COMPUTATIONAL MODEL OF AN ELECTRIC POWER GENERATION SYSTEM BASED ON BIOGAS OBTAINED FROM CATTLE MANUREODELO

COMPUTACIONAL DE UN SISTEMA DE GENERACIÓN DE ENERGÍA ELÉCTRICA BASADO EN BIOGÁS OBTENIDO A PARTIR DEL ESTIÉRCOL DE GANADO

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Abstract

This paper proposes a model to estimate the electricity produced by biogas obtained from cattle manure. The amount of biofuel was obtained using the anaerobic digestion model No-1 (ADM1), while the electricity generation system is composed for a gas-microturbine, a synchronous generator, a rectifier/inverter, a controller and a lowpass filter. The proposed generation model was simulated using Matlab/Simulink®. The test scenario uses data from the municipality of Puerto Berrio (department of Antioquia), which is one of the regions of Colombia with the highest average livestock density (258 animals per farm). According to the simulations, a typical farm in Puerto Berrio can produce 9.3 m^3/day of manure. For this waste, a 590 m^3 is need, which can generate 123 m^3/day of biogas with a methane concentration of almost 50%. Finally, the biogas produced during 100 days is capable of supply 2952 kWh.

Keywords: ADM1, biogas, cow manure, gas-microturbine, MATLAB/Simulink®.

Resumen

Este artículo propone un modelo para estimar la electricidad producida por biogás obtenido del estiércol de ganado. La cantidad de biocombustible se obtiene usando el modelo de digestión anaeróbica No-1 (ADM1), mientras que el sistema de generación de electricidad está compuesto por una microturbina, un generador síncrono, un rectificador/inversor, un controlador y un filtro paso-bajo. El modelo de generación propuesto se simuló usando Matlab/Simulink®. El escenario de prueba emplea datos del municipio de Puerto Berrio (departamento de Antioquia), el cual es una de las regiones de Colombia con mayor densidad promedio de ganado (258 animales por granja). Según las simulaciones, una granja típica en Puerto Berrio puede producir 9.3 m^3/día de estiércol. Para este residuo, se necesita un biodigestor de 590 m3 que puede generar 123 m^3/día de biogás con una concentración de metano cercana al 50%. Finalmente, el biogás producido durante 100 días es capaz de suministrar 2952 kWh.

Palabras Clave: *ADM1, biogás, estiércol de vaca, MATLAB/Simulink®, microturbina de gas.*

1. Introduction

Biogas is a biofuel mainly composed of methane (CH_4) and carbon dioxide (CO_2), capable of partially replacing fossil fuels [Farret, 2010]. This fuel is produced by the anaerobic digestion (AD), a controlled process occurred in airtight reactors called biodigesters which transforms the organic matter (vegetable and fruit residues, food residues, manure of farm animals, seeds, agricultural waste and energy crops, among others) and biomass in biogas [Deublein, 2008). The biodigestor also produces a liquid sub-product called biol that works better than ordinary fertilizer.

The correct use of organic waste brings with it greater environmental and social benefits, since it reduces the emission of greenhouse gases generated by the bad disposal of waste. In addition, the biogas produced by the anaerobic treatment of residues can be transformed into thermal, mechanical or electrical energy, using different conversion systems. This conversion process can be used by homes, farmers and different industries in order to achieve its energy self-sufficiency and increase their economic income through the sale of surplus electrical energy to the grid (power distribution network).

This business plan can be applied by the agricultural industry, which is one of the main economic activities in different countries in Latin-America. In the special case of Colombia, one of the most representative subsector in agriculture is livestock, which currently has more than 28.2 million animals and produce around 570 tons of manure per day [ICA, 2020]. Nevertheless, to use biogas as a renewable energy source it is necessary to quantify the fuel produced by the reactor and later estimate its energy potential.

Among the tools used to estimate the biogas production, simple and complex mathematical models that represent the AD have been developed. One of the most relevant works in this area is the anaerobic digestion model No.1 (ADM1), which is based on the biochemical and physicochemical processes that arise between different types of microorganism. In addition, ADM1 considers the AD as a non-linear process, which depends on sequential and simultaneous threads that are mainly affected by variables such as temperature, Carbon/Nitrogen ratio and pH [Boe, 2006]; [Morales, 2017].

The ADM1 is the most referenced model in the literature because it can be used in any type of biodigester or with any organic matter. Thanks to this, the ADM1 can be applied under different conditions with slight variations in some of its parameters [Batstone, 2006]; [Donoso, 2011]. However, a good characterization of the input waste and the steady state substrate (organic matter) inside the reactor must be carried out in order to obtain reliable results about the production of biogas [Jeppsson, 2007].

Once the biogas is produced, it is possible to estimate its energy from its methane content and its calorific value. The biogas-electricity conversion process is one of the preferred ways to harness the chemical energy of the biofuel and it can be accomplished using technologies such as internal combustion engines (ICE), fuel cells and gas turbines [Deublein, 2008]; [Farret, 2010]. Although in most cases an ICE coupled to an electric generator can achieve efficiencies of up to 40%, this technology generates high emissions of greenhouse gases and it has high maintenance costs [Razbani, 2011]. In addition, these engines are more susceptible to the contaminants present in the biogas (traces of hydrogen sulfide and siloxanes) [Deublein, 2008].

On the other hand, fuel cells have the best conversion efficiency (above 70%), but they are still limited to experimental applications due to high investment costs and short service life [Weiland, 2010]. In contrast, gas turbines and gas microturbines have high reliability, high flexibility and they can be used with different types of fuel, from low calorific gases (such as the biogas) up to liquid fuels. This ability to adapt to different amounts of biogas without significantly affecting their performance, make gas turbine the ideal machine for fuels that are not homogeneous and whose composition varies according to the type of waste [Gupta, 2010].

Although the methods for the production of biogas and their applications are widely known in industrialized countries such as USA, Germany, Italy or China, the use of this biofuel as an alternative energy source has been poorly studied and documented in Colombia, even in comparison with some Latin American countries such as Brazil and Costa Rica. This is partly due to the high costs of implementing biogas-electricity conversion systems, the lack of experience and the lack of knowledge about the AD process [UPME, 2014].Taking into account the above, this paper proposes a computational model of an electric power generation system based on biogas. The model includes a first stage to estimate the biofuel obtained from cow manure using the ADM1. Later, a biogas-electricity conversion stage composed for a microturbine coupled to a synchronous generator is presented. Thus, the aim of this manuscript is to spread the knowledge about the AD and to show the potential of the biogas as a renewable energy source that can support the development of rural areas of Colombia in the post-conflict framework.

Materials and methods

The AD is a process susceptible to several operational parameters (temperature, pH, Carbon/Nitrogen ratio, among others), which often generates stability problems that can only be minimized by means of adequate control strategies [Lyberatos, 1999]. In general, these strategies require the development of mathematical models that are capable of estimating the behavior of AD within a wide range of operating conditions [Cendales, 2014]; [Husain, 1998]; [Zaher, 2005]. These models can simulate the operating conditions of the facilities on a laboratory scale or a pilot plant scale, minimizing the economic risk with a notable reduction in the time required to obtain results [Galí, 2009].

The first models of the AD process had a number of limited equations that allowed estimating the behavior of groups of microorganisms in general with simple kinetic rates [Cendales, 2011]. The next generation of models had a more complex structure based on several process such as hydrolysis, acidogenesis, acetogenesis and methanogenesis [Batstone, 2002]; [Bernard, 2001]; [Siegrist, 2002]. In these models, the stoichiometric relationships were defined. From these, it was possible to describe in detail the bioconversion processes of AD as well as the microbial growth rates and their inhibitions [Yu, 2013]. From these models, the most widely used and extended is the ADM1, which will be used in this work.

The anaerobic digestion model N° 1 (ADM1)

The ADM1 was presented by the International Water Association (IWA) in 2002 [Batstone, 2002]. This model was developed by several experts (review consensus) to describe the AD process and it provides a common basis for validating and comparing results obtained experimentally [Batstone, 2006]; [Morales, 2017]. In addition, the model allows developing control strategies and optimize the AD process. For these reasons, the ADM1 has become an important tool for scientific investigation and industrial applications [Batstone, 2002]; [Zaher, 2005].

The model uses as basis the chemical oxygen demand (COD) to emulate the different concentrations of biomass, allowing to relate the oxygen used, the organic substrate and the active biomass while maintaining the mass balance. In addition, the test to estimate the COD is fast and repeatable, making it easier to monitor the AD process [Díaz, 2003].

A basic scheme of the ADM1 is shown in figure 1, where q_{in} is the input flow, q_{out} is the effluent (output flow) and q_{gas} is the biogas flow (all of them in m^3/s). In its structure, the model is divided into a liquid phase and a gaseous phase which are related by means of transfer rates of liquid-gas mass ($\rho_{gas,T}$ in kg/m^3). The liquid phase brings together the concentrations of the physicochemical components of the input flow and those found inside the biodigester, while the gaseous phase groups the gases produced by the AD from the biomass inside the biodigester. In these phases occur biochemical and physicochemical reactions.

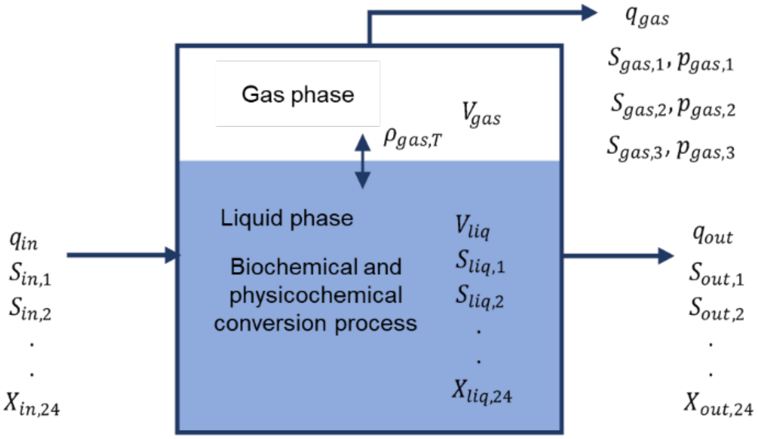


Figure 1 Scheme of the ADM1 in a single tank type biodigester.

In the biochemical reaction, the acidogenesis, acetogenesis and methanogenesis occur, including an extracellular disintegration and one-step of extracellular hydrolysis. On the other hand, the physicochemical reactions are divided into liquid–liquid reactions and gas-liquid exchanges. These reactions are used to describe the acid-base equilibria and the biological inhibition factors due to variations of the pH and the concentration of gases [Batstone, 2002]; [Rosen, 2008], figure 2 synthetizes the transformation process of biomass to biogas.

The ADM1 are divided into 26 state variables for the liquid phase and 3 variables for the gas phase (concentrations of methane - CH_4; carbon dioxide - CO_2; and dihydrogen - H_2) [Rosen, 2008]. Inside the model, each state variable has a mass balance represented by the equation 1, where m_x is the specific mass of the chemical or biological species (x) given in kg, $\dot{m}_{x,in}$ and $\dot{m}_{x,out}$ are the input and output mass flow rates in kg/s and $\dot{r}$ is the mass generation rate for each specie, also expressed in kg/s [Khanal, 2009].

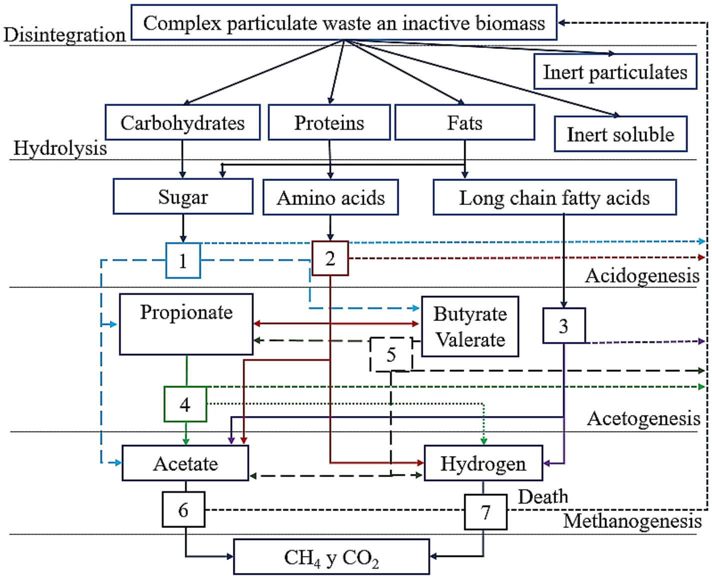


Figure 2 AD process including in the ADM1 [Morales, 2017].

$$\frac{dm_x}{dt} = \dot{m}_{x,in} - \dot{m}_{x,out} + \dot{r} \tag{1}$$

When the mass balance is applied to an anaerobic reactor with continued agitation, it can be assumed that the concentration of the effluent is equal to the concentration of the substrate inside the system (S_x). In this way, the mass balance described in equation 1 becomes the equation 2. In this expression, $S_{x,in}$ is the concentration of the chemical or biological species (x) expressed in kg/m^3 and $\dot{\rho}_x$ is the volumetric ratio of the mass generation in kg/m^{3}s. Using equation 2 is possible to know the concentration of the material (S_x) at any instant. However, it is valid under the following restrictions: (a) the liquid volume of the reactor ($V_{reactor}$ in m^3) does not change over time; and (b) the substrate mixture is homogeneous [Cendales, 2011].

$$\frac{dS_x}{dt} = \frac{q_{in}S_{x,in}}{V_{reactor}} - \frac{q_{out}S_x}{V_{reactor}} + \dot{\rho_x} \tag{2}$$

In order to calculate the mass balance, it is necessary to determine $\dot{\rho_x}$, which depends on various parameters such as inhibitions, mean values of the saturation constants, the rate of biomass production and the rate of microbial growth, among others. Furthermore, when the system reaches its steady state, the rate of change of the substrate (dS_x/dt) becomes zero and the equation 3 can be solved algebraically. On the other hand, if the balance is applied to a closed system with a initial concentration (Batch type biodigester), the equation 2 can be reduced to equation 4, where dS_x/dt will depend only from $\dot{\rho}_x$ [Cendales, 2011].

$$0 = \frac{q_{in}S_{x,in}}{V_{reactor}} - \frac{q_{out}S_x}{V_{reactor}} + \dot{\rho_x} \tag{3}$$

$$\frac{dS_x}{dt} = \dot{\rho_x} \tag{4}$$

A complete explanation about the ADM1, including a sensitivity analysis and several aspects to take into account during its computational implementation, are presented in [Morales, 2017].

Simplified solid waste co-digestion model (simplified ADM1)

One of the main difficulties during the ADM1 implementation is the correct characterization of waste. This situation has led several methodologies that simplify the model and improve its diffusion. Among these, the procedure proposed by Zaher for the characterization of the input substrate stands out [Zaher, 2009]. This method uses an interface based on the continuity of the state variables and a transformation matrix that allows to simulate dynamic changes in the input parameters. Using the simplified model is possible to obtain the 26 input variables of ADM1 from the conversion of 11 variables of the waste. These input parameters, and their units using the international system, are presented in table 1.

Table 1 Input data for the simplified model.

Variables of the waste	Nomenclature	Unit
Particulate COD	CODp	(kg COD/m^3)
COD soluble without volatile fatty acids	CODs AGV	(kg COD/m^3)
Volatile fatty acids	AGV	(kg COD/ m^3)
Total organic carbon	TOC	(kg C/ m^3)
Total organic nitrogen	Norg	(kg N/ m^3)
Total Ammoniacal Nitrogen	TAN	(kg AN/ m^3)
Organic phosphorus	TP orthoP	(kg P m^3)
Orthophosphate	orthoP	(kg P/ m^3)
Total Inorganic Carbon	TIC	(kmol HCO3/m^3)
Total alkalinity	Scat	(equ/ m^3)
Fixed solids	FS	(kg/m^3)

COD: *chemical oxygen demand*

On this way, using algebraic equations inside a matrix composed of stoichiometric coefficients, the simplified model transforms a set of measurements made to a substrate into the input vector of the ADM1 [Zaher, 2006]. These coefficients were defined to maintain the balance of charge inside the reactor and the COD for the macronutrients present in the model (carbon, hydrogen, nitrogen, oxygen and phosphorus). This reduction in the measurements, necessary to characterize the input waste, reduces the complexity during the ADM1 implementation.

The functionality of this transformation model was tested with 19 different types of waste. In those tests, positive transformation results (correlation > 88%) were obtained in the concentrations of proteins, lipids, carbohydrates and inert contents [Zaher, 2009]. Additionally, the simplified model offers the possibility of including several types of waste at the same time in order to carry out their simultaneous digestion (co-digestion) [Zaher, 2009].

Biogas-electricity conversion system

As mentioned in the introduction, there are several technologies that can be applied to harness the chemical energy of biogas and convert it into electricity. However, gas turbines and microturbines have the lowest investment costs, exhibit a low cost-per-kWh ratio (cost/kWh) and they can be used with different types of fuel, including biogas. For these reasons, the biogas-electricity conversion system (generation module) used in this work is composed for a gas microturbine coupled to a synchronous generator.

Considering that the generation module produces electricity at high frequencies, due to its high rotational speed (up to 100000 rpm), it is necessary to add a power electronics stage where the generated voltage is rectified and then converted to 60 Hz (alternating current). This is possible through an inverter modulated with PWM and a LC filter. The computational model of the turbine-generator-inverter-filter was implemented in MATLAB/Simulink® and it is shown in figure 3. In this figure, the turbine-generator module is highlighted using the dotted red rectangle, the rectifier and the PWM inverter are colored blue and the LC filter is marked with a purple square.

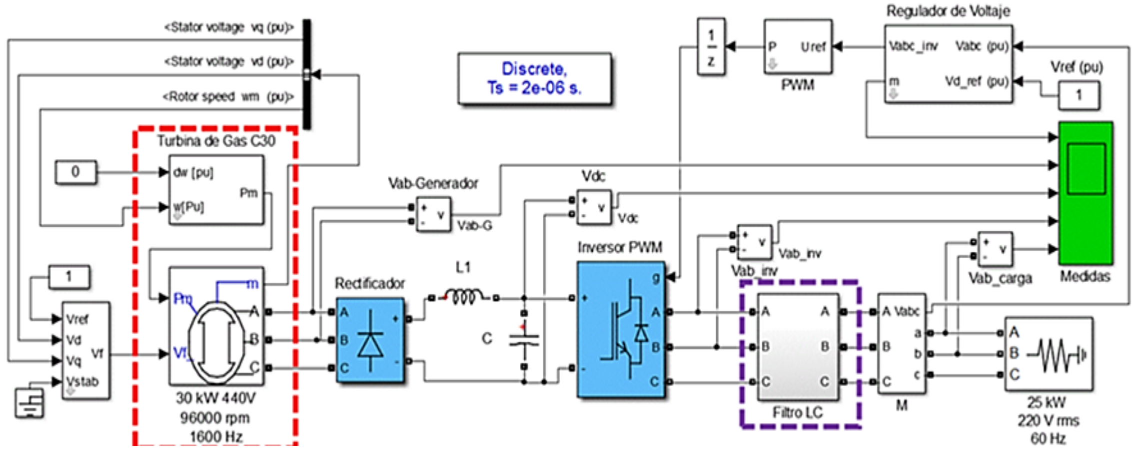


Figure 3 Model of the biogas-electricity conversion system.

During simulations, the microturbine was implemented based on the Rowen’s model [Bank, 2009]. In this model the generated torque, exhaust gases, fuel system, fuel consumption and mechanical power were taken into account. In addition, temperature and frequency control systems were included to keep the turbine operating within its limits (MAX and MIN). Figure 4 shows the complete model of the microturbine. In this case, the orange and green rectangles highlight the torque block and the temperature block, respectively. The first block depends on the constants A, B and C, while the second one is computed using the constants D and E. These parameters can be obtained using the methodology proposed by Bank et. al. in [Bank, 2009].

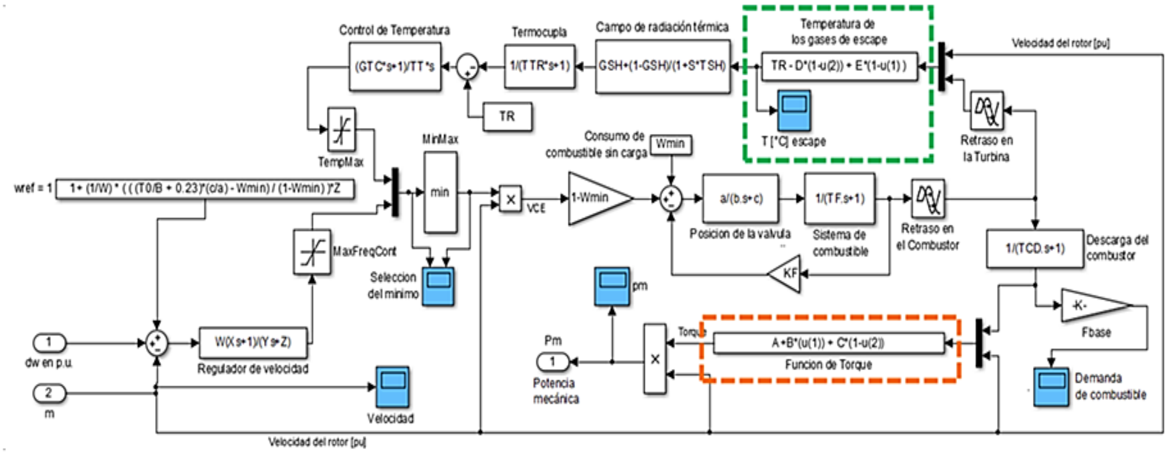


Figure 4 Model of the gas microturbine implemented in Matlab/Simulink® (Rowen's model)

2. Methods

In order to estimate the biogas produced from cattle manure (cow manure), and later the energy potential of the biofuel, a test scenario based on the characteristics of the Colombian cattle is proposed. First, according to the National livestock census 2020, presented by the Instituto Colombiano Agropecuario (ICA), the bovine population in the country is distributed in more than 655000 farms and totals 28.24 million of the animals. This production is led by the department of Antioquia with 3.18 million (11.3% of the total) [ICA, 2020].

Using the census information, it was possible to determine that the municipality of Puerto Berrio has one of the highest average livestock densities in Colombia with 258 animals per farm. In order to determine the production of manure produced by these animals, the methodology proposed by the Unidad de Planeación Minero Energética (UPME) was applied [UPME, 2003]. Following this process, a daily charge of 9.3 m^3 of manure was obtained. For this input flow, it is necessary a biodigester with an approximate volume of 590 m^3 of which 472 m^3 will be used to house the substrate and the remaining 118 m^3 will be used to store the biogas directly. As mentioned in section 2, the characteristics of the input waste are grouped into 26 variables necessary to apply the ADM1, including the input flow (in m3/ day) and the operating temperature of the system (generally 35 °C). However, using the simplified model, the ADM1 variables were obtained from the conversion of 11 parameters of the manure. These input parameters were taken from [Rosen, 2008]; [Zaher, 2009] and they are synthetized in table 2.

Table 2 Input data for the simplified model using bovine manure.

Nomenclature	Value	Unit
CODp	23550	($gCOD/m^3$)
CODs AGV	2521	($gCOD/m^3$)
AGV	1146	($gCOD/m^3$)
TOC	9339.6	(gC/m^3)
Norg	598	(gN/m^3)
TAN	284	(gN/m^3)
TP orthoP	187	(gP/m^3)
orthoP	32	(gP/m^3)
TIC	60.4	(mol $HCO3/m^3$)
Scat	60	(equ/m^3)
FS	5397	(g/m^3)

It is important to note that during the ADM1 implementation the input variables are divided into three groups:

- Characteristics of the input waste.
- Characteristics of the substrate.
- A set of stoichiometric, biochemical, physicochemical and physical parameters.

On the other hand, for the biogas-electricity conversion process, a Capstone C30 gas microturbine was selected. This module is composed by a turbine coupled to a permanent magnet generator (single pair of poles with a frequency of 1600 Hz). In addition, it has a high efficiency and it also supports small amounts of hydrogen sulfide (H_2S) that may be present in the biofuel. The operational parameters of the microturbine module are shown in table 3.

Table 3 Operational parameters of the Capstone C30 microturbine.

Parameter	Value	Units
Nominal power	30	kW
Output voltage	400-480	VAC
Frequency	50/60	Hz
Nominal speed	Up to 96000	rpm
Pressure ratio	4	-
Electrical efficiency	26	%
Exhaust gases	0.31	Kg/s
Exhaust gas temperature	275	°C
Heat rate	13.8	MJ/kWh
Specific fuel consumption	11	liters/hour
Compatible fuels	Biogas (landfill, biodigester)	

Note: parameters obtained under standard conditions

Since the compression and expansion processes are not isotropic, the efficiency of the biogas and the microturbine was estimated at 80%. In addition, it must be taken into account that the biogas cannot carry out a complete combustion since CO_2 occupies a space in the combustion chamber, although it does not provide energy. On the other hand, the parameters of the torque block and the temperature block inside the microturbine model (highlighted blocks in figure 4) were obtained using the methodology presented in [Bank, 2009]. These parameters and the remaining values for the microturbine model are presented in table 4. The physical quantities are expressed in per-unit (pu) and the temperature is given in Celsius degrees (ºC).

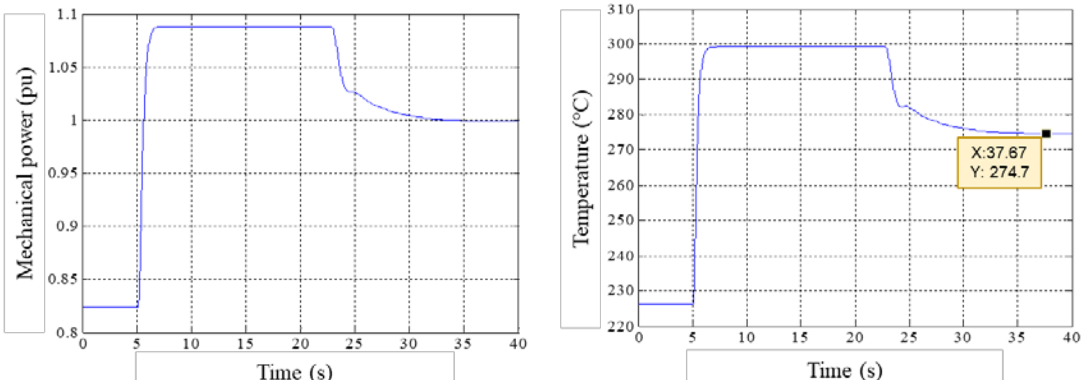
Table 4 Parameters of the microturbine.

Block	Parameters	Symbol	Value	Units
Torque	Constant A	A	-0.5277	-
	Constant B	B	1.5277	-
	Constant C	C	0.5	-
Temperature	Constant D	D	421.06	°C
	Constant E	E	165	°C
Fuel	Maximum limit	MAX	1.5	pu
	Minimum limit	MIN	-0.13	pu
Exhaust gases	Nominal temperature	TR	275	°C
Others	Compressor efficiency	ηc	0.8	-
	Turbine efficiency	ηt	0.8	-
	Generator power	S	0.030	MW

3. Results and discussion

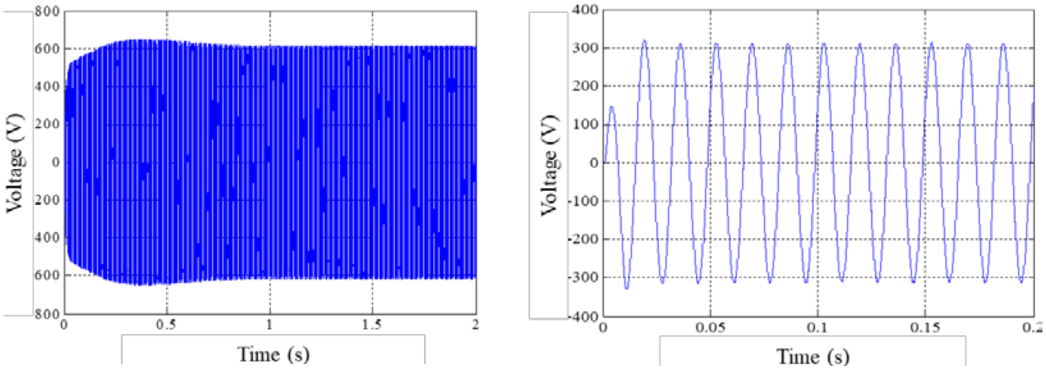
Using the input parameters presented in table 2, the biogas generated and its characteristics were obtained using a computer tool based on the ADM1. This tool was developed by the authors in Matlab/Simulink® based on the method described by Rosen and Jeppsson in [Rosen, 2008] and it can be reviewed in [Rodriguez, 2017]. For the estimated daily charge of manure (9.3 m^3/day), the biogas production was calculated taking into account a constant organic charge rate (stable behavior). Under this condition, the AD process inside the biodigester can generate 123 m^3/day of biogas with a combination of methane (47.8%), carbon dioxide (42.3%) and other gases (9.9%). Considering this methane composition, the biogas obtained from manure is flammable, can be used as fuel and its calorific value (heating value) is approximately 7.18 kWh/kg (25848 kJ/kg).

On the other hand, in order to verify the adequate operation of the microturbine control scheme, a test using a unit step of 0.9% was carried out. This scenario causes the system to exceed the maximum operating temperature. Figure 5 shows the response of the microturbine at steady state $t < 5$ [s] (mechanical power 0.825 p.u. and temperature 226 ºC) and its behavior with respect to the unit step applied at $t = 5$ [s]. At this time, the disturbance causes an increase in the temperature of the exhaust gases reaching 299.3 °C (see figure 5(b)). Subsequently, at $t = 22$ [s] the temperature control operates and the output mechanical power is reduced until the temperature returns to the reference value (275 °C). In addition, figure 6 shows the output voltage signal in the synchronous generator and the filtered output voltage after passing through the AC-DC-AC conversion stage (308 V-peak at 60 Hz).



a) Mechanical power *b) Temperature of exhaust gases*

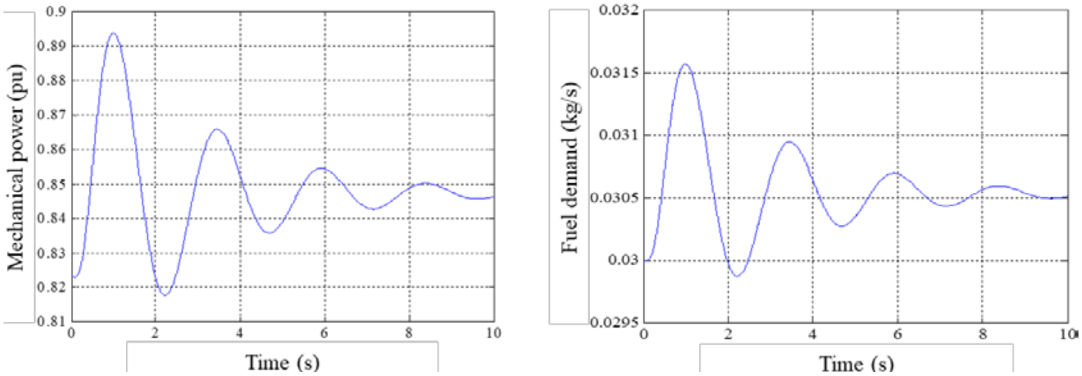
Figure 5 Microturbine response.



a) Output in the generator at 1600 Hz *b) Output at 60 Hz – load*

Figure 6 Voltage signals.

Once the model of the biogas-electricity conversion system has been configured (see figure 3), its performance was evaluated connecting a 24 kW three-phase load (80% of the generator power). In this way, the mechanical power and the fuel demand are shown in figure 7. It is observed that both parameters have an oscillatory response while the system overcomes the inertia of the generator and reaches its steady state. In this case, assuming that the microturbine works continuously, the fuel demand in the steady state region after the first 15 seconds (0.0305 kg/s) can be used to estimate the operating time of the microturbine.



a) Mechanical power in pu *b) Fuel demand*

Figure 1 Electricity generation system.

To estimate this time, the biogas can be converted to mass units (kg/day) using the density of the gases that compose it and following the method proposed in [Jeppsson, 2007]. For the case study, the biogas generated (123m^3/day) is mainly composed of 38.98 kg/day of methane and 95.69 kg/day of carbon dioxide. Subsequently, the total mass of biogas produced during 100 days (13467 kg) was divided by the fuel demand obtaining an approximated operation of 123 hours (441540 seconds). Finally, the biogas produced is capable of supplying an electric power of about 2952 kWh for the previous selected three-phase load (123 hours * 24 kW).

4. Conclusions

From the tests and results obtained in this paper, the following conclusions are presented:

- The ADM1 and its simplified model facilitate the design of biogas plants. In addition, their application allows to validate and improve energy projects in prefeasibility and feasibility stages. An example of this situation was shown through a case study with real information of the cattle subsector in Colombia (Puerto Berrio, Antioquia). For 258 heads of cattle, a daily charge of 9.3 m^3/day of manure and 123 m^3/day of biogas were obtained.

- A computational model for electricity generation from biogas was conducted using MATLAB/Simulink®. For a biogas concentration of 47.8% methane and 42.3% carbon dioxide, with a gas flow rate of 0.0305 kg/s for a gas microturbine (coupled to a synchronous generator) the energy obtained from the generation system was 2.95 MWh. This energy is enough to feed a 24 kW three-phase load during 123 h.
- It was shown that gas microturbines could be a good alternative for the biogas-electricity conversion process since they can work with this biofuel even if it has a methane content below 50%. Furthermore, using this type of technology represents a saving in the investment cost, since the gas turbines are more resistant to fuels that may have traces of hydrogen sulfide as is the case of biogas. This is even more relevant when microturbines are compared to other conversion technologies that require stricter filtration and purification stages for biogas.
- The simulation results show that the use of models for both the AD process and the biogas-electricity conversion process can be used to identify alternative energy sources. In addition, computational models allow to determine the potential for electricity generation using an adequate conversion technology. The above, without incurring previous expenses and avoiding the implementation of electricity generation systems based on trial and error tests.
- In Colombia, the use of biogas is a good energy alternative for rural regions or those zones without connection to the national interconnected system. Likewise, the exploitation of this biofuel offers an integrated solution to social, energy and environmental problems. It is important to highlight that there are agricultural industries in many countries that produce large amounts of manure and other residual biomass, which have a high energy potential when it is converted to biogas.

  The aim of this work, in addition to presenting a technical perspective to the biogas-based electricity generation systems, seeks to make visible the opportunity that Colombia (and other countries in the region) has in the development of systems of this type and its permanent inclusion in the country's energy matrix.

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