INGE CUC, Vol. 20, No. 1, Enero – Junio, 2024 (IN PRESS)

Análisis Exergético de la Generación de Vapor Integrada a Gasificación de Biomasa

Exergy Analysis of Steam Generation Integrated with Biomass Gasification

DOI: http://dx.doi.org/10.17981/ingecuc.20.1.2024.03
Artículo de Investigación Científica. Fecha de Recepción: 22/08/2022 , Fecha de Aceptación: 28/12/2022

Stiven Javier Sofan Germán https://orcid.org/0000-0002-2567-8243
University of Cordoba, Montería, Colombia.
ssofangerman@correo.unicordoba.edu.co

Jorge Mario Mendoza Fandiño https://orcid.org/0000-0001-5349-9958
University of Cordoba, Montería, Colombia.
Jorge.mendoza@correo.unicordoba.edu.co

Jesús David Rhenals Julio https://orcid.org/0000-0002-8975-8584
University of Cordoba, Montería, Colombia.
jesusrhenalsj@correo.unicordoba.edu.co

Julissa Jiménez López https://orcid.org/0000-0002-2892-0269
University of Cordoba, Montería, Colombia.
jjimenezlopez@correo.unicordoba.edu.co

Taylor de Jesús De la Vega González https://orcid.org/0000-0003-3533-0424
University of Cordoba, Montería, Colombia.
tdelavegagonzalez@correo.unicordoba.edu.co

To cite this paper

S. Sofan-German, J. Mendoza-Fandiño, J. Rhenals-Julio, J. Jimenez-Lopez & T. De la Vega-Gonzalez “Exergy Analysis of Steam Generation Integrated with Biomass Gasification” DOI: *http://dx.doi.org/10.17981/ingecuc.20.1.2024.03*

Resumen

Introducción: La biomasa es una fuente de energía que adquiere relevancia, ya que tiene alto potencial y produce bajo impacto medioambiental. La biomasa puede ser aprovechada procesos termoquímicos como la gasificación, la combustión y el pirólisis. La gasificación de biomasa es un proceso bien estudiado ya que permite la producción de gases combustibles con propiedades que dependen del agente gasificante utilizado. **Objetivo:** realizar un análisis exergético a la generación de vapor mediante la gasificación de residuos agroindustriales del maíz. **Metodología:** Primeramente, se realizó una caracterización de la biomasa para determinar sus propiedades. Luego se realizó un modelo computacional en Aspen Plus® del proceso de gasificación de biomasa. El modelo se realizó en estado estacionario y se tuvo en cuenta que todos los gases se comporten de manera ideal. **Resultados:** el modelo desarrollado estima un syngas con poder calorífico inferior (LHV) de 6.18 MJ/Nm^3, el cual posteriormente se inyectó a una caldera para la generación de vapor del sistema. Luego de esto se realizó un análisis exergético con los datos arrojados en la simulación, que arrojó como resultado que 14.37 kW son los utilizados en la generación de vapor, así mismo se determinó que la eficiencia exergética del sistema es de un 35%. **Conclusiones:** Se pudieron obtener datos teóricos de un sistema de gasificación acoplado a una caldera que permite generar vapor para su uso en diversas aplicaciones. Así mismo, se observa que gran parte de la energía que se produce no es utilizada, debido a perdidas e irreversibilidades del sistema.

Palabras clave

Energías Renovables, Gasificación, Biomasa, Aspen Plus, Análisis Exergético, Syngas, Irreversibilidades.

Abstract

Introduction: Biomass is an important energy source, as it has high potential and produces low environmental impact. Biomass can be harnessed thermochemical processes such as gasification, combustion and pyrolysis. Biomass gasification is a well-studied process as it allows the production of combustible gases with properties that depend on the gasifying agent used. **Objective:** perform an exergetic analysis of steam generation by gasification of agro-industrial corn residues. **Method:** First, a biomass characterization was performed to determine its properties. A computational model of the biomass gasification process was then performed in Aspen Plus. The model was made in a stationary state and it was taken into account that all the gases behave in an ideal way. **Results:** the developed model estimates a syngas with lower heating value (LHV) of 6.18 MJ/Nm^3, which was subsequently injected into a boiler for the generation of steam of the system. After this, an exergetic analysis was made with the data thrown in the simulation, which resulted in 14.37 kW are used in the generation of steam, likewise it was determined that the exergetic efficiency of the system is of 35%. **Conclusions:** Theoretical data could be obtained from a gasification system coupled to a boiler that allows generating steam for use in various applications. Also, it is observed that much of the energy that is produced is not used, due to losses and irreversibility of the system.

Key Words

Renewable Energies, Gasification, Biomass, Aspen Plus, Exergetic Analysis, Syngas, Irreversibility’s.

I. INTRODUCCIÓN

Biomass is a renewable energy source that is gaining participation in the global use in energy, and it is an alternative for fossil fuels due to its high availability and renewable nature. Among the most promising biomass sources for energy generation is the corn industry that generates corn cob as waste, which has a great energy potential that can be used as feedstock in gasification technology [1].

The role of biomass in thermal processes is highly recognized. Nonetheless, its application has limitations due to its high moisture content and low density. Therefore, agro-industrial waste is used to generate a large amount of biomass that was previously discarded. On the other hand, steam generation occupies a very important place and is used in industries ranging from power generation from turbines, preheating processes, drying and others [2]. Likewise, there is also a growing trend in the future to use biomass gasification for electricity generation, heat generation, steam generation, drying, etc.

Gasification is a thermochemical conversion process where a mostly solid substance is converted into a gaseous fuel called synthesis gas in a slightly oxidizing environment. This gas is mainly composed of a mixture of carbon monoxide (CO), hydrogen (H_2) and methane (CH_4), together with non-energy species such as carbon dioxide (CO_2) and nitrogen (N_2) [3]. Gasification technology gives the possibility of being configured as a transitional solution between renewable and non-renewable energies. This will allow a bridge between conventional energy sources and modern energy generation technologies. On the other hand, there is a benefit of taking advantage of the residual material whose management represents additional costs to agricultural activity. This ultimately becomes an alternative to the combustion of traditional fossil fuels, resulting in a mitigation of greenhouse gases released into the atmosphere [4].

Exergy destruction analyses have gained a significant importance in recent years as a tool to quantify useful energy losses due to thermodynamic irreversibility’s such as friction or heat transfer [5], [6]. Exergy analysis is based on the second principle of thermodynamics. Its application to the investigation of processes and systems makes it possible to propose engineering improvements to them and to make the implementation of resources more efficient. The estimation of exergy losses identifies the possible efficiency gains that can improve the process performance. Therefore, help to reduce the environmental impact [7]. In this work, an exergy analysis of steam generation by gasification of corn agro-industrial residues is carried out after performing a computational model using Aspen Plus software in order to calculate the exergy losses generated in these processes.

II. METHODOLOGY

A. *Physicochemical characteristics of corn cob*

Corn cob is a lignocellulosic residue from agroindustry that is generated in large quantities due to the existing demand for this product in the world. Particularly in the department of Córdoba in Colombia, where approximately 57 thousand tons of this biomass are generated per year [8]. In addition, this biomass presents good physicochemical characteristics for energetic use. For the analysis of the gasification process, the thermochemical characterization of the residual corn biomass was considered. The proximate and elemental analysis are shown in Table 1.

Characteristics	**Values**
C	46.59% P/p
H	5.97% P/p
N	0.51% P/p
O	44.81% P/p
Moisture	10.1% P/p
Fixed carbon	17.82% P/p
Volatile Material	80.06% P/p
Ash	2.12 P/p
Low heating value	18.56 MJ/kg

Table 1. Thermochemical characteristics of corn cobs [9].

Based on the literature review, the bulk density and particle size characteristics of corn stover were determined. Thus, the value 240 kg/m^3 was established for bulk density, with a particle size distribution as shown in Table 2, it could there are no particles with dimension greater than 63 mm, while the amount of fine particles (<8 mm) is significant [9].

Particle size distribution (% P/p)	
>63 mm	0.0
8-63 mm	75.1
3.15-8 mm	13.4
<3.15 mm	11.5

Table 2. Particle size distribution of processed corn cob [9].

B. Computational Model

The simulation model built integrates the zones of a Downdraft type fixed bed gasifier (drying, pyrolysis, oxidation, and reduction). It uses two-unit operations. A performance reactor, to simulate drying and pyrolysis and a Gibbs reactor for oxidation and reduction [10].

Considering authors [10], [11] and [12], the following considerations were taken into account::

- The model is in steady state and reaches equilibrium.
- All gases behave as ideal gases.
- Tars are assumed to be negligible in syngas.
- The residence time is long enough to reach thermodynamic equilibrium in the R-Gibbs block.
- There are no pressure losses in the system.
- Chars contain only charcoal and ash; the ash is inert and does not participate in chemical reactions.

The boiler was modeled using an equilibrium reactor to simulate combustion integrated with a heat exchanger for heat transfer, as shown in Figure 1.

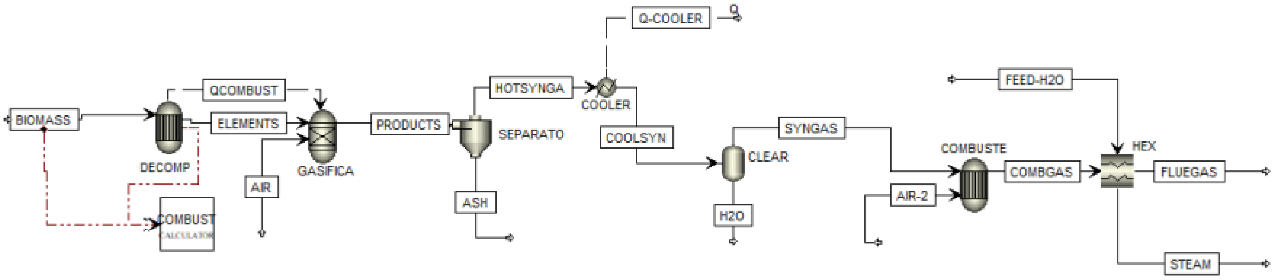

Fig. 1. Gasification and boiler process flow diagram at Aspen Plus ®.

Biomass is specified as a non-conventional component in the Aspen Plus® software and is defined by its properties. Likewise, a yield reactor was used to model devolatilization using a break-up algorithm programmed in Fortran according to [13]. The enthalpy and biomass density were estimated by both, the HCOALGEN and DCOALIGT models [14], [15]. In addition, the ashes which are considered as non-reactive and non-conventional solids. On the other hand, Robinson equations of state with Boston - Mathias (PR - BM) modifications are used for the estimation of properties of conventional species present in the process [16], [17].

For the simulation setup, unit operations were taken into account, which are shown in Table 3, as well as the names assigned to them and the function of each operation.

Default ID	Assigned ID	Description
RYield	DECOMP	Decomposing unconventional biomass into conventional components.
RGibbs	GASIFICA	Simulates reactions between conventional components by means of Gibbs free energy minimization and chemical equilibrium constraint.
	COMBUSTE	Simulates the boiler combustion chamber.
SSplit	CYCLONE	Separates solids from hot gases.
Flash2	SEPARATO	Separates water from cold synthesis gas to remove moisture.
Heater	COOLER	Cool the hot syngas to room temperature to remove moisture.
MHeatX	HEX	Simulates the exchange of hot gases and water to produce steam.

Table 3. List of unit operations used in the flow chart in Aspen Plus ®. Fuente: [18].

C. *Exergetic Analysis*

The following considerations were taken into account in the exergy analysis [19].

- The gasifier operates at steady state.
- Potential and kinetic energies are negligible.
- The reference state was considered as (P_o = 1 atm y T_o = 293,15 K).
- The synthesis gas is assumed to be an ideal gas.

The total energy includes three parts: the energy induced by the mass flow, the work exchanged with the exterior and the energy lost to the environment [20]. Therefore, the energy balance can be expressed as shown in equation 1.

$$\dot{En}_{in} + \dot{W}_{in} = \dot{En}_{out} + \dot{Q}_1 \qquad (1)$$

Where:

$\dot{En}_{in}$ is the energy rate of the system at input, kW.
$\dot{W}_{in}$ is the work rate, kW.
$\dot{En}_{out}$ is the energy rate of the system at output, kW.
$\dot{Q}_1$ is the rate of heat exchanged with the ambient environment, kW.

Thus, the energy efficiency of a component or system is defined as the ratio between the useful energy and the energy supplied, which is defined according to equation 2 [20], [21].

$$\eta_{En} = \frac{\dot{En}_{out}}{\dot{En}_{in}} \qquad (2)$$

The total exergy transfer through the control volume was calculated for all material and energy lines [22], as shown in Equation 3.

$$\dot{Ex}_{system} = \dot{Ex}_{material} + \dot{Ex}_{heat} + \dot{Ex}_{work} \qquad (3)$$

Where:

$\dot{Ex}_{system}$ is the exergy of the system.
$\dot{Ex}_{material}$ is the exergy of the currents of material.
$\dot{Ex}_{heat}$ is the exergy of the heat flow.
$\dot{Ex}_{work}$ is the work exergy.

The exergy of the material is formed by a chemical and a physical component, as shown in Equation 4.

$$\dot{Ex}_{material} = \dot{Ex}_{ph} + \dot{Ex}_{ch} \qquad (4)$$

Where $\dot{Ex}_{ph}$ is the physical exergy and $\dot{Ex}_{ch}$ is the chemical exergy which are defined according to equations 5 and 6 respectively [22].

$$\dot{Ex}_{ph} = \dot{m}[(h - h_0) - T_0(s - s_0)] \qquad (5)$$

$$\dot{Ex}_{ch} = M\left(\sum_{i}^{n} x_i ex_{ch,i} + RT_0 \sum_{i}^{n} x_i \ln(x_i)\right) \qquad (6)$$

Where:

$ex_{ch,i}$ is the standard chemical exergy of the stream components as shown in Table 4.
x_i is the mole fraction of the stream components.
R is the universal gas constant [23].

Component	Standard chemical exergy (kJ/mol)
$O_2(g)$	3.97
CO (g)	275
$H_2(g)$	236.09
$N_2(g)$	0.72
$CO_2(g)$	27.9
$H_2O\ (l)$	0.9
$H_2O\ (g)$	9.5
H_2S (g	812
$CH_4(g)$	831.65
$SO_2(g)$	313.4
S (g)	609.6
C (s)	410.26

Table 4. Standard chemical exergy of some components [24].

For biomass, the chemical exergy was estimated by equation 7.

$$\dot{Ex}_{biomass} = \dot{m}_{biomass} * \beta * LHV_{biomass} \qquad (7)$$

Where:

$\dot{m}_{biomass}$ is the mass flow of biomass.
β is given in terms of the oxygen-to-carbon and hydrogen-to-carbon ratios as shown in equation 8.
$LHV_{biomass}$ is the lower heating value of the biomass.

$$\beta = \frac{1.0414 + 0.0177(H/C) - 0.3328(O/C)[1 + 0.0537(H/C)]}{1 - 0.4021(O/C)} \qquad (8)$$

Where O, H and C are the percentages by weight of oxygen, hydrogen and carbon present in the biomass obtained from the final analysis.

The exergy of the flow of the heat lines was estimated by means of equation 9 [22], [25].

$$\dot{Ex}_{heat} = Q * \left(1 - \frac{T_0}{T}\right) \qquad (9)$$

The exergy efficiency was determined for each subsystem by means of the equation 10 [26].

$$\eta_{Ex} = \frac{exergy\ products}{Total\ exergy\ input} = \frac{\dot{Ex}_{out}}{\dot{Ex}_{in}} \qquad (10)$$

The exergy balance allowed estimating the exergies destroyed in the system, as shown in Equation 11 [20]:

$$\dot{Ex}_{in} + \dot{W} = \dot{Ex}_{out} + \dot{Ex}_{heat} + \dot{Ex}_{d} \qquad (11)$$

Where:

$\dot{Ex}_{d}$ is the destroyed exergy of the system or component.

III. RESULTS

The computational simulation for the gasification process allowed estimating the chemical components that make up the syngas, as shown in Table 5.

COMPONENT	MOLAR FRACTION
N_2	0.492
CO	0.030
CO_2	0.114
CH_4	0.086
H_2	0.252

Table 5. Molar fractions of syngas obtained at Aspen Plus ®.

A volumetric flow rate of 152.4 m^3/h of clean syngas with a LHV$_{syngas}$ of 6285.85 kJ/kg and a molecular weight of 23.95 kg/kmol was obtained.

Table 6 shows the input and output energies of the process, as well as the thermodynamic temperature conditions at a pressure of 1 atm.

COMPONENT	MASS FLOW (kg/s)	LHV (kJ/kg)	h (kJ/kg)	E (kW)	T_i (°C)	T_f (°C)
BIOMASS	0.0225	17330	4334.3	512.12	-	-
AIR	0.0311	-	513.55	15.98	25	515.52
PRODUCTS	0.0437	5478.86	-	239.64	-	-
QCOOLER	-	-	-	48.09	-	-
SYNGAS	0.0381	6285.85	2769.69	345.23	-	-
H_2O	0.0056	-	0	0	25	25
AIR-2	0.0481	-	1220.15	58.63	25	1229.19
FEED-H_2O	0.0472	-	649.48	30.67	25	182.67
FLUEGAS	0.0862	-	1332.22	114.81	1229.19	119.85
STEAM	0.0472	-	304.31	14.37	25	182.67

Table 6. Input and output energies of the gasification system.

Where:

T_i is the inlet temperature of each component.
T_f is the output temperature of each component.
E is the energy produced by each process line.

From the exergy balance of the gasification subsystem, the exergy values for the different mass and heat streams were obtained as shown in Table 7.

STREAM	$Ex_{ph}(kW)$	M (mol/s)	$Ex_{ch}(kW)$	$Ex_{material}(kW)$
BIOMASS	0	0	458.67	458.67
AIR	0	1.078	0.14	0.14
PRODUCTS	15.07	2.044	242.92	257.99
QCOOLER	29.92	0	0	29.92
SYNGAS	0	1.732	241.4	241.4
H_2O	0	0.312	0.28	0.28
AIR-2	0	1.666	0.21	0.21
FEED-H_2O	0	2.621	2.36	2.36
FLUEGAS	2.88	3.346	101.87	104.75
STEAM	25.36	2.621	2.36	27.72

Table 7. System input and output energies.

A. Gasifier and boiler efficiency

For the calculation of the energy efficiency, the different energies entering and leaving the gasification and boiler subsystem are taken into account according to Table 6. Now, for the gasification subsystem, the energy efficiency is calculated by equation 2 as follows:

$$\eta_{En}=\frac{\dot{En}_{out}}{\dot{En}_{in}}=\frac{\dot{En}_{Syng}}{\dot{En}_{biom}+\dot{En}_{air}}=\frac{345.30}{528.10}=0.6538$$

This means that the energy efficiency of the gasification subsystem is of 65.38%.

Likewise, the energy efficiency of the boiler subsystem is:

$$\eta_{En}=\frac{\dot{En}_{out}}{\dot{En}_{in}}=\frac{\dot{En}_{flue}+\dot{En}_{Steam}}{\dot{En}_{Syng}}=\frac{129.18}{345.30}=0.3741$$

This means that the energy efficiency of the boiler subsystem is of 37.41%.

To calculate the exergy efficiency, the different physical and chemical exergies entering and leaving the gasification and boiler subsystem are considered according to Table 7. The exergy efficiency and destruction exergy of each subsystem are calculated, which are defined by Equation 10 and 11, respectively.

Now, for the gasification subsystem, the exergetic efficiency and the exergy destroyed are:

$$\eta_{Ex}=\frac{exergy\ products}{Total\ exergy\ input}=\frac{\dot{Ex}_{out}}{\dot{Ex}_{in}}=\frac{\dot{Ex}_{COOL}+\dot{Ex}_{H_2O}+\dot{Ex}_{Syng}}{\dot{Ex}_{biom}+\dot{Ex}_{air}}=\frac{271.6}{458.81}=0.5919$$

$$\dot{Ex}_d=\dot{Ex}_{in}-\dot{Ex}_{out}=458.81-271.6=187.21\ kW$$

Thus, the exergy efficiency of the gasification subsystem is 59.19% with a destroyed exergy of 187.21 kW, due to the irreversibility's of the subsystem.

Now, for the boiler subsystem, the exergetic efficiency and the exergy destroyed are:

$$\eta_{Ex}=\frac{exergy\ products}{Total\ exergy\ input}=\frac{\dot{Ex}_{out}}{\dot{Ex}_{in}}=\frac{\dot{Ex}_{flue}+\dot{Ex}_{Steam}}{\dot{Ex}_{Syng}+\dot{Ex}_{air-2}+\dot{Ex}_{feed}}=\frac{132.47}{243.89}=0.5431$$

$$\dot{Ex}_d=\dot{Ex}_{in}-\dot{Ex}_{out}=243.89-132.47=111.42\ kW$$

Thus, the exergy efficiency of the boiler subsystem is 54.31% with an exergy destroyed of 111.42 kW, due to the irreversibility's that the subsystem presents.

With this, it is evident that the exergy destroyed in the gasifier is much higher than in the boiler. The reason in that in the gasifier the reactions that take place internally generate greater irreversibility's compared to the reactions that take place in the boiler zone.

B. Efficiency of the system

The energy and exergy efficiencies of the entire system were calculated, taking into account the physical and chemical energies, as well as the heat energies found in the control volume.

For the energy efficiency, after performing an energy balance of the system, the energies for the input and output streams were determined, thus the energy provided was 495.21 kW.

Now, taking into account the results of table 6, the energy efficiency of the system is calculated with equation 2:

$$\eta_{En}=\frac{\dot{En}_{out}}{\dot{En}_{in}}=\frac{177.27}{495.21}=0.3579$$

With this we have that the energy efficiency of the system is 35.79%, which indicates that the system in general has losses in the different subsystems it has.

From table 7, we calculate the exergy efficiency and the exergy of destruction of the system, which are defined by equations 10 and 11, respectively.

$$\eta_{Ex}=\frac{exergy\ products}{Total\ exergy\ input}=\frac{\dot{Ex}_{out}}{\dot{Ex}_{in}}=\frac{162.67}{461.38}=0.3526$$

$$\dot{Ex}_d = \dot{Ex}_{in} - \dot{Ex}_{out} = 461.38 - 162.67 = 298.7\ kW$$

Thus, the cycle exergy efficiency is 35.26% with a destroyed exergy of the whole system obtained through a system exergy balance of 298.7 kW.

Figure 2, which depicts a Sankey diagram, allows us to see the amount of energy entering the system, the exergy, the useful exergy and the destroyed exergy of the whole system.

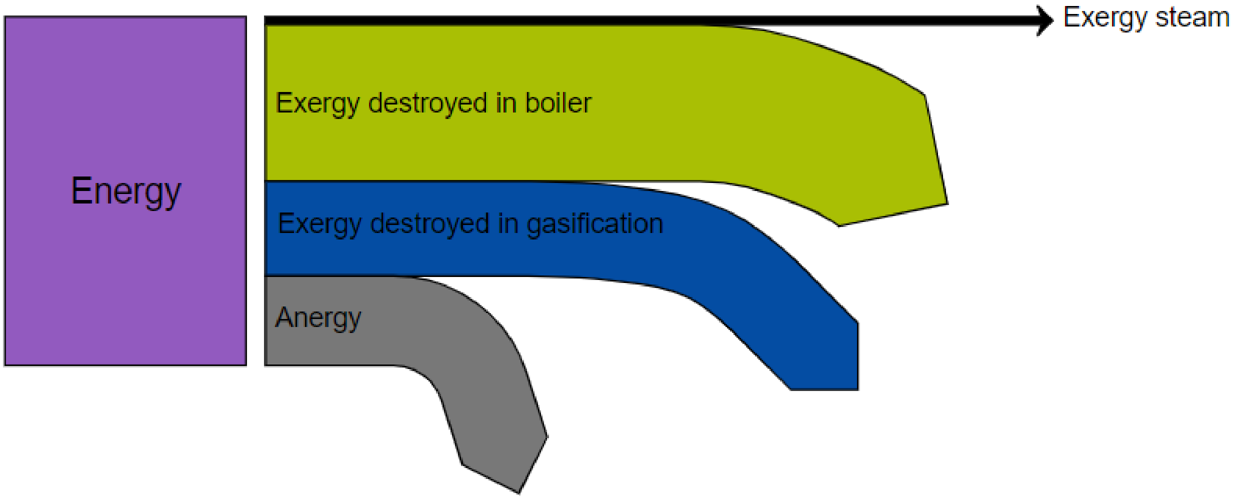

Fig. 2. Sankey diagram of the process.

C. *Sensitivity analysis*

A variation of the ER (Equivalent Ratio) versus the mole fractions of the components is made in order to see their behavior with the increase of the air flow in the RGibbs reactor. For the sensitivity analysis, this ratio was varied from 0.18 to 0.5 and also the corresponding air flow variation.

The data were entered into the sensibility tool of the Aspen Plus® software, shown in Figure 3. It shows the relationship with the various chemical species that make up the syngas. Then, the equivalent ratio (ER) used was determined and has a value of 0.259.

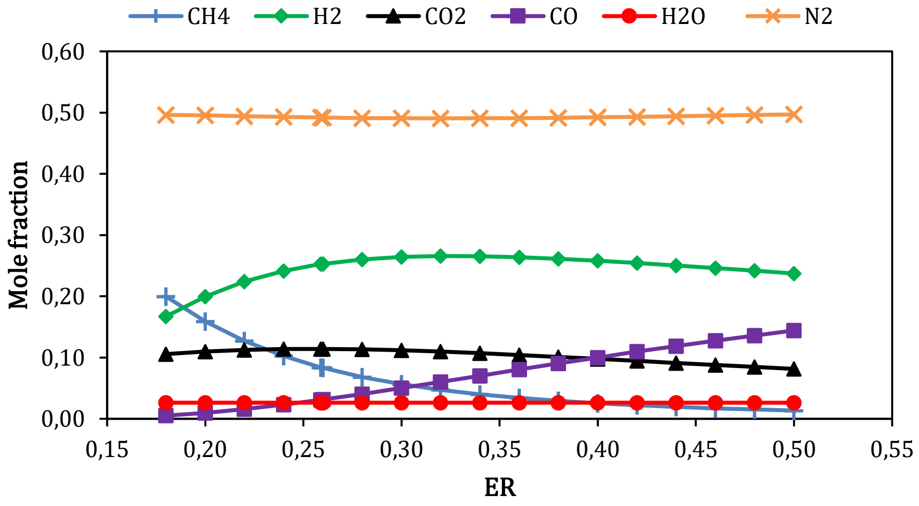

Fig. 3. Air mass flow vs. Syngas mole fractions.

Figure 3 shows the different components such as CH_4. It is noticed that decreases noticeably when the ER increases. For H_2, it is observed that when the ER increases, its mole fraction also increases and reaches its maximum value of mole fraction at an ER = 0.32. On the other hand, for CO_2, it is observed that its mole fraction value is around 0.1. However, as the ER increases this value begins to decrease slowly. For CO, a proportional behavior is observed, as the ER increases so does its mole fraction. Finally, for N_2, it could be concluded that its behavior remains almost constant with slight drops as the ER increases. However, towards the final values it recovers its initial value.

A review of the efficiency of the subsystems is carried out as shown in Figure 4. The sensitivity analysis is applied to the syngas stream, which is common to both systems. The exergy efficiency of the gasifier decreases as the equivalent ratio (ER) increases, the opposite being the case for the exergy efficiency of the boiler, which shows a considerable increase. The exergy destroyed in the gasifier increases as the ER also increases, this is because the increase of air causes a greater amount of internal chemical reactions in the gasifier. Thus, a greater amount of irreversibility's is generated and therefore the efficiency decreases.

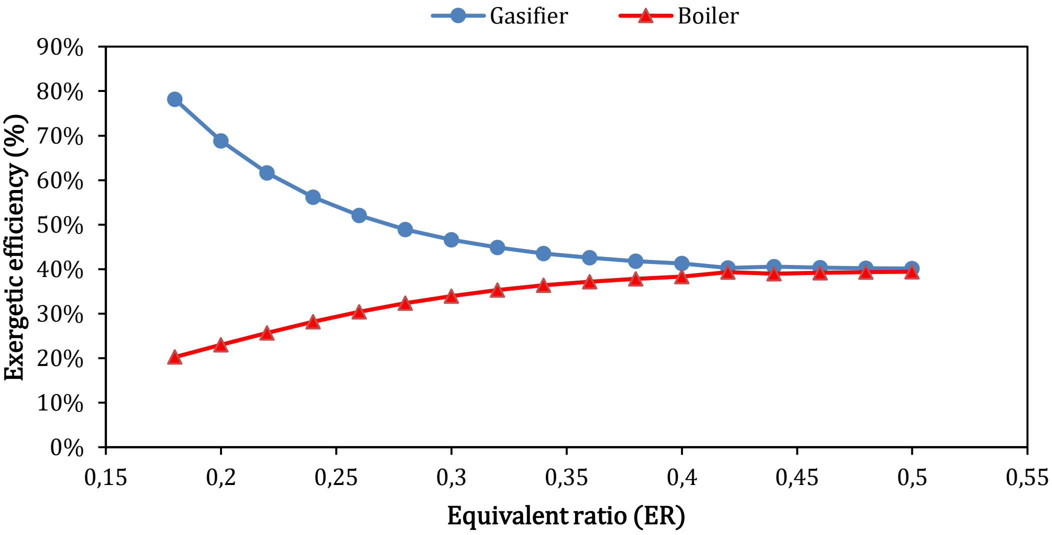

Fig. 4. ER vs Exergetic efficiency.

Figure 9 shows the behavior of the LHV of the syngas which is decreasing as the ER increases. In addition, it is shown that from ER=0.35 to ER=0.5, the LHV value is constant and is where it would be lower. Therefore, a further increasing the air flow would be inefficient, due to the increase in the oxidation rate of the syngas components. This decreases the mole fractions of the syngas components and therefore decreases the value of the LHV obtained. On the other hand, from ER=0.18 to ER=0.35, higher LHV values are obtained, which decrease as a function of the increase in the ER value. Thus, there is a range between ER=0.2 and ER=0.3, where the LHV has higher efficiency and the concentrations of its chemical species are optimal, as stated by [27].

D. VALIDATION

The validation of the results obtained from the gasifier and the steam generation in the boiler considered studies carried out by other authors. [9] Obtained a syngas with a volumetric flow of 149 m3/h, a molecular weight of 25.2 kg/kmol and a LHV of 5.4 kJ/Nm^3 after a gasification process with corn agro-industrial residues. Likewise, [28] obtained a LHV value of 5.45 kJ/Nm^3. These data have a certain similarity to those provided by the Aspen Plus® software, in the gasification section with similar parameters, from which we obtained a flow rate of 152.4 m^3/h, a molecular weight of 22 kg/kmol and a LHV of 6.18 MJ/Nm^3. Thus, having a percentage error of approximately 14.4% with respect to [9] and 13.4% with respect to [28]. For the lower heating value (LHV); 5% in the molecular weight and, finally, 2.3% for the syngas flow rate, compared to [9]. The results provided by the Aspen Plus® software were general, because of some determining factors that were not taken as parameters in the simulation process, resulting in a higher LHV than to those found in the scientific literature, however, within an acceptable range.

On the other hand, [29] obtained after an exergetic analysis of a boiler fed by biomass gases that the exergetic efficiency was 42.47%. [30] proposed a method of exergetic analysis, where he studied steam generation in boilers, and obtained as a result an exergetic efficiency of 53.7% and finally. In addition, [31] obtained an exergetic efficiency in a steam generation boiler of 38.57%. On the other hand, the exergetic efficiency in this study was 54.31%, due to heat losses in the boiler and other factors that influence the results, which is a result in accordance with studies in the literature.

IV. CONCLUSIONS

An exergy analysis of steam generation using synthesis gas from the gasification of corn cob. For this purpose, a model was developed in Aspen Plus software and the results obtained were validated with experimental data reported in the literature.

From the exergetic analysis, the exergetic efficiency of the process was 35.26%, with a destroyed exergy of 298 kW. The steam generation process is mainly responsible for these irreversibility's. It could be concluded that for the implementation of steam generation using biomass gasification it should be considered some alternatives for the optimization of the operation of the combustion process and the heat transfer in the boiler

Concluding, it is noticed that the energy consumption for steam generation is 0.1099 kWh/kg. It is recommended an analysis of this system in a CFD tool. The geometry can be designed and control several variables such as materials, insulators, and flows. This to verify theoretically before an experimental validation.

V. CRediT AUTHORSHIP CONTRIBUTION STATEMENT

Stiven Javier Sofan Germán: Conceptualization, Investigation, Methodology, Formal analysis, Supervision, Writing – original draft, Writing – review & editing. **Jorge Mario Mendoza Fandiño:** Funding acquisition, Project administration, Writing – review & editing. **Jesús David Rhenals Julio:** Methodology, Investigation, Writing – original draft, Writing – review & editing. **Julissa Jiménez López:** Writing – review & editing. **Taylor de Jesús De la Vega González:** Writing – original draft, Writing – review & editing.

ACKNOWLEDGMENTS

The authors would like to thank the University of Córdoba as a source of funding for this project.

REFERENCES

[1] R. L. Lesme, J. Martillo, and L. Oliva, "Estudio de la gasificación de la tusa del maíz para la generación de electricidad Study of the corn cob gasification of the for the electricity generation Métodos y Materiales," vol. 23, no. 3, pp. 1–9, 2020.

[2] Compañía Especialista en Vapor, "Aplicaciones Principales para el Vapor de Agua | TLV - Compañía Especialista en Vapor (America Latina)," 2021. https://www.tlv.com/global/LA/steam-theory/principal-applications-for-steam.html (accessed May 12, 2022).

[3] R. D. Gómez, D. A. Camargo, and C. C. Soto, "Synergistic evaluation of residual biomass gasification in mixtures of corn and cotton," *Inf. Tecnológica*, vol. 30, no. 6, pp. 11–20, 2019.

[4] J. A. Ruiz, M. C. Juárez, M. P. Morales, P. Muñoz, and M. A. Mendívil, "Biomass gasification for electricity generation: Review of current technology barriers," *Renewable and Sustainable Energy Reviews*, vol. 18. Pergamon, pp. 174–183, Feb. 01, 2013, doi: 10.1016/j.rser.2012.10.021.

[5] A. Bejan, "Advanced Engineering Thermodynamics," *Adv. Eng. Thermodyn.*, pp. 1–746, Sep. 2016, doi: 10.1002/9781119245964.

[6] F. Kock and H. Herwig, "Local entropy production in turbulent shear flows: A high-Reynolds number model with wall functions," *Int. J. Heat Mass Transf.*, vol. 47, no. 10–11, pp. 2205–2215, 2004, doi: 10.1016/j.ijheatmasstransfer.2003.11.025.

[7] I. Joaquina and N. García, "Energía y Exergía: Enfoques hacia la Sostenibilidad mediante el Análisis de Ciclo de Vida," pp. 1–5, 2012.

[8] Ministerio de Agricultura, "Maíz Dirección de Cadenas Agrícolas y Forestales," Mar. 31, 2020. https://sioc.minagricultura.gov.co/AlimentosBalanceados/Documentos/2020-03-31 Cifras Sectoriales Maíz.pdf (accessed May 19, 2022).

[9] E. Biagini, F. Barontini, and L. Tognotti, "Gasification of agricultural residues in a demonstrative plant: Corn cobs," *Bioresour. Technol.*, vol. 173, pp. 110–116, 2015, doi: 10.1016/j.biortech.2014.09.086.

[10] A. Gagliano, F. Nocera, M. Bruno, and G. Cardillo, "Development of an Equilibrium-based Model of Gasification of Biomass by Aspen Plus," *Energy Procedia*, vol. 111, pp. 1010–1019, 2017, doi: 10.1016/j.egypro.2017.03.264.

[11] S. Begum, M. G. Rasul, D. Akbar, and N. Ramzan, "Performance analysis of an integrated fixed bed gasifier model for different biomass feedstocks," *Energies*, vol. 6, no. 12, pp. 6508–6524, 2013, doi: 10.3390/en6126508.

[12] A. J. Keche, A. P. R. Gaddale, and R. G. Tated, "Simulation of biomass gasification in downdraft gasifier for different biomass fuels using ASPEN PLUS," *Clean Technol. Environ. Policy*, vol. 17, no. 2, pp. 465–473, 2015, doi: 10.1007/s10098-014-0804-x.

[13] U. Kumar and M. C. Paul, "CFD modelling of biomass gasification with a volatile break-up approach," *Chem. Eng. Sci.*, vol. 195, pp. 413–422, 2019, doi: 10.1016/j.ces.2018.09.038.

[14] K. N. Dhanavath, K. Shah, S. K. Bhargava, S. Bankupalli, and R. Parthasarathy, "Oxygen-steam gasification of karanja press seed cake: Fixed bed experiments, ASPEN Plus process model development and benchmarking with saw dust, rice husk and sunflower husk," *J. Environ. Chem. Eng.*, vol. 6, no. 2, pp. 3061–3069, 2018, doi: 10.1016/j.jece.2018.04.046.

[15] M. Faraji and M. Saidi, "Hydrogen-rich syngas production via integrated configuration of pyrolysis and air gasification processes of various algal biomass: Process simulation and evaluation using Aspen Plus software," *Int. J. Hydrogen Energy*, vol. 46, no. 36, pp. 18844–18856, 2021, doi: 10.1016/j.ijhydene.2021.03.047.

[16] M. Fernandez-Lopez, J. Pedroche, J. L. Valverde, and L. Sanchez-Silva, "Simulation of the gasification of animal wastes in a dual gasifier using Aspen Plus®," *Energy Convers. Manag.*, vol. 140, pp. 211–217, 2017, doi: 10.1016/j.enconman.2017.03.008.

[17] L. P. R. Pala, Q. Wang, G. Kolb, and V. Hessel, "Steam gasification of biomass with subsequent syngas adjustment using shift reaction for syngas production: An Aspen Plus model," *Renew. Energy*, vol. 101, pp. 484–492, 2017, doi: 10.1016/j.renene.2016.08.069.

[18] J. Han *et al.*, "Modeling downdraft biomass gasification process by restricting chemical reaction equilibrium with Aspen Plus," *Energy Convers. Manag.*, vol. 153, no. October, pp. 641–648, 2017, doi: 10.1016/j.enconman.2017.10.030.

[19] A. Mahapatro, A. Kumar, and P. Mahanta, "Parametric study and exergy analysis of the gasification of sugarcane bagasse in a pressurized circulating fluidized bed gasifier," *J. Therm. Anal. Calorim.*, vol. 141, no. 6, pp. 2635–2645, 2020, doi: 10.1007/s10973-020-10108-z.

[20] X. Zhang, K. Li, C. Zhang, and A. Wang, "Performance analysis of biomass gasification coupled with a coal-fired boiler system at various loads," *Waste Manag.*, vol. 105, pp. 84–91, 2020, doi: 10.1016/j.wasman.2020.01.039.

[21] Q. Zhang *et al.*, "Energy-exergy analysis and energy efficiency improvement of coal-fired industrial boilers based on thermal test data," *Appl. Therm. Eng.*, vol. 144, pp. 614–627, 2018, doi: 10.1016/j.applthermaleng.2018.08.069.

[22] E. S. Dogbe, M. A. Mandegari, and J. F. Görgens, "Exergetic diagnosis and performance analysis of a typical sugar mill based on Aspen Plus® simulation of the process," *Energy*, vol. 145, pp. 614–625, 2018, doi: 10.1016/j.energy.2017.12.134.

[23] G. Vilardi, C. Bassano, P. Deiana, and N. Verdone, "Exergy and energy analysis of three biogas upgrading processes," *Energy Convers. Manag.*, vol. 224, no. June, p. 113323, 2020, doi: 10.1016/j.enconman.2020.113323.

[24] G. Li *et al.*, "Advanced exergy analysis of ash agglomerating fluidized bed gasification," *Energy Convers. Manag.*, vol. 199, no. 2001, 2019, doi: 10.1016/j.enconman.2019.111952.

[25] M. Ucar and O. Arslan, "Assessment of improvement potential of a condensed combi boiler via advanced exergy analysis," *Therm. Sci. Eng. Prog.*, vol. 23, no. January, p. 100853, 2021, doi: 10.1016/j.tsep.2021.100853.

[26] D. M. Mitrović, B. V. Stojanović, J. N. Janevski, M. G. Ignjatović, and G. D. Vučković, "Exergy and exergoeconomic analysis of a steam boiler," *Therm. Sci.*, vol. 22, pp. S1601–S1612, 2018, doi: 10.2298/TSCI18S5601M.

[27] J. Cai *et al.*, "Synergistic effects of co-gasification of municipal solid waste and biomass in fixed-bed gasifier," *Process Saf. Environ. Prot.*, vol. 148, pp. 1–12, 2021, doi: 10.1016/j.psep.2020.09.063.

[28] F. Guo, Y. Dong, L. Dong, and C. Guo, "Effect of design and operating parameters on the gasification process of biomass in a downdraft fixed bed: An experimental study," *Int. J. Hydrogen Energy*, vol. 39, no. 11, pp. 5625–5633, Apr. 2014, doi: 10.1016/J.IJHYDENE.2014.01.130.

[29] V. F. Ramos, O. S. Pinheiro, E. Ferreira da Costa, and A. O. Souza da Costa, “A method for exergetic analysis of a real kraft biomass boiler,” *Energy*, vol. 183, pp. 946–957, Sep. 2019, doi: 10.1016/J.ENERGY.2019.07.001.

[30] A. Behbahaninia, S. Ramezani, and M. Lotfi Hejrandoost, “A loss method for exergy auditing of steam boilers,” *Energy*, vol. 140, pp. 253–260, 2017, doi: 10.1016/J.ENERGY.2017.08.090.

[31] I. O. Ohijeagbon, M. A. Waheed, and S. O. Jekayinfa, “Methodology for the physical and chemical exergetic analysis of steam boilers,” *Energy*, vol. 53, pp. 153–164, May 2013, doi: 10.1016/J.ENERGY.2013.02.039.