{h}_{air} = [0.7748\bar{h}_{N_2} + 0.2059\bar{h}_{O_2} + 0.0003\bar{h}_{CO_2} + 0.019\bar{h}_{H_2O}]_{T=T_{air,in}} \quad (22)$$

$$\bar{h}_{prod} = [Y_{N_2}\bar{h}_{N_2} + Y_{O_2}\bar{h}_{O_2} + Y_{CO_2}\bar{h}_{CO_2} + Y_{H_2O}\bar{h}_{H_2O}]_{T=T_{prod}} \quad (23)$$

The enthalpy associated with the biogas used as fuel can be calculated according to Eq. (24).

$$\bar{h}_{fuel} = [0.4\bar{h}_{CO_2} + 0.6\bar{h}_{CH_4}]_{T=T_{BG}} \quad (24)$$

It should be noted that the enthalpy of the biogas is calculated at the temperature of the biodigester. In this case, this is the same temperature that was used to estimate the biogas production in the section “Method used for Estimating the Biogas Production”.

In turn, the value of the lower heating value resulting from the combustion of biogas was explained by Eq. (25).

$$LHV_{biogas} = H_{prod} - H_{reac} = \sum N_{prod}(\bar{h}_{f,prod}^{A^\circ} + \Delta\bar{h}) - \sum N_{reac}(\bar{h}_{f,reac}^{A^\circ} + \Delta\bar{h}) \quad (25)$$

where: LHV [kJ kmol⁻¹] corresponds to the lower heating value of the fuel mixture; H [kJ/kmol] is the total enthalpy of formation of the product or reactant; $\bar{h}_{f,i}^{A^\circ}$ [kJ/kmol] represents the enthalpy of formation of a specific chemical component;

$\Delta\bar{h}$ [kJ/kmol] denotes the difference between the component enthalpy and the reference enthalpy at 25°C and N_i [dimensionless] corresponds to the respective mole fraction of a reactant or product.

2.5.4. Gas Turbine

By thermally evaluating the turbine that was inserted after combustion, an analysis like the one performed in the air compressor is applied. The efficiency and energy balance of the turbine used were described by Eq. (26) and (27).

$$\eta_{GT} = \frac{\bar{h}_{in} - \bar{h}_{out}}{\bar{h}_{in} - \bar{h}_{out,is}} \quad (26)$$

$$\dot{W}_{GT} = \dot{m}_{prod} \frac{\bar{h}_{in} - \bar{h}_{out}}{M_{prod}} \quad (27)$$

where: η_{GT} [dimensionless] is the thermal efficiency of the gas turbine; \bar{h}_{in} [kJ kg⁻¹ mol⁻¹] means the molar enthalpy of the turbine inlet; $\bar{h}_{out,is}$ [kJ kg⁻¹ mol⁻¹] denotes the molar enthalpy considering a process as isentropic at the turbine outlet; \bar{h}_{out} [kJ kg⁻¹ mol⁻¹] represents the real molar enthalpy at the turbine outlet; \dot{m}_{prod} [kg s⁻¹] is the mass flow rate of the product resulting from combustion; M_{prod} [kg mol⁻¹] corresponds to the molar mass of the product and \dot{W}_{GT} [kW] represents the power produced by the turbine.

2.5.5. Cycle Thermal Efficiency

At the end of the entire study, an analysis of the thermal efficiency of all the processes (the air compressor, the combustion chamber, and the gas turbine) used was carried out. The equation used to calculate the efficiency of the system was Eq. (28).

$$\eta_h = \frac{\dot{W}_{GT} - \dot{W}_{AC}}{\dot{n}_{biogas} LHV_{biogas}} \quad (28)$$

where: η_h [dimensionless] is the thermal efficiency of the thermal system as a whole; \dot{W}_{GT} [kW] means the power developed by the gas turbine; \dot{W}_{AC} [kW] corresponds to the power consumed by the air compressor; \dot{n}_{biogas} [mol s⁻¹] denotes the molar flow rate of biogas entering the combustion chamber and LHV_{biogas} [kJ mol⁻¹] is the lower heating value of biogas entering the combustion chamber.

In addition, the net power of the system was equated according to Eq. (29).

$$\dot{W}_{liq} = \dot{W}_{GT} - \dot{W}_{AC} \quad (29)$$

where: \dot{W}_{liq} [kW] is the net power of the studied thermal system.

Finally, it should be noted that all fixed values used for the thermal cycle calculations are exposed and explained in Table 4.

Table 4. Value of parameters used for thermal process calculations.

Parameter	Value	Ref.
Reference temp., T_0 [°C]	20	(HOSSEINI et al., 2016)
Reference pressure, p_0 [kPa]	101.325	(HOSSEINI et al., 2016)
Isentropic compressor efficiency, η_{AC} [%]	86	(HOSSEINI et al., 2016)
Compression ratio, r_{AC}	10	(HOSSEINI et al., 2016)
Isentropic gas turbine efficiency, η_{TG} [%]	86	(HOSSEINI et al., 2016)
Temp. at the combustion chamber inlet, T_3 [°C]	426.85	(HOSSEINI et al., 2016)
Temp. at the gas turbine inlet, T_5 [°C]	976.85	(HOSSEINI et al., 2016)
Intermediate fuel pressure, p_4 [kPa]	1062	(GHOLIZADEH; VAJDI; MOHAMMADKHANI, 2019)

However, this stage also presented several parameters that were varied only in some situations. So, if the result does not specify any parameter, it was assumed that the values used were the same as in Table 5.

Table 5. Value of parameters used for thermal process calculations.

Parameter	Value
Fuel temp. (biogas), T_4 [°C]	35
RT [Days]	30
Number of animals [-]	10
Fuel-Air ratio, $\bar{\lambda}$	0.172

The standard temperature of the biogas was chosen as 35°C, as this value represents the average temperature for the mesophilic state. Furthermore, the bacterial reactivity factor equation (Eq.05) was adjusted to be equivalent to 1 ($B = 1$) at this temperature (LIER; MARTIN; LETTINGA, 1996; WU et al., 2016). The adopted values of hydraulic retention time (RT) and number of animals (N) were respectively 30 days and 10 animals, as these values showed good results in the first solutions obtained.

The default value of the Fuel-Air ratio ($\bar{\lambda}$) was assumed to be approximately 0.172 because this amount of fuel and air results in an ideal reaction, with neither excess nor lack of air. Therefore, values below 0.172 mean that mixing occurs with excess air, while higher values mean that the operation is occurring with lack of air.

3. RESULTS AND DISCUSSION

3.1. Numerical Simulation

This study was carried out in two parts. First, only the behavior of biogas production was analyzed. MS Excel (ver. 2010 build 13328.20356) was used as a program to calculate all parameters and plot the resulting graphs.

In this step, the type of herd studied (swine and cattle), the operating temperature of the digester (T of Eq. (05)), the hydraulic retention time (RT) and the number of animals used (N) were varied. With the variation of these initial parameters, the amount of biogas production (V_{BG}) was calculated for each case.

It should be noted that, in some cases, the input parameters were considered fixed; under these circumstances, the values of these parameters are explained in the name of the respective Figures throughout the text.

In a second moment, the thermal system was studied separately. The program EES: *Engineering Equation Solver* (ver. 6.883-3D) was used to perform all thermodynamic calculations. With the results tables generated, all values were transferred to Excel to plot their respective graphs.

In this case, the operation temperature of the digester (represented by T in Eq. (05)), the type of slurry (pig or cattle), the number of animals (denoted by N) and the Fuel-Air ratio ($\bar{\lambda}$). For each situation, the thermal efficiency of the system and the net power of the process were calculated.

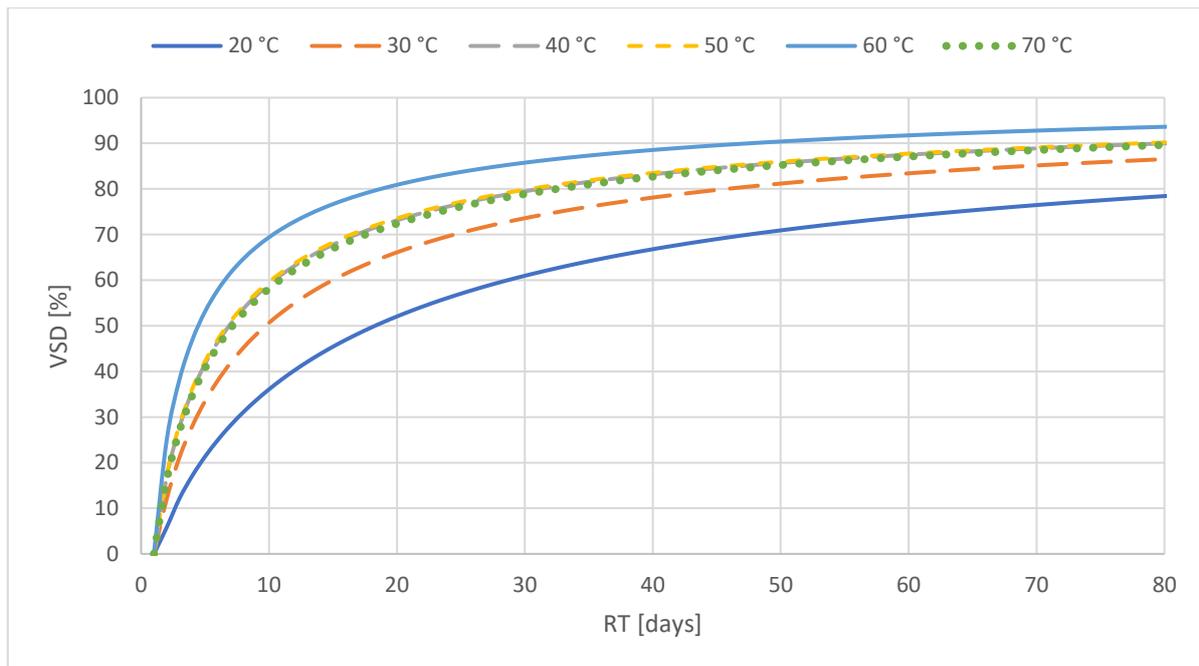


Figure 3. Volatile solids destruction [%] X hydraulic retention time [days] in different temperature ranges.

3.2. Biogas Production

Through the analysis of the variation of the VSD (Volatile Solids Destruction) in relation to the hydraulic retention time and the operating temperature of the biodigester, it was possible to obtain Figure 3. It can be seen that, over time, the percentage of volatile solids destruction increases; however, after very long hydraulic retention times, variations from one day to the next are minimal, thus getting closer to a supposed asymptote of the plotted curves.

Furthermore, it is noted that the higher the temperature, the faster the VSD of the manure grows. This is due to the relative activity factor “B” exposed in the graph of Figure 2. In fact, in the graph of Figure 3, three temperature curves are almost superimposed. As the B factor decreases rapidly after reaching its peak, the B values at temperatures of 40, 50 and 70 °C are very close. Furthermore, this graph showcases that there is an optimal point of operation of the biodigester, which would result in a higher production of biogas.

The entirety of this analysis confirms the hypothesis raised above. Generating biogas in a thermophilic range is ideal, as much more biogas will be produced.

However, working in high temperature mixtures is not easy. A factor that this work does not analyze is the energy cost needed to maintain a biodigester at high temperatures. In a way, despite the greater production of biogas, maintaining the digester at these temperatures can be disadvantageous in economic aspects.

Then, using an operating temperature equivalent to 35°C (when factor B equals 1), the biogas production potential of cattle and swine was calculated, resulting in the graph in Figure 4.

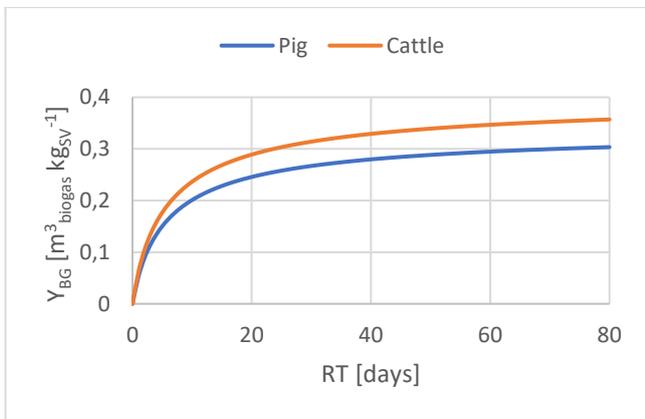


Figure 4. Biogas production potential of a specific biomass [$\text{m}^3_{\text{biogas}} \text{kgVS}^{-1}$] X hydraulic retention time [days] for a pig and a bovine slurry at a fixed temperature of 35 °C.

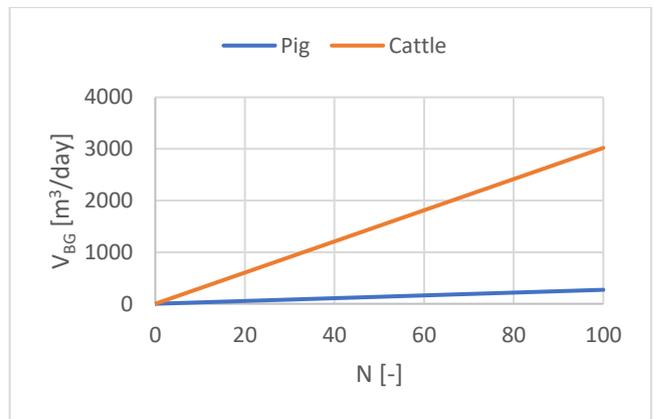


Figure 5. Biogas production [m^3/day] X number of animals from a pig slurry and another bovine herd at a fixed temperature of 35°C and 30 days of hydraulic retention.

Initially, it is perceived that cattle herds have a much greater potential for biogas production, as explained by the values in Table 2. In addition, similarly to the VSD graph, the production potential grows rapidly until it stabilizes after several days of hydraulic retention.

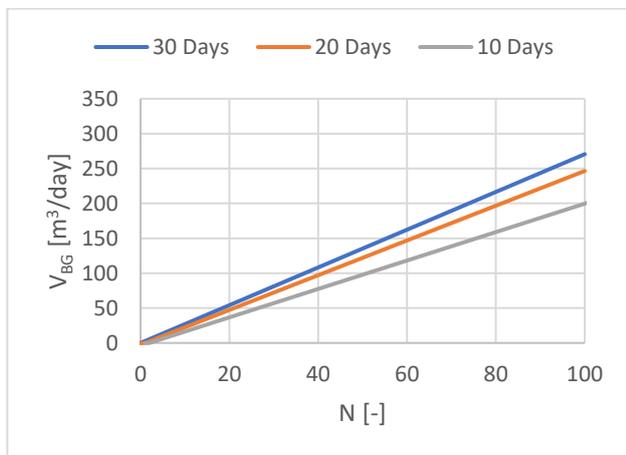


Figure 6. Biogas production [m^3/day] X number of animals in a pig slurry at different hydraulic retention times at a fixed temperature of 35°C.

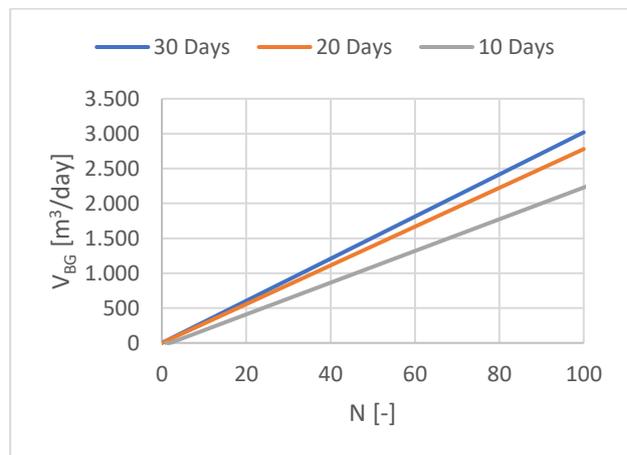


Figure 7. Biogas production [m^3/day] X number of animals in a cattle slurry at different hydraulic retention times at a fixed temperature of 35°C.

Once the potential was calculated, and considering an operating temperature of 35°C and a hydraulic retention time equivalent to 1 month (30 days), a graph of daily biogas production was constructed, varying the number of animals in each herd, which resulted in Figure 5.

As in the analysis of the previous Figures, the bovine herd produces much more biogas than a swine herd. This occurs for two main reasons: the biogas production potential discussed above and the daily effluent production of each animal (Table 3). In both cases, in the potential and in the effluents, an ox has much higher values than a pig, resulting in a much higher biogas production by a bovine herd.

To better understand this variation, similar graphs were drawn, but the hydraulic retention time for cattle and swine was varied. As in the previous graph, the operating temperature of the biodigester was kept equal to 35°C (Figures 6 and 7).

As the amount of days in the biodigester increases, the angular coefficient of the drawn lines also increases. This is because one of the main factors in the manufacturing of biogas, the production potential, is directly proportional to the hydraulic retention time. This fact has already been pointed out by the analysis of Figure 4, but now the impact of this factor can be seen in the final production of biogas.

Furthermore, the graph of Figure 6 has a vertical scale ten times smaller than that of Figure 7. Therefore, the difference between pork and bovine production is remarkable, since the values of bovine production are almost 10 times larger, at least when considering the parameters used in this analysis.

Despite these results, the analysis of the biogas potential and the amount of effluents can be easily questioned. The end of the work released by Embrapa (MITO et al., 2018) presents a major bibliographic review of the parameters used by different authors. It is noted that, in addition to a large amount of work done in the area, the values found by the different authors are not easily comparable. Thus, ideally, a practical study should collect its own data with trials and experiments to certify the results obtained. This problem is further aggravated considering that the manure density was taken from an English study (WU et al., 2016), while the effluent production was taken from a Brazilian study (MITO et al., 2018). Considering that the parameters already vary between local herds, it is not possible to affirm the veracity of the calculated values without an experimental validation process, since the studies used as a basis were carried out in different continents (South America and Europe).

3.3. Thermodynamic Process

With the thermal process calculated, the relationship between the number of animals and the net power developed by the system was first sought, which resulted in the graph in Figure 8.

Analogously to the results obtained in the production of biogas, it can be seen that the amount of animals present is directly proportional to the net power developed by the system. In addition, similar to the previous cases, bovine production is superior to pork. These two facts happen because the net power of the system is directly affected by the amount of biogas used as fuel; the more biogas is burned, a greater amount of the combustion product will pass through the turbines, thus generating much more energy (when coupled to an Electric Generator).

In this same case, it was analyzed whether the thermal efficiency of the system is affected by variation in the amount and type of animal, resulting in Figure 9.

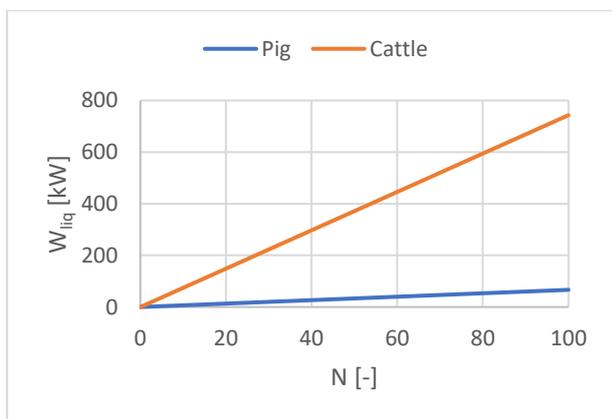


Figure 8. Net power [kW] developed by the system X number of animals in a specific slurry.

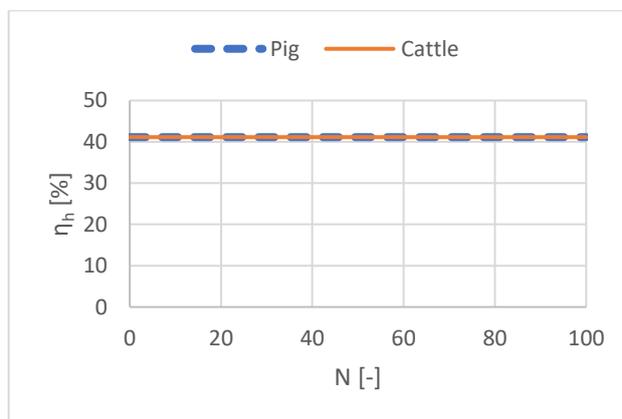


Figure 9. Thermal efficiency [%] developed by the system X number of animals in a specific slurry.

Initially, it is noticed that the efficiency of the system is not affected by the number of animals nor by the difference between swine and cattle herds. As this analysis considered that biogas is always composed of 60% CH₄ and 40% CO₂, there is no difference in chemical properties between the different origins of the biofuel. However, a more realistic analysis would show a small difference, since, as shown in Table 2, there is a variation between the mole fractions of CH₄ and CO₂ depending on the origin of the biomass.

Another important analysis of this graph is the value of the thermal efficiency itself. An efficiency of approximately 41.13% is within the range found by similar studies (GHOLIZADEH; VAJDI; MOHAMMADKHANI, 2019; HOSSEINI et al., 2016), which reached values close to 50%. It is assumed that this difference occurred due to the absence of a cogeneration system at the end of the combustion process.

While other works use the remaining energy of the combustion product (such as a boiler, for example) for other thermal systems (mainly for a Rankine Cycle), this analysis ends with the passage of the product through the Gas Turbine. It should be noted that regardless of the thermal process, the maximum production potential depends exclusively on the biogas LHV; thus, it is emphasized that the thermal efficiency value found in this study is not necessarily a bad result, but proof that the system can be optimized to generate even more energy with the same amounts of biogas.

In addition, thanks to the difference in efficiency between this study and other works used as a model (GHOLIZADEH; VAJDI; MOHAMMADKHANI, 2019; HOSSEINI et al., 2016), it is evident that a considerable part of the energy developed by the system is generated during the cogeneration process, and is not a direct result of biogas combustion.

In short, the relatively low thermal efficiency of the system shows that an energy cogeneration process can be used to guarantee good results in the use of biogas as a fuel.

Considering the analyzes performed previously, the operation temperature of the biodigester was varied to analyze a possible variation in the efficiency of the system, resulting in Figure 10.

As in the previous cases, there is no difference between a swine or cattle herd.

In addition, a small difference in the efficiency of the system, when considering the variation of the biogas temperature, is noticeable. This occurs because the LHV value was calculated according to Eq. (25); then, as the biogas enthalpy is in the “reagents” portion of the calculation, the biogas enthalpy and the fuel LHV value are inversely proportional. However, as explained by Eq. (28), the biogas LHV and the efficiency of the system are also, in turn, inversely proportional, causing the increase in the operating temperature of the biodigester to increase the enthalpy of the final biogas mixture; thus causing a decrease in the value of LHV and ultimately increasing the overall system efficiency value.

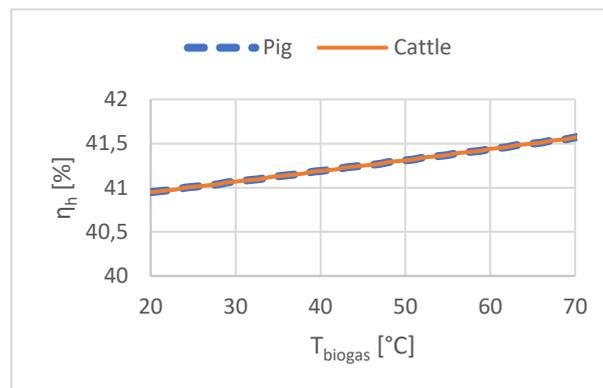


Figure 10. Thermal efficiency [%] developed by the system X production temperature of biogas [°C].

However, it is important to emphasize two other facts of this analysis. First, as the temperatures of the air at the entrance and the product at the exit of the combustion chamber were considered constant, any variation in the enthalpy of the biogas was minimized. This would not happen in a mathematical model that calculates the product temperature taking into account the combustion chamber inlet parameters.

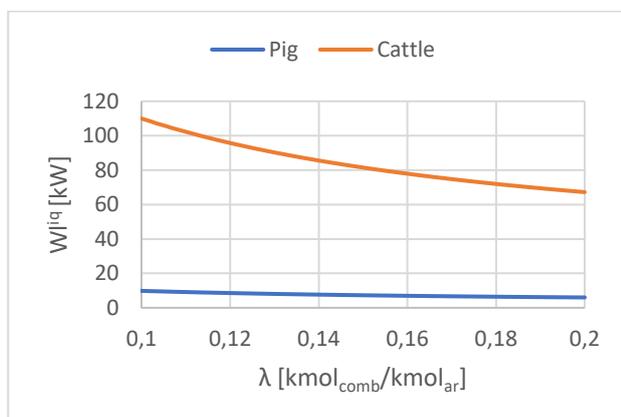


Figure 11. Net power [kW] developed by the system X Fuel-Air ratio [kmol/kmol].

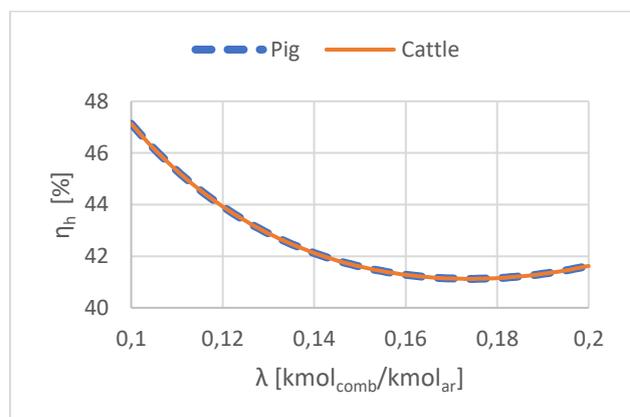


Figure 12. Thermal efficiency [%] developed by the X Fuel-Air Ratio [kmol/kmol] system.

Furthermore, the variation from 20 to 70°C of biogas (which in this case is already at the limit of the analysis allowed by Eq. (05)) resulted in a variation in efficiency of only 0.6%. Therefore, the influence of biogas temperature on system efficiency can be easily ignored since its effects are minimal.

Finally, the effect of the variation of the Fuel-Air ratio ($\bar{\lambda}$) on the thermal efficiency and on the net power production of the system was studied, resulting in the graphs shown in Figures 11 and 12.

Again, it is highlighted that there is no significant difference between the efficiency of swine and cattle herds, as shown in Figure 12. In addition, the cattle herd produced a much higher net power in Figure 11 for the same reasons discussed above.

Regarding the Fuel-Air ratio, it is observed that it presented a parabolic behavior. For small values of $\bar{\lambda}$, the smaller this ratio, the greater the net power and thermal efficiency of the system. However, the efficiency reaches a minimum value close to the ideal Fuel-Air condition (in the case $\bar{\lambda}$ equal to 0.172) and then goes up again. On the other hand, this behavior does not occur with the net power developed by the system; this has a higher value at low C/A ratios. Therefore, a mixture with excess air (a lower value of the Fuel-Air ratio) is advantageous, since the system will work more efficiently and generate more net power.

4. CONCLUSION

The entire study of biogas production showed promising and satisfactory results, proving that it is possible to generate large volumes of biogas from a relatively small amount of animals. However, as commented during the work, this whole process needs to be carried out experimentally to verify the results obtained. In addition, an empirical analysis would be necessary to resize all the constants used, bringing the results even closer to a reality that can be applied by local farmers.

On the other hand, the thermal process showed a lower thermal efficiency than other similar works. However, this does not necessarily represent a disadvantage, but an opportunity to optimize the system and generate more energy with the same amount of biogas.

It is noteworthy that the process of producing and burning biogas is not something seen as fundamental in Brazilian agriculture, especially for small producers. However, the presence of the biodigester generates an additional profit for farmers in addition to reducing the environmental impact of releasing large amounts of CH₄ without any type of treatment directly into the atmosphere. In this way, the presence of biodigesters in small to large farms can be a great investment, aiming to reduce waste, increase profit and minimize environmental impacts.

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6. RESPONSABILITY NOTICE

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