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Exergoeconomic Analysis of a Syngas Micro Turbine Cogeneration System

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One of the main challenges in the chemical industry is to reduce dependence on fossil fuels and the emission of greenhouse gases through the use of renewable raw materials. The International Energy Agency (IEA) has identified biomass as the future technology to mitigate this effect, which can be achieved through the use of synthesis gases (Syngas) as fuel for the energy generation. On the other hand, the cogeneration systems using microturbine are appropriate technologies to take advantage of the energy available in exhaust gases that is generally wasted in conventional power generation systems. The article presents the energy and exergetic efficiencies analysis of the system, and the total costs in the generation of energy through the use of synthesis gas obtained by the gasification of sugarcane bagasse, native product of Colombia with compositions of carbon dioxide (13.7 %), carbon monoxide (13.7 %), water (10.7 %), hydrogen (13.91 %), oxygen (4.21 %), methane (4.12 %), and nitrogen (39.6 %). The physical and chemical properties of the system were calculated using the Matlab and Unisim software, allowing identifying through an exergoeconomic analysis the equipment where the greatest irreversibilities are presented. The results reveal that the increase of the compression ratio, improves the thermodynamic performance of the system. However, increasing the compression ratio of the compressor increases the rate of system costs per unit time. Moreover, rising of the outlet temperature of the preheater will be useful for the system in thermal and exergoeconomic terms. Finally, the higher exergy destruction were found out at the Combustion chamber

1. Introducción

Currently, the increasing energy demand and limited fossil fuels have promoted the exploitation and utilization of renewable energy sources (Wang et al. 2017). Biomass can be used as a clean, renewable and relatively abundant energy resource for electricity generation and another purpose (Athari et al. 2016). Among the various routes available for biomass-based energy generation, biomass gasification is one of the most important routes that are being studied extensively (Baruah & Baruah 2014). Biomass has a potential to be a very promising alternative source of raw material for syngas production (Ahmad et al. 2016). Syngas technology is one of a well-known alternatives process way to produce valuable chemical products (Glinwong & Wongchang 2017), and at the same time, as a viable source for energy applications, decreasing the use of fossil fuels and reducing the rate of greenhouse gases (Arvidsson et al. 2015). On the other hand, electric power generation systems play a fundamental role in industrial activities around the world (Issakhov 2016). Coal is still the major primary energy source for the production of electric energy with coal power plants producing globally more than 39% of the total electricity (International Energy Agency 2016). One of the most widely used alternatives in small-scale power generation is a Micro gas turbine, which operates under a Bryton thermodynamic cycle whose main objective is to transform the chemical energy of the fuel into mechanical work in the gas turbine (Soares 2015). However, this transformation process involves energy losses in the form of heat and an exergy destruction process that affects the exergetic performance on the plant (Cengel & Michael 2012).

The exergoeconomic analysis is a robust method that combines exergy analysis with economic studies (Lazzaretto & Tsatsaronis 2006; Bejan et al. 1995). Exergoeconomic theories have been applied to different energy system such as convectional power plants (Zhang et al. 2006) and energy generation systems from biomass (Athari et al. 2016; Klimantos et al. 2009; Soltani et al. 2013; Datta et al. 2010). Many researchers have developed various energetic and exergetic studies in cogeneration systems using synthesis gas, which have allowed to describe the characteristics of the system thermodynamically and also to identify potential opportunities for improvement in the process. Kraussler et al. (2017) presented an experimental work to produce a synthesis gas mixture from biomass to replace natural gas in industrial applications. Yao et al. (2018), assessed the production of synthesis gas and Biochar through a comprehensive fixed-bed gasification model to facilitate the optimization of the energy efficiency and economic viability of gasification systems. Athari et al. (2016) carried out an energy, exergy and exergoeconomic analyses of two proposed biomass integrated steam injection cycles and combined power cycles, assessed for similar sets of conditions. Soltani et al. (2013) investigated the application of gasification for electricity production via energy, exergy and exergoeconomic analyses for two configurations. Renzi et al. (2017) evaluated the performance of a gas microturbine fed by natural gas a biomass-derived synthesis gas.
In the present work, an exergoeconomic analysis is carried out for a cogeneration system using a gas microturbine, fed by pure methane and synthesis gas.

2. System description and Assumptions

The cogeneration system as shown in Figure 1 consists of a compressor that enters air at 25 ºC and 101.3 kPa, which is compressed up to 506.5 kPa at 224 ºC. The air is fed to a heat exchanger which carries its temperature up to 350 ºC, and then it is conducted to the combustion chamber where it reacts with the Syngas. The exhaust gases enter the turbine at 612 °C where it performs work to then continue to the heat exchanger, and finally, the gases are cooled using water to reduce their temperature. The thermodynamic model was developed based on some fundamental assumptions (Ahmadi & Dincer 2011), such as the processes are considered steady state, all components were considered adiabatic except the combustion chamber. The dead state conditions was P_o= 101.3 kPa and T_o= 293.15 K, and the air compositions was assumed as 21.12 % O_2, 78.82 % N_2, 0.3 % CO_2, and 0.3 % H_2O.

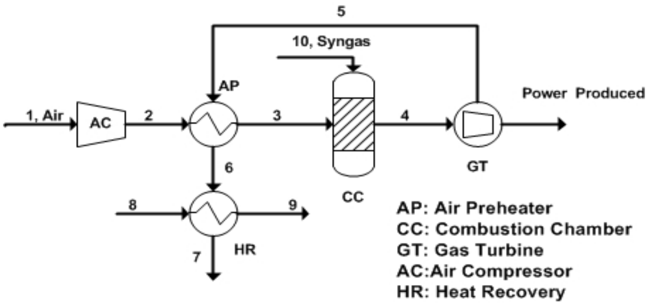

Figure 1: Schematic diagram of the cogeneration system

Heat loss from the combustion chamber (CC) was considered to be 2% fuel lower heating value (LHV), complete combustion for methane was assumed and for syngas was according to the following reaction, as shown in Eq (1) (Athari et al. 2016).

$$\begin{aligned} n_a H_2 + n_b CO + n_c CO_2 + n_d H_2O + n_e CH_4 + n_f N_2 + n_{air}(0.2112O_2 + 0.7882N_2 \\ + 0.0003H_2O0.0003CO_2) \rightarrow n_{CO_2} CO_2 + n_{H_2O} H_2O + n_{N_2} N_2 + n_{O_2} O_2 \end{aligned} \quad (1)$$

The Syngas composition used in this work is shown in Table 1, which was obtained by the gasification of sugarcane bagasse native product of Colombia (Cabrera 2012), and the compositions of polluting gases were not considered in this case study.

Table 1: Syngas Composition and LHV. Taken from (Cabrera 2012)

Molecule	CH_4	CO_2	CO	H_2	H_2O	O_2	N_2	Total mixture
Mole Fraction	4.12	13.7	13.7	13.97	10.7	4.21	39.6	100%
LHV [MJ/Nm^3]	-	-	-	-	-	-	-	4.69

The most important operating parameters of the cogeneration system using the Methane and Syngas as fuel are presented in Table 2.

Table 2: Main Operating Parameters of the System Cogeneration fed by Methane and Syngas

Descriptions	Methane	Syngas
Inlet Air Temperature [K]	298.15	298.15
Air Mass flow rate [kg/h]	1000	1000
Fuel Consumptions [kg/h]	11	240
Compressor Adiabatic Efficiency	0.85	0.85
Compressor Pressure Ratio	5	5
Inlet Air Combustion Chamber [K]	623.15	623.15
Inlet Turbine Temperature [K]	1085.15	1085.15
Turbine Pressure Ratio	0.2	0.2
Turbine Adiabatic Efficiency	0.85	0.85
Turbine Power Produced [Kw]	100	100

3. Thermodynamic Model

3.1 Exergy Analysis

Exergy can be divided into four components as shown in Eq (2). The physical and chemical exergy component were the two considered in this study, so the two other components which are kinetic exergy and potential exergy were assumed to be negligible (Bejan et al. 1995; Ahmadi & Dincer 2011).

$$\mathrm{E} = \mathrm{E}^{\mathrm{PH}} + \mathrm{E}^{\mathrm{KN}} + \mathrm{E}^{\mathrm{PT}} + \mathrm{E}^{\mathrm{CH}}, \tag{2}$$

and the physical exergy and chemical exergy are given as Eq (3) (Ahmadi & Dincer 2011).

$$\mathrm{E}^{\mathrm{PH}} = (\mathrm{h} - \mathrm{h}_0) - \mathrm{T}_0(\mathrm{S} - \mathrm{S}_0), \tag{3}$$

where h, s, and T are the enthalpy, entropy, and temperature respectively. Subscript 0 is referred to the environmental conditions. The mixture chemical exergy is defined as follow in Eq (4).

$$ex_{\mathrm{mix}}^{\mathrm{ch}} = \left[\sum_{\mathrm{i}=1}^{\mathrm{n}} \mathrm{X_i ex^{ch_i}} + \mathrm{RT_0} \sum_{\mathrm{i}=1}^{\mathrm{n}} \mathrm{X_i ln X_i}\right], \tag{4}$$

where R represents the universal gas constant, and $\mathrm{X_i}$ the molar fraction of the gas, and the term ex^{ch_i} were selected from a table of standard chemical exergies (Bejan et al. 1995).

3.2 Exergy destruction

In this paper, the exergy of each line was calculated at all states, and the changes in the exergy were determined for each component, according to Eq (5) (Bejan et al. 1995).

$$\frac{\mathrm{dE_{cv}}}{\mathrm{dt}} = \sum_{\mathrm{j}} \left(1 - \frac{\mathrm{T_0}}{\mathrm{T_j}}\right) \dot{\mathrm{Q}}_{\mathrm{j}} - \left(\dot{\mathrm{W}}_{\mathrm{cv}} - \dot{\mathrm{P}}_0 \frac{\mathrm{dV_{cv}}}{\mathrm{dt}}\right) + \sum_{\mathrm{i}} \dot{\mathrm{m}}_{\mathrm{i}} \mathrm{e_i} - \sum_{\mathrm{e}} \dot{\mathrm{m}}_{\mathrm{e}} \mathrm{e_e} - \dot{\mathrm{E}}_{\mathrm{D}}, \tag{5}$$

where the subscripts "i" and "e" denote inlet and outlet, respectively, the term $\frac{\mathrm{dE_{cv}}}{\mathrm{dt}}$ represent the time rate of change in the exergy of the volume control, the term $\dot{\mathrm{Q}}_{\mathrm{j}}$ represent the time rate of heat transfer, $\dot{\mathrm{W}}_{\mathrm{cv}}$ represent the time rate of energy transfer by work, $\frac{\mathrm{dV_{cv}}}{\mathrm{dt}}$ the rate of change of the control volume, and finally the terms $\dot{\mathrm{m}}_{\mathrm{i}}\mathrm{e_i}$ and $\dot{\mathrm{m}}_{\mathrm{e}}\mathrm{e_e}$ are related to the inlet and outlet mass exergy transfer.

3.3. Exergoeconomic Analysis: SPECO method

The SPECO method was applied to thermal system to investigate them from an economic point of view which is explained in more details (Bejan et al. 1995). The SPECO method is a systematic and general methodology for calculating efficiencies and costs in thermal systems. SPECO approach expresses the strongest possible effort in the direction of 'validating' the calculated cost values (Kalinci et al. 2012; Lazzaretto & Tsatsaronis 2006). A cost accounting in a company is concerned primarily with (i) determining the actual cost of products or services, (ii) providing a rational basis for pricing goods or services, (iii) providing a means for allocating and controlling expenditures, and (iv) providing information on which operating decisions may be based and evaluated. The natural gas price considered was 0.0038 \$ USD / kJ (Silveira & Tuna 2003) and the syngas price 10×10^{-6} \$ USD / kJ (Kalinci et al. 2012). The interest rate of the equipment was set to 10 %, the total working hours in a year was 7200 hours operating at maximum load, and the useful lifetime of the plant is 20 years. The main exergoeconomic balance of the system is shown in Table 3.

Table 3: Exergoeconomic balance (Bejan et al. 1995)

Component	Exergoeconomic Balance
Air Compressor	$\dot{C}_6 + \dot{C}_8 + \dot{Z}_{hrsg} = \dot{C}_7 + \dot{C}_9$; $\dot{C}_1 = 0$
Air Preheater	$\dot{C}_2 + \dot{C}_5 + \dot{Z}_{ph} = \dot{C}_3 + \dot{C}_6$ $\quad$ $\dot{C}_6\dot{E}_5 = \dot{C}_6 E_6$
Combustion Chamber	$\dot{C}_3 + \dot{C}_{10} + \dot{Z}_{cc} = \dot{C}_4$
Gas Turbine	$\dot{C}_4 + \dot{Z}_{gt} = \dot{C}_5 + \dot{C}_{11} + \dot{C}_{12}$ $\quad$ $C_5\dot{E}_4 = C_4\dot{E}_5$ $\dot{E}_{12} = \dot{W}_{12}$ $\quad$ $C_{11}E_{12} = C_{12}E_{11}$
Heat Recovery	$\dot{C}_6 + \dot{C}_8 + \dot{Z}_{hrsg} = \dot{C}_7 + \dot{C}_9$; $\dot{C}_8 = 0$; $\dot{C}_7\dot{E}_6 = \dot{C}_6\dot{E}_7$

4. Result and Discussion

Several case studies have been carried out to study the behavior of the system in terms of energy and exegetic efficiencies and costs. Figure 2a shows the total exergy by states when the fuel in the system is Methane and Syngas, where the highest rates of exergy are obtained in states 4 and 10. Likewise, according to Figure 2b, the highest rate of exergy destruction in both cases is located in the combustion chamber, which is related to the investigation results obtained by (Kohl et al. 2015; Ahmadi & Dincer 2011). The destruction rate of exergy in the combustion chamber represents 57.79 % and 71.41 % of the total system for the Methane and Syngas respectively. These high values are associated with irreversibilities such as reaction, heat transfer, and friction, which are present in the combustion chamber, this being one of the thermodynamically inefficient equipment (Bejan et al., 1995). It is also observed that the Heat Recovery is the second equipment with the highest rate of exergy destruction, being the heat transfer and friction the main source of irreversibilities.

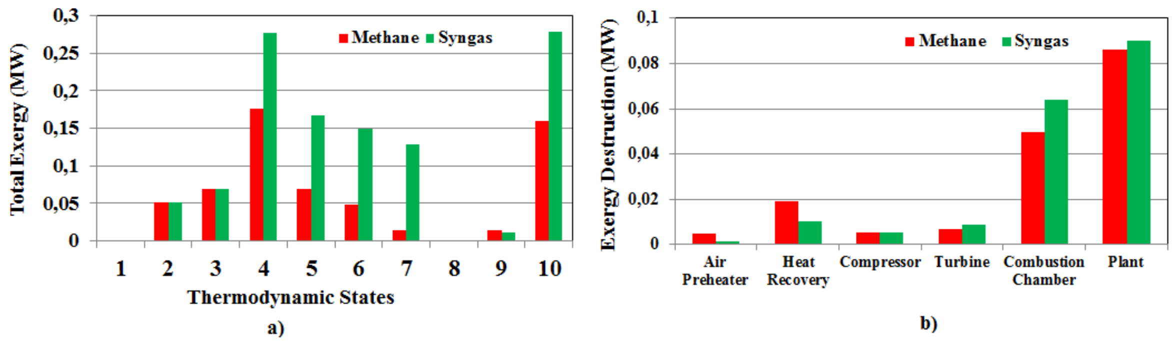

Figure 2: a) Total exergy for states, b) Exergy destruction by components

Figure 3a shows the variation in the cost of the system as a function of the Compressor Pressure ratio, where is observed for the lower value of pressure ratio than 4, the cost of the system tends to decrease, but for values higher than 4, the cost of the system increases. The increase in the compression ratio to 3.5 reduces the total cost of the cogeneration system per hour from 2.8 to 2.5 dollars per hour approximately as shown in figure 3a, behavior that is related to some works carried out recently (Soltani et al. 2013; Athari et al. 2016), which is explained because of the reduction of fuel required. In addition, with the increase in the compression ratio the exergy destruction rate in the system is reduced, and the flow of fuel consumed is reduced, meaning a total cost reduced in the operating system. When the compression ratio increases to more than 3.5, the rate of the total costs of the cogeneration system increases, since from this point the cost of the flows per unit time of the cogeneration system increase due to the increase in the compressor, becoming more significant than the cost reduction due to exergy destruction requirement.

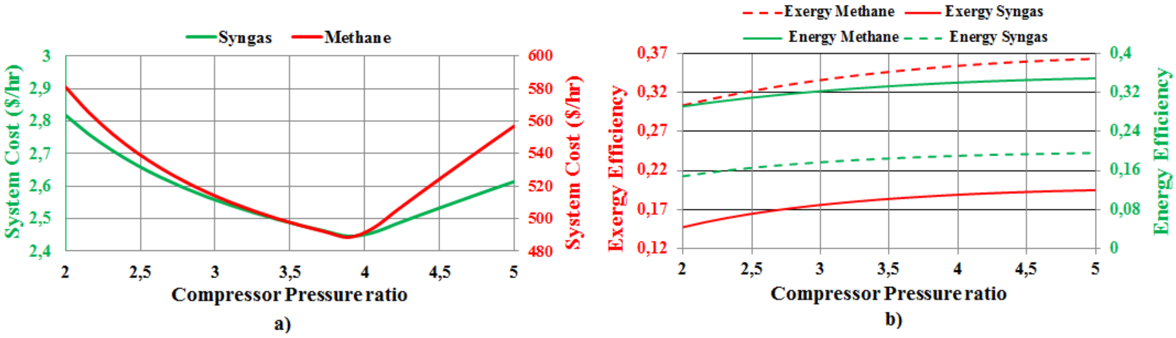

Figure 3: Effect of Compressor Pressure ratio on a) Cost of the system, and b) exergy and energy efficiency

The cost of the systems behavior when the methane and syngas are used as fuel is shown in Figure 4a, where is it observed a reduction on the total cost of the system as the inlet air temperature combustion chamber increase, which is related to the increase on the exergy efficiency and the high energy available in this thermodynamic state. In addition, the effect of the change in the inlet air temperature combustion chamber on the exergy and energy efficiency is shown in Figure 4b, where the increase in the temperature represents an enhancement in both efficciency for the methane and syngas fuels, improving the heat recovery in the heat exchanger from the combustion gases, and exergy required.

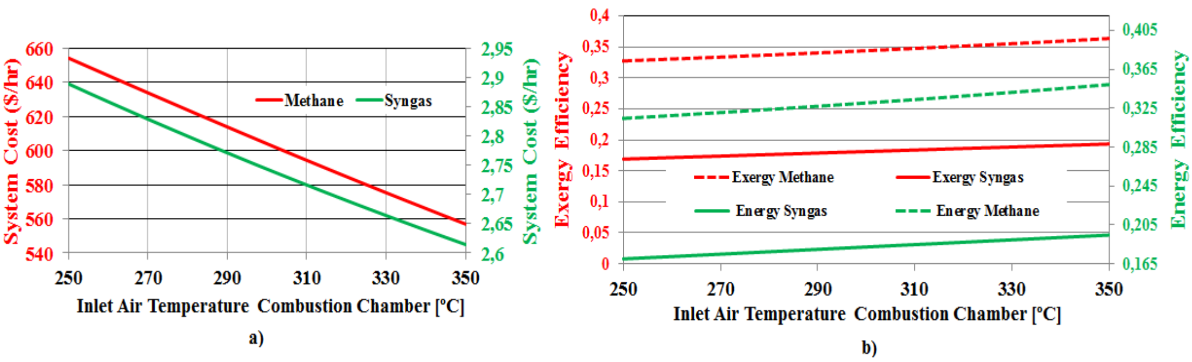

Figure 4: Effect of Inlet air Temperature Combustion chamber on a) system cost, and b) exergy and energy efficiency

5. Conclusions

As a conclusion, the highest exergoeconomic analysis rate costs were obtained for the compressor outlet flow, because of the exergy supplied to this flow is given by the mechanical compressor power. Also, the results show that increasing the compression ratio, improves thermodynamic system performance, however, increasing the compression ratio of the compressor increases the rate system costs per unit of time. Also, increasing the outlet temperature of the preheater is useful for the system in thermal and economic terms. On the other hand, the highest rate of exergy destruction was obtained in the combustion chamber, where all irreversibility sources are present. Finally, considering several air preheaters in series located at the combustion chamber inlet, the overall efficiency of the whole system improves as long as the cost of these preheaters does not exceed the reduction of the total cost of the fuel saved.

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