



COB-2021-2321

EXERGETIC ANALYSIS OF BRAYTON CYCLE POWER GENERATION USING BIOGAS AS FUEL

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Abstract. *The high environmental impact combined with the risk of future availability associated with fossil fuels has led to the search for partial or total substitution of these fuels, seeking new sources of energy that generate a low environmental impact and are renewable. In this context, fuels produced from biomass promise to be an important alternative, among them biogas, which is produced through the process of anaerobic digestion, this fuel can be an ideal substitute for natural gas, since it has good properties as a fuel due to its high percentage of methane. Natural gas has several applications in industry, for example, it is widely used in power generation in thermoelectric power plants. In this work, an exergetic analysis of the power generation process utilizing a gas turbine using bovine biogas as working fuel is carried out. For this purpose, a thermodynamic model of the process is developed in Aspen HYSYS software, in which the combustion process is calculated using the chemical equilibrium equations and the combustion chamber is considered adiabatic. The Peng-Robinson equations are used for the estimation of the properties and then the equations are programmed to calculate the exergy of all the flow lines of the system, subsequently using the exergy balance the exergy destroyed, and the energy efficiency of the process is calculated. Finally, to optimize the process, a sensitivity analysis is performed in which the air-fuel ratio and the pressure ratio of the turbine and compressor are varied, thus determining the impact of these variables on the efficiency of the process. The results shows that power generation using a Brayton turbine with biogas as fuels could be technically feasible. It was observed that to increase the exergy efficiency, it could be possible to work in an intermediate RC but increasing the RAF. From the study, it was observed that a biogas with a low methane concentration will need a higher RC.*

Keywords: Exergy, Brayton, biogas,

1. INTRODUCTION

Power generation is essential for development, but it is necessary to reduce the use of fossil fuels and greenhouse gas emissions (Santos, Barros e Tiago Filho 2016), being that in recent decades, energy consumption around the world is mainly based on carbon fossil fuels, accounting for more than 80% of the world's consumption today (Ghasemian et al., 2020). The excessive consumption of non-renewable energies has been a much-discussed issue, mainly due to the exaggerated use that contributes to deforestation, soil degradation, and especially pollution. Several consequences caused by these sources are well known to mankind, such as climate change and the consequent global warming of the planet, contributing to the greenhouse effect that has methane (CH₄) and carbon dioxide (CO₂) as its main villains. (Goldenberg et al., 2008). This is the situation that cannot continue for long, due not only the gradually dwindling reserves of fossil fuels, but also to the damage to the environment resulting from their use. Another factor is that the price of oil and its derivatives have reached historic records. Even if the world's economic growth continues, there are no prospects for their prices to decline significantly in the coming years. (Agência Nacional do Petróleo, Gás Natural e Biocombustíveis., 2012). Consequently, there has been a search for renewable energies with the objective of decreasing GHG emissions into the atmosphere, taking into consideration that the current forms of energy production from fossil fuels always have a negative impact on the environment (Brazil, 2009). Demonstrating the importance of alternative energy sources being necessary, especially renewable ones, we find, in this context, biogas, originating from anaerobic digestion becomes an important excellent for distributed energy generation (Santos, 2016). The biogas is produced from the anaerobic digestion of organic material and can be used to generate renewable energy (Santos, 2016), being a promising renewable fuel that can be produced from a variety of organic feedstocks and provide energy for a variety of uses (Lantz et al., 2007). Unlike other renewable energy, biogas has no geographical limitations, the technology required to produce energy from it is not complex or monopolistic (Taleghani and Kia, 2005). In this context, electric power generation with biogas is important. Another advantage is the decentralization of energy production in the proximity of large consumer centers, where waste and effluents predominate. Also coupling the growing need for renewable energy sources and decentralized energy generation near urban centers since they present lower transmission costs and losses. In this context, it becomes interesting the use of biogas (Santos, 2016). Biogas in general is composed mainly of methane, CH₄ (35-65%), carbon dioxide, CO₂

Table 1 describes each of the elements used in the development of the model.

Table 1. Description of model elements.

Item	Type	Description
Biogas	Matter line	Biogas feed
Air	Matter line	Atmospheric air
I-01	Equipment	Gas injector
C-01	Equipment	Compressor
Air-c	Matter line	Compressed air
Biogas-c	Matter line	Biogas at high pressure
CBR-01	Equipment	Combustion chamber
Lix	Matter line	Liquid line (zero mass flow rate)
Gas	Matter line	High pressure combustion gases
T-01	Equipment	Turbine
Gas combustion	Matter line	Low pressure combustion gases
RAF	Control element	Air-fuel ratio controller
RC	Control element	Compression ratio controller
P-P	Control element	Injection pressure controller (equal pressures)
Wi	Energy line	Work consumed in injection
Wc	Energy line	Work consumed in the compressor
Wt	Energy line	Work generated in the turbine

2.2 Exergetic Analysis

To perform the exergetic analysis it is necessary to calculate the exergy in each line of matter and energy in the system, for this purpose the physical and chemical exergies must be calculated independently and then the total exergy must be calculated by means of the following equation (1).

$$b_i = b_i^{ph} + b_i^{ch} \quad (1)$$

Where b_i^{ph} is the physical exergy and b_i^{ch} represents the chemical exergy of substance. The physical exergy is calculated by means of the enthalpy and entropy properties, in the studied state and in the reference state, as shown in the equation (2).

$$b_i^{ph} = h_i - h_0 - T_0 \cdot (s_i - s_0) \quad (2)$$

The chemical exergy equation for gases was used to calculate the chemical exergy, equation (3)

$$b_i^{ch} = \sum_k y_k \cdot b_k^{0ch} + R \cdot T_0 \cdot \sum_k y_k \cdot \ln(y_k) \quad (3)$$

Where y_k is the mole fraction of component k, R is the universal gas constant and b_k^{0ch} is the chemical exergy in the reference state, the values of which are shown in the Table 2.

Table 2. Chemical exergy in the reference state for the substances used in the model (Bejan, 2016).

Substance	Formula	b_k^{0ch} [kJ/kmol]
Methane	CH ₄	831650
Carbon dioxide	CO ₂	19870
Carbon monoxide	CO	275100
Oxygen	O ₂	3970
Nitrogen	N ₂	720
Water steam	H ₂ O	9500

Subsequently, the exergy destroyed in each element of the system is calculated, using the exergy balance shown in the following equation (4).

$$\psi = \sum \dot{m}_{in} \cdot b_{in} - \sum \dot{m}_{out} \cdot b_{out} \quad (4)$$

Finally, the exergetic efficiency of the power generation cycle is calculated, by means of the equation (5)

$$\eta_{ex} = \frac{W_t - W_c - W_i}{\dot{m}_{biogas} \cdot b_{biogas}} \quad (5)$$

2.3 Parametric analysis

The parametric analysis was carried out to determine the behaviour of the power cycle energy efficiency versus the change of the compression ratio, the air-fuel ratio, and the percentage of methane in the biogas, in Table 3 the restrictions imposed on the process input variables are shown.

Table 3. Variations of the model parameters.

Parameter	Minimum	Maximum
Compression ratio	5	15
Air fuel ratio	1	10
Methane fraction	30%	75%

3. RESULTS AND DISCUSSION

3.1 Exergetic analysis

The results of the exergetic analysis of the system are shown in Table 4. The exergy efficiency of the system is higher than those found by Barzegaravval et al. (2018) who found values of 28.3% in regenerative Brayton cycle with lower isentropic efficiencies in turbine and compressor.

Table 4. Exergetic analysis of the system.

Response variable	Value
Exergy efficiency	34.85%
Net power produced	176.3 kJ/mol-Biogas
Total exergy destroyed	126.9 kJ/mol-Biogas

Figure 2 shows the exergy destroyed distributed by elements, where the most exergy destroying element is the combustion unit, since it degrades the high energy available in the combustion, to convert it into enthalpy of the combustion gases at high temperature, this result was also reported by Barzegaravval et al. (2018) for the regenerative Brayton cycle.

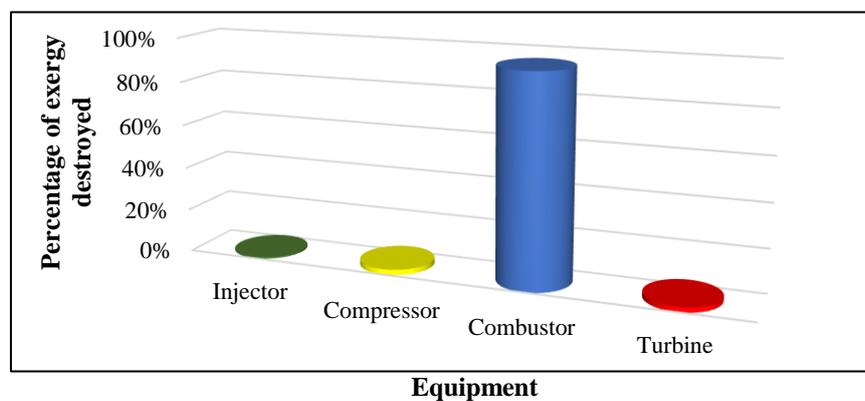


Figure 2. Distribution of destroyed exergy by element.

3.2 Parametric analysis

Figure 3 presents the variation of net power produced and exergy efficiency with respect to the mole fraction of methane in the biogas. It is observed that the power produced increases until reaching a maximum between 0.65 and 0.7 and thereafter decreases, this behavior is due to the fact that the increase in the proportion of methane also increases the amount of air required for combustion, so the compressor work increases and in turn also increases the work produced in the turbine and when reaching values of methane fraction above 0.7 the increase of work in the turbine is no longer significant compared to the increase in work consumed by the compressor, which generates a decrease in net work produced.

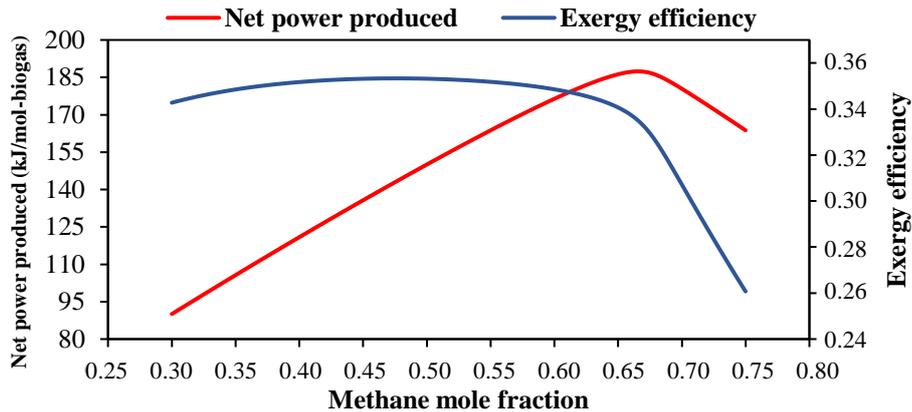


Figure 3. Impact of methane fraction on power and exergy efficiency.

As for the exergy efficiency it is observed that this increases up to values close to 0.5 and from there on it begins to decrease, this is because the increase in the amount of air required for combustion decreases the temperature of the flame in the combustion process. This effect was observed by Gholizadeh et al. (2019) in organic Brayton-Rankine combined cycle and by Yang et al. (2009) in experimental studies with microturbine of Brayton cycle. Figure 4 shows the combined effect of methane mole fraction and air-fuel ratio, where it is evident that the phenomenon described above occurs for methane fractions between 0.45 and 0.65 and air-fuel ratios (RAF) close to 9, which is equivalent to air excesses of 25% in that region.

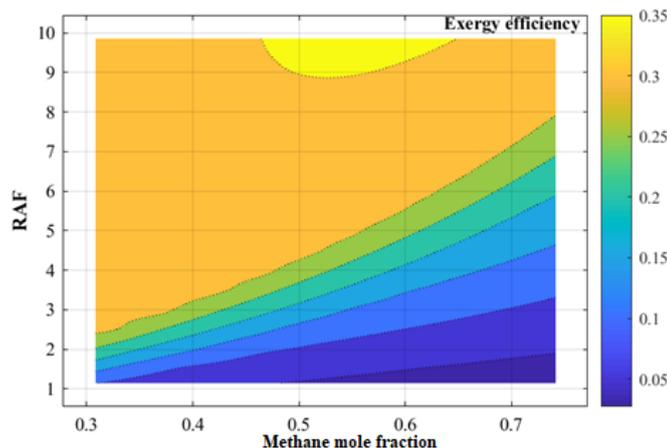


Figure 4. Impact of methane fraction and RAF on exergy efficiency

The combined effect of the compression ratio and the methane mole fraction is shown in Figure 5. The highest energy efficiencies are obtained with high compression ratios and low methane fractions, which can be explained by the fact that the increase in the compression ratio also increases the turbine inlet pressure, thus producing more work in the turbine. It should also be considered that carbon dioxide responds to pressure gradients with little variation in its enthalpy, so greater efficiency is obtained at low methane fractions and high CO₂ fractions.

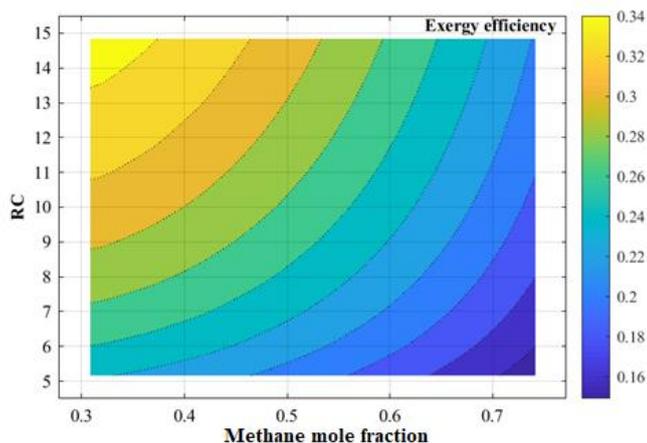


Figure 5. Impact of methane fraction and RC on exergy efficiency

On the other hand, when high compression ratios and high air-fuel ratios are handled, there is an increase in efficiency, as shown in Figure 6, this is due to the combined effect of increasing the mass of combustion gases entering the turbine and its high inlet pressure, which increases the work produced, it should be noted that by continuing to increase these parameters, a limit point will be reached where the increased work in the turbine is not sufficient to compensate for the increased consumption of the compressor so the efficiency will tend to decrease again, however, this effect was not reached at the limits of RC and RAF defined.

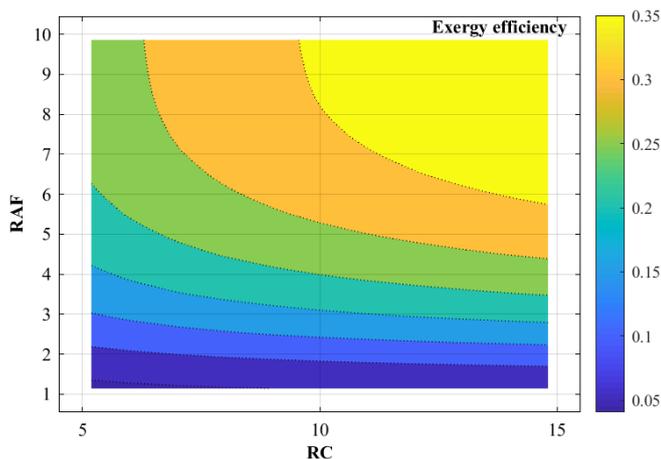


Figure 6. Impact of RC and RAF on exergy efficiency

After observing the combined impact of air-fuel ratio, methane mole fraction and compression ratio, superimposing the results shown in the contours, it is suggested for system operation, the point where the input parameters take the values shown in Table 5, together with the results obtained in the response variables.

Table 5. Recommended operating point for the system

Parameter		Value
Input variables	Compression ratio	15
	Air fuel ratio	10
	Methane fraction	66.40%
Output variables	Exergy efficiency	40.25%
	Net power produced	214.6 kJ/mol-Biogas
	Total exergy destroyed	141.8 kJ/mol-Biogas

At the defined operating point, there is an increase in efficiency of 15.49%, an increase in work produced of 21.72% and an increase in exergy destroyed of 11.74%. Figure 7 shows the new distribution of exergy destruction in the system components, where it is observed that the combustor continues to be the most exergy destroying element, however it goes from destroying 94.7% to destroying 92.9% of the total exergy destruction in the work cycle.

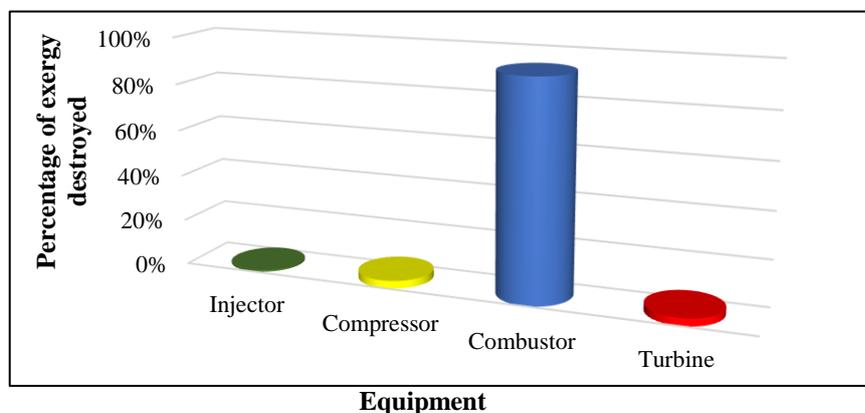


Figure 7. Distribution of destroyed exergy by element

4. CONCLUSIONS

An exergy analysis of a biogas-fired gas turbine cycle was developed, concluding that power generation using a Brayton turbine with biogas as fuels could be technically feasible. In addition, methane concentration has a significant effect on cycle performance. It was also observed that to increase the exergy efficiency, it could be possible to work in an intermediate RC but increasing the RAF. From the study, it was observed that a biogas with a low methane concentration will need a higher RC.

5. ACKNOWLEDGEMENTS

The authors would like to thank the National Council for Scientific and Technological Development (CNPq) (Processes – 439125/2018) and Coordination for the Improvement of Higher Education Personnel (CAPES).

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