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THERMODYNAMIC ANALYSIS OF THE INTEGRATION OF GASIFIED BIOMASS TO THE COMBINED CYCLE (BIG/GTCC) IN THE SUGARCANE INDUSTRY

Isabella Cristina Boroto Vieira
Carlos Eduardo Silva Abreu
Federal Institute of Espírito Santo - São Mateus - ES
isabellacbv2@gmail.com
carlos.abreu@ifes.edu.br

Abstract: Due to the concern with the depletion of fossil fuel reserves, increased consumption of electricity due to population growth, as well as the need to preserve the environment, in recent years the demand for research aimed at the use of fuels from renewable sources, such as biomass, have grown significantly. Bagasse is an attractive by-product coming from the crushing of sugarcane, used in sugarcane cogeneration plants, to meet the steam demands required by the process, in addition to generating electricity, due to its high energy potential. In order to provide an increase in steam and electricity generation efficiencies, in a traditional cogeneration plant, which uses extraction and condensation steam turbines (CEST), modern technologies were developed that aim at more efficient cogeneration plants, such as the integration of sugarcane bagasse gasification into the combined cycle (BIG/GTCC). In view of this, in this article, with the objective of verifying the effect of the implementation of this technology, analyzes of the performances in the energetic and exergetic basis, of the "pure" CEST and BIG/GTCC configurations were developed, and later a comparison was made between them. Thus, by analyzing the results, the global efficiency on an energy and exergetic basis decreased by 4.04% and 0.55%, respectively, with the implementation of the "pure" BIG/ GTCC. On the other hand, by the combination of drying pre-treatment and bubbling fluidized bed gasifier, it allowed an increase in electricity generation efficiency of 37.29% and an increase in exergetic efficiency of 30.61%, compared to CEST, presenting itself as the best alternative, to increase electricity generation.

Keywords: *Renewable energy, Sugarcane Bagasse, CEST, BIG/GTCC, Energetic Efficiency*

1. INTRODUCTION

The continuous population growth has led to an increase in electricity consumption and therefore a greater need for electricity demand. Thus, energy scarcity and availability are a point of concern, since the amount of fossil fuel reserves are currently limited (Ahmed and Gupta, 2012).

According to Guan *et al.* (2020), the unbalanced consumption of products such as oil, coal, and natural gas will result in a decline in their production in the near future, inducing possible energy shortages and economic crises in dependent countries, since these energy sources take millions of years to develop.

Moreover, this global dependence on nonrenewable fuels raises concerns about the negative consequences arising from the burning of these energy sources, which has serious effects on the environment due to the emission of pollutant gases that contribute to the greenhouse effect. For this reason, the generation of energy with sustainable inputs becomes attractive to reduce dependence on non-renewable fuels, besides collaborating to mitigate climate change (De Castro and Dantas, 2018).

Currently, there are many sustainable solutions that are being developed and used as an alternative for the clean generation of electric power, and one of them is the use of biomass. According to the National Bank of Economic and Social Development (BNDES, 2008), biomass is defined as every natural resource (vegetable or animal) that presents accumulated chemical energy from photosynthetic processes, which can be processed in order to provide bioenery in a clean way.

Basu (2013), defines biomass as all living species or that contained life a short time ago, examples are plants and animal remains. These have the advantage of being renewable, which eliminates the possibility of their depletion. Through the phenomenon of photosynthesis, plants metabolize water and CO_2 with the help of sunlight in order to obtain the energy necessary for their survival, while animals grow by consuming plants or other biological species. In this way, the CO_2 from the atmosphere is absorbed and when this energy source is burned, this newly trapped gas is released. Then, due to the refixation of CO_2, carried out by other plants that are still in their development phase, makes the biomass is considered "carbon neutral", and as a consequence will not contribute to the emissions of CO_2 in the atmosphere.

Authors such as Basu (2013) and Larson et al. (2001), cite that bagasse is one of the byproducts from biomass fuel, which is understood as a fibrous residue when sugarcane goes through the milling process. In addition, it represents about one-third of the energy absorbed above ground, the rest being stored as sugar. Such a residue is composed of cellulose (30-60%), hemicellulose (20 - 35%) and lignin (15 - 30%), which are responsible for its high energy content (De Velden et al., 2010).

The composition, structure, and calorific value of the residue are attributes that vary according to climatic conditions, soil quality, sugarcane species, harvesting system, washing for cleaning the cane, and the competence of the milling machinery (Pérez et al., 2014). Due to its high volatility and low ash content, this biomass presents high reactivity, making it attractive for gasification (Pedroso et al., 2017).

In Brazil, according to Iriya et al. (2009), the transformations of sugar and ethanol sector started about 50 years ago, which led the country to become one of the largest producers and exporters of sugarcane derivatives in the world. In these sugarcane mills it is common to use the same source to produce more than one useful form of energy, such as the combined application of heat and electricity, which is defined as the cogeneration process (Çengel and Boles, 2013). Thus, the need to employ cogeneration, take advantage of the waste generation, follow the social and environmental requirements, and the reduction of the cost of the process are important points that contribute to the modernization of the sugarcane agroindustry (CONAB, 2020; Pippo et al. 2007).

In line with the BNDES (2008), bagasse, besides being a biofuel, also allows these plants to be activated in periods of the sugarcane harvest, a period that coincides with the months of low rainfall, when the performance of hydroelectric plants is directly affected.

Therefore, in order to verify the effect of the implementation of BIG/GTCC technology, to increase the energy and exergetic yield of sugarcane mills, aimed at the sustainable generation of electricity, this work aimed to select a plant model to carry out the implementation of BIG/GTCC, calculate all energy and exergetic efficiency parameters of selected plants and carry out a comparative analysis of the thermodynamic performance of CEST and BIG/GTCC technologies.

2. THE CONVENTIONAL CONDENSING-EXTRACTION STEAM-TURBINE TECHNOLOGY

It is common for sugarcane mills to operate with a conventional condensing-extraction steam-turbine (CEST) technology as shown in Figure 1. In this system the bagasse that has high moisture content is used as fuel in boilers to generate superheated steam and power. This technique is based on a Rankine cycle, in which water is used as a working fluid, which will be heated and transformed into high pressure superheated steam. Then, the energy is converted into mechanical work as it passes through the turbine, and electricity is generated (Pedroso et al., 2017).

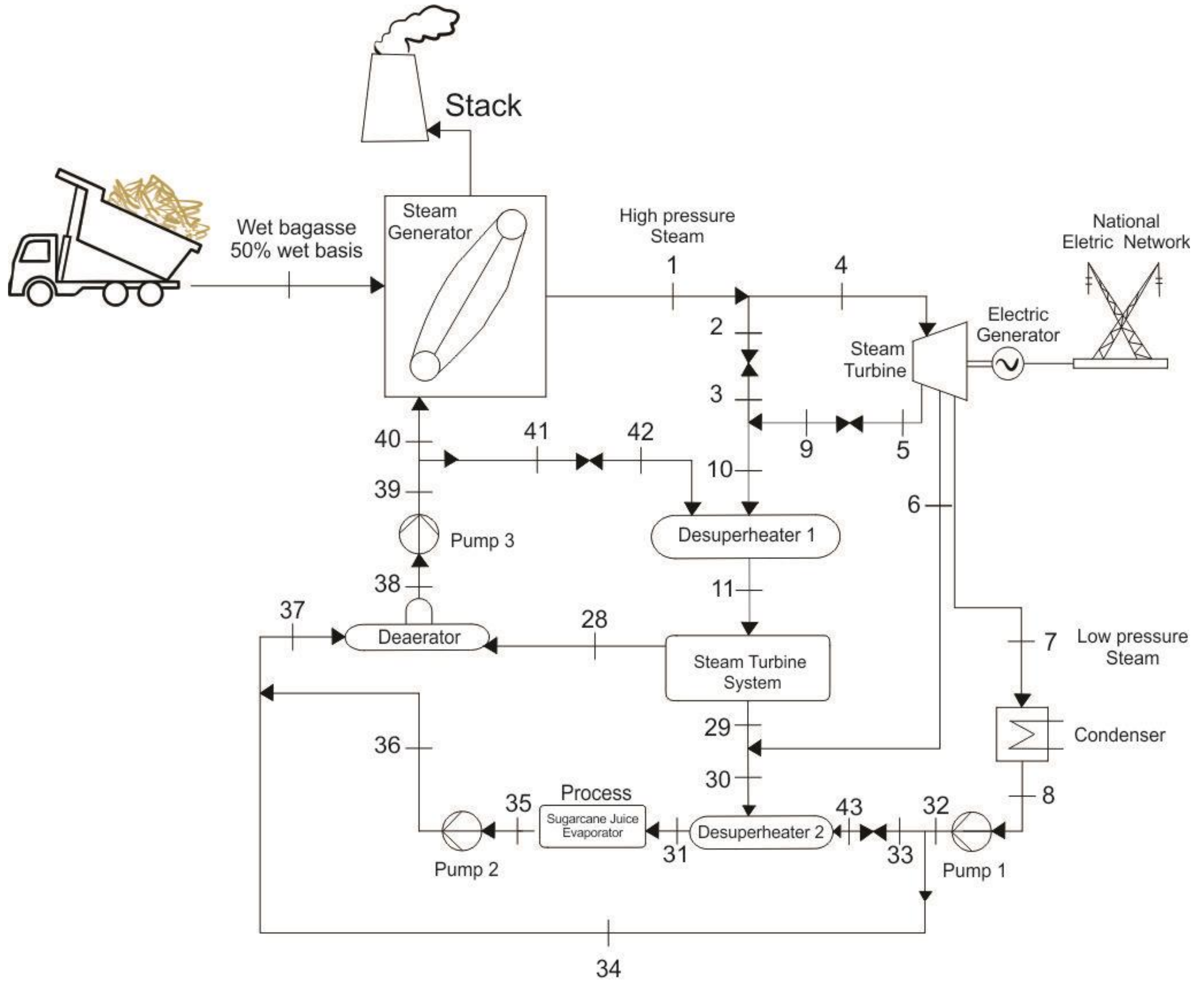

Figure 1. CEST configuration.

According to Yan et al. (2020), the direct burning of biomass is one of the causes of the low electrical efficiency generated in sugar and ethanol plants using CEST technology, because when converting bioenergy into electricity, this method is considered extremely irreversible, and thus the exergy destruction is significant.

Furthermore, the high exergy destruction rate in the Rankine cycle is a worrisome factor when maximum work is desired with the intention of achieving the best plant efficiency. This is due to increased external irreversibilities when having large temperature differences during heat transfer to the surroundings (Moran et al., 2013).

3. COMBINED CYCLE

Through the introduction of Heat Recovery Steam Generator (HRSG) and the combination of Rankine (steam cycle) and Brayton (gas cycle) cycles, the plant's electric power generation efficiency could be increased, since the hot exhaust gas with high energy, coming from the gas turbine, is used and thus there will be no waste of exergy in the system. Furthermore, it helps to reduce the amount of fuel that must be burned in the combustion chamber. Therefore, it is possible that through the high average temperature of heat addition of the gas turbines and the low average heat rejection temperature of the Rankine cycle, an increase in the global efficiency of the cycle is provided (Moran et al., 2013). In Figure 2 the arrangement of the combined cycle is shown.

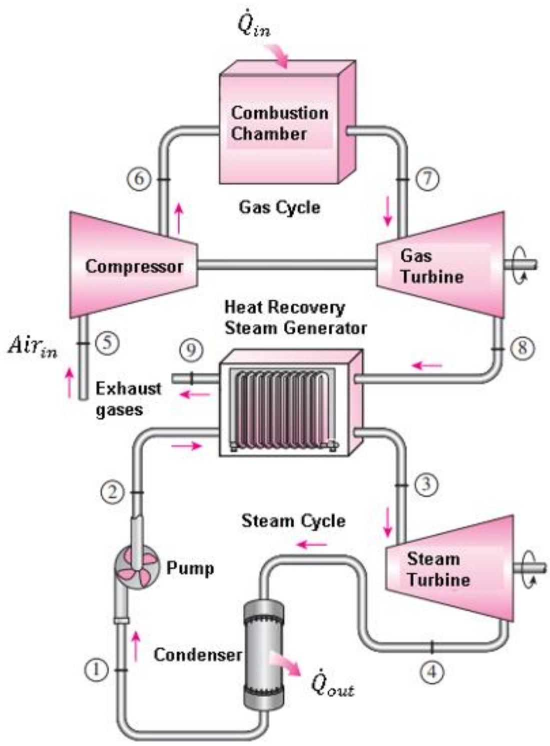

Figure 2. Combined Cycle
Source: Adapted from Çengel and Boles (2013)

4. BIOMASS INTEGRATED GASIFICATION/GAS TURBINE COMBINED CYCLE (BIG/GTCC) IN THE SUGAR INDUSTRY

The BIG/GTCC system consists of a combination of the Brayton and Rankine cycles, linked by a e Heat Recovery Steam Generator (HRSG), a biomass dryer, a gasifier and finally a gas cleaning system (Larson et al., 2001).

During the operation of the BIG/GTCC technology, the biomass goes through a drying process, as a way to decrease its moisture concentration, and then enters the gasifier, where it is transformed into fuel gas and then flows into a cleaning unit to eliminate solids, tars, and other contaminants. The gas is then delivered to a boost compressor that compresses it to the operating pressure of the combustion chamber. In the Heat Recovery Steam Generator (HRSG), the heat from the exhaust gases of the gas turbine is recovered, part of which is used to sustain the biomass dryer and the other part is destined to generate steam, which drives the steam turbine, to drive the electric generator. In addition, the steam should also meet the process requirements (Pedroso et al., 2017).

According to Parvez and Khan (2019), the biomass gasifier integrated into a combined cycle, (BIG/GTCC), is a more efficient and sustainable possibility, which allows to correct the thermodynamic limitations of the CEST technology, since the solid biomass fuel is transformed into energy-carrying gases.

5. BIOMASS GASIFICATION

Gasification is a thermochemical conversion of biomass, which uses partial oxidation to form a flammable gaseous mixture at temperatures above 750 °C (Shukla and Kumar, 2017). Such a mixture is called syngas, which is composed of hydrogen (H_2), carbon monoxide (CO), methane (CH_4) and carbon dioxide (CO_2), water vapor, nitrogen gas (N_2) depending on the gasification agent, as well as smaller amounts of heavier hydrocarbons (Higman, 2008 and Shukla; Kumar, 2017). Then, the process adds hydrogen and removes carbon from the feedstock to produce gases that have a high hydrogen-to-carbon (H/C) ratio (Basu, 2013).

Hydrogen and carbon monoxide are the desired gases because they have a high calorific value. This is due to the thermal oxidation of carbon with oxygen in lower amounts than is required in stoichiometry for complete combustion to occur (Pedroso et al., 2017). Thus, the syngas with high energy value, originating from the incomplete combustion of the carbonaceous by-product input, can be used as fuel gas for power generation. The main reactions of the gasification process appear on the Table 1, that results on the formation of CO and H_2 (Basu, 2013 and Pedroso et al., 2017).

Table 1. Main reactions of the biomass gasification process.

Reaction Type	Reaction
Water-gas or steam	$C + H_2O \leftrightarrow CO + H_2 \quad \Delta H^0_{298} = +131.5\, kJ\, mol^{-1}$
Boudouard	$C + CO_2 \leftrightarrow 2CO \quad \Delta H^0_{298} = +172\, kJ\, mol^{-1}$
Shift	$CO + H_2O \leftrightarrow CO_2 + H_2 \quad \Delta H^0_{298} = -41\, kJ\, mol^{-1}$
Methane steam reforming	$CH_4 + H_2O \leftrightarrow CO + 3H_2 \quad \Delta H^0_{298} = +206\, kJ\, mol^{-1}$

According to Basu (2013), the procedure of biomass gasification in reactors (gasifiers), includes some process zones, which are: drying, pyrolysis, combustion zone and reduction zone.

The drying area receives heat from the combustion zone for moisture evaporation. In the pyrolysis zone, endothermic reactions occur in the absence of oxygen, where there is thermochemical degradation of the dry biomass at high temperatures, resulting in liquid products (tar, heavier hydrocarbons and water), solids (mainly coal or carbon) and pyrolytic gases CO_2, H_2O, CO, C_2H_2, C_2H_4, C_2H_6, C_6H_6) (Basu, 2013).

The combustion zone, is determined by the injection position of the gasifying agent (air, steam, oxygen or carbon dioxide), thus, by means of these, the products generated in pyrolysis are partially oxidized (Lora et al., 2012). The process is characterized by exothermic reactions, in which products such as water vapor and carbon dioxide are generated. Moreover, the heat released is used for the reactions of the other zones of the gasifier (De Castro et al., 2009).

Finally, the reduction zone involves endothermic and exothermic reactions in an oxygen-poor medium, in which the fixed carbon from pyrolysis and the resulting high temperature products from the combustion zone (H_2O, CO_2), react in order to convert the fixed carbon into low molecular weight gases, CO e H_2 (Barreto et al.2008 and Basu, 2013).

There are several types of gasifiers for the thermochemical transformation of biomass, being classified according to the relative direction between the flow of biomass and gasification agent, in addition to the way in which heat is transferred to the gasifier. Thus, they can be divided into three categories: fixed bed, fluidized bed, and entrained flow gasifiers. Among the fixed-bed reactors, there are three types: Updraft, downdraft, and crossdraft (Higman, 2008 and Lora et al., 2012). Fluidized bed reactors can be further subdivided into circulating or bubbling (Pedroso et al., 2017).

6. METHODOLOGY

In this study, the methodology applied by Machin (2015) was followed. Therefore, it was proposed to implement the BIG/GTCC technology at a sugarcane mill, which is supported by a conventional cogeneration system (CEST) shown in Figure 1, whose processing capacity is 276.9 t/h of sugarcane during the harvest. This plant features a turbo generator, with a multi-stage extraction/condensation turbine, capable of generating 40 MVA of electricity. In addition, it produces 78.9 t/h of sugarcane bagasse, $\dot{m}_{wb,50}$, with a moisture content of 50%, of which 70.5 t/h, with lower calorific value of 7.32 MJ/kg, LHV$_{wb,50}$, are burned in a boiler. Also, the mechanical energy consumed in the sugar production process, W_{mec}, is 3,919 MW (Fiomari, 2004).

The second arrangement will take the CEST configuration as a premise, however, with the "pure" implementation of the BIG/GTCC technology, Figure 3, which fully replaces the traditional cogeneration system, since there are other possibilities to implement the BIG/GTCC, when maintain the plant's existing cogeneration system, using the combustion chamber in parallel with the boiler. Thus, the cycle in question is composed of a bubbling fluidized bed gasifier, in addition, air is used as a gasification agent. As a way to reduce the negative effects caused by the moisture in the bagasse, the raw material is pre-treated for drying. In order to keep the grinding processes unchanged, the steam parameters at the boiler outlet, as well as the energy consumed by the pumps associated with the HRSG, were kept in accordance with the CEST setting. The energy consumed by the fuel gas compressor in this configuration, W$_{cgc}$, is 0.80 MW, (Pedroso et al., 2017).

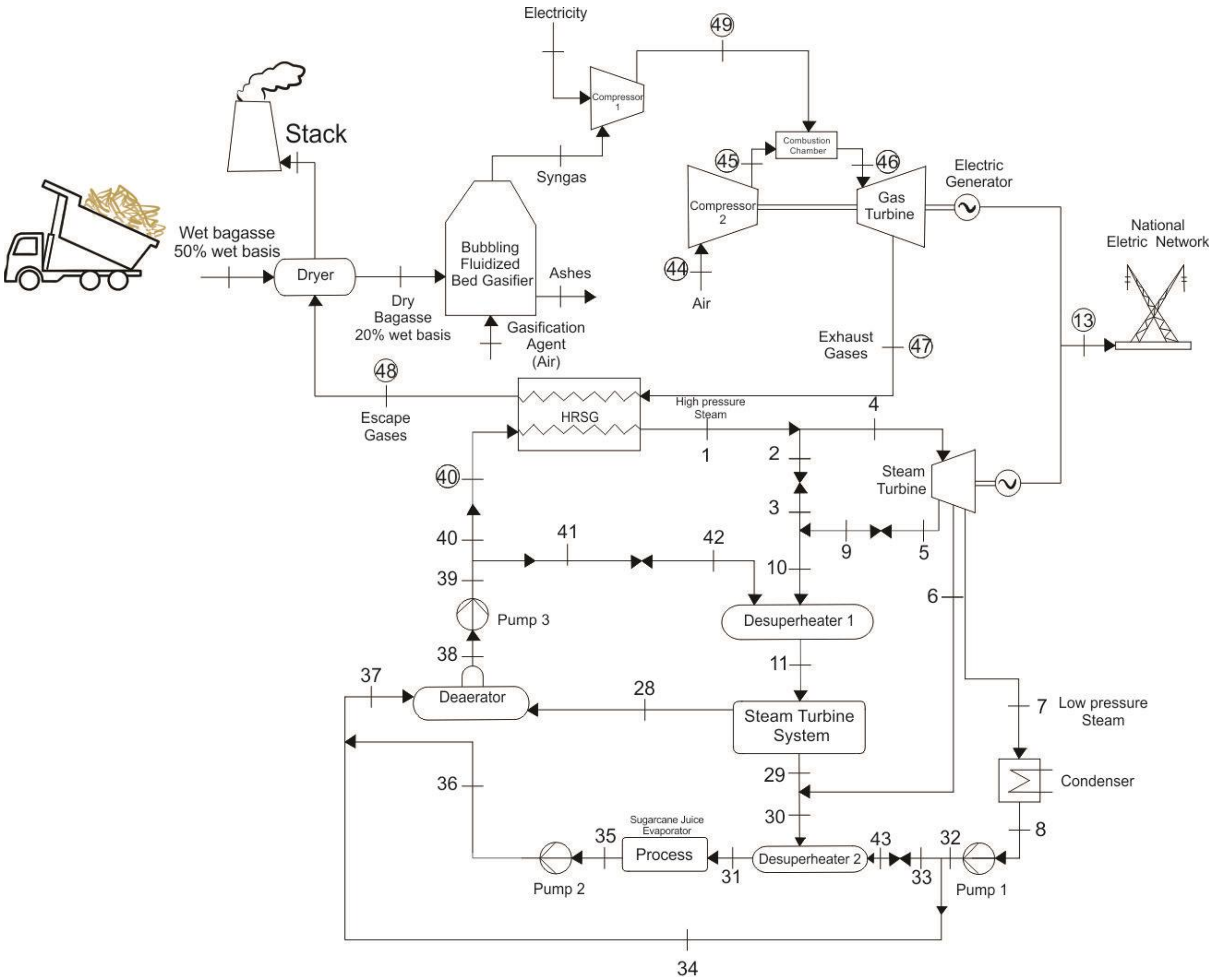

Figure 3. BIG/GTCC configuration.

The Table 2, shows the operating parameters of the plant with the implementation of "pure" BIG/GTCC (Pedroso *et al.*, 2017).

Table 2. Operational parameters of the plant with the implementation of "pure" BIG/GTCC.

State	Fluid	Mass flow (kg/s)	Pressure (kPa)	Temperature (°C)	Enthalpy (kJ/kg)	Entropy (kJ/kg.K)
1	Water/Steam	41.67	6468	530	3489	6.934
2	Water/Steam	8.14	6468	530	3489	6.934
3	Water/Steam	8.14	2156	510.2	3489	7.426
4	Water/Steam	33.53	6468	530	3489	6.934
5	Water/Steam	10	2650	426	3296	7.072
6	Water/Steam	17.8	245	147.2	2760	7.167
7	Water/Steam	5.75	8.5	42.7	2578	8.206
8	Water/Steam	5.75	8.5	42.6	178.4	0.607
9	Water/Steam	10	2156	422.7	3296	7.165
10	Water/Steam	18.14	2156	462	3383	7.286
11	Water/Steam	20.33	2156	320	3066	6.807
28	Water/Steam	0.83	245	190.7	2850	7.371
29	Water/Steam	19.5	245	190.7	2850	7.371
30	Water/Steam	37.28	245	169.8	2807	7.276
31	Water/Steam	38.33	245	135	2734	7.104
32	Water/Steam	5.75	490	42.7	179.2	0.6081
33	Water/Steam	1.06	490	42.7	179.2	0.6081
34	Water/Steam	4.69	490	42.7	179.2	0.6081

35	Water/Steam	38.33	245	100	419.3	1.307
36	Water/Steam	38.33	490	100.1	419.9	1.308
37	Water/Steam	43.03	490	93.8	393.3	1.236
38	Water/Steam	43.86	245	105	440.4	1.363
39	Water/Steam	43.86	8820	106.8	454.3	1.376
40	Water/Steam	41.67	8820	106.8	454.3	1.376
41	Water/Steam	2.19	8820	106.8	454.3	1.376
42	Water/Steam	2.19	2156	107.8	453.6	1.393
43	Water/Steam	1.06	245	42.8	179.4	0.6095
44	Air	352.5	101.3	25	577.1	6.357
45	Air	352.5	1931	518	1120	6.192
46	Combustion Gases	468.7	1834	1290	2048	6.861
47	Combustion Gases	468.7	107	587	1200	7.096
48	Combustion Gases	468.7	101.3	271	841.2	6.741
49	Syngas	116.2	1931	25	-	-

Also, other relevant data were used for the thermodynamic analysis of the technologies studied, as presented in Table 3.

Table 3. Data used for the thermodynamic analysis of the technologies studied.

Data	Symbology	Value	Reference
Gas and steam turbine electricity generation efficiency, %	η_e	0.95	Pedroso *et al.* (2017)
Mass flow of Fuel gas, kg/s	$\dot{m}_{fg}$	116.2	Machin (2015)
Reference temperature, K	T_0	298.00	Çengel and Boles (2013)

Table 4, shows the bagasse mass fraction with 50% on the wet basis.

Table 4. Bagasse mass fraction with 50% wet basis.

Variable	Representation	Value	Reference
Mass fraction of carbon (%)	Z_C	46.3	Fiomari (2004) apud Szargut, (1988)
Mass fraction of nitrogen (%)	Z_{N_2}	0	
Mass fraction of oxygen (%)	Z_{O_2}	43.3	
Mass fraction of hydrogen (%)	Z_{H_2}	6.4	

Table 5, shows the molar fraction on a wet basis of the gas produced in a fluidized bed gasifier, as well as the molar mass, lower heating value (LHV) and standard chemical exergy on a molar basis of the component of each fuel element.

Table 5. Molar fraction on a wet basis of syngas and other characteristics of biofuel components

Variable	Representation	Value
Mole fraction on wet basis of carbon dioxide (%) (1)	y_{CO_2}	13.4
Mole fraction on wet basis of nitrogen (%) (1)	y_{N_2}	4.02
Mole fraction on wet basis of carbon monoxide (%) (1)	y_{CO}	13.4
Mole fraction on wet basis of oxygen (%) (1)	y_{O_2}	0.9
Mole fraction on wet basis of hydrogen (%) (1)	y_{H_2}	17.9
Mole fraction on wet basis of methane (%) (1)	y_{CH_4}	3.60
Mole fraction on wet basis of water (%) (1)	y_{H_2O}	10.6
Molar Mass of carbon dioxide (kg/kmol)	MM_{CO_2}	44.01
Molar Mass of nitrogen (kg/kmol)	MM_{N_2}	28.01
Molar Mass of carbon monoxide (kg/kmol)	MM_{CO}	28.01
Molar Mass of oxygen (kg/kmol)	MM_{O_2}	32
Molar Mass of hydrogen (kg/kmol)	MM_{H_2}	2.016
Molar Mass of methane (kg/kmol)	MM_{CH_4}	16.04
Molar Mass of water (kg/kmol)	MM_{H_2O}	18.02

LHV of carbon dioxide (kJ/kg)	LHV_{CO_2}	0
LHV of nitrogen (kJ/kg)	LHV_{N_2}	0
LHV of carbon monoxide(kJ/kg)	LHV_{CO}	10102
LHV of oxygen (kJ/kg)	LHV_{O_2}	0
LHV of hydrogen (kJ/kg)	LHV_{H_2}	119946
LHV of methane (kJ/kg)	LHV_{CH_4}	50023
LHV of water (kJ/kg)	LHV_{H_2O}	0
Chemical exergy of carbon dioxide (kJ/kmol) (2)	$\bar{e}_{CO_2}{}^{Q}$	275100
Chemical exergy of nitrogen (kJ/kmol) (2)	$\bar{e}_{N_2}{}^{Q}$	720
Chemical exergy of carbon monoxide (kJ/kmol) (2)	$\bar{e}_{CO}{}^{Q}$	275100
Chemical exergy of oxygen (kJ/kmol) (2)	$\bar{e}_{O_2}{}^{Q}$	720
Chemical exergy of hydrogen (kJ/kmol) (2)	$\bar{e}_{H_2}{}^{Q}$	236100
Chemical exergy of methane (kJ/kmol) (2)	$\bar{e}_{CH_4}{}^{Q}$	831650
Chemical exergy of water (kJ/kmol) (2)	$\bar{e}_{H_2O}{}^{Q}$	9500

(1) Coronado (2006)
(2) Moran *et al.* (2013)

The energy analysis was applied through the First Law of Thermodynamics, and the process was considered to be steady state, as determined by Eq. (1).

$$0 = \dot{Q}_{cv} - \dot{W}_{cv} + \Sigma \dot{m}_i h_i + \Sigma \dot{m}_o h_o \quad (1)$$

where h_i; h_o; $\dot{Q}_{cv}$ and $\dot{W}_{cv}$ are a specific enthalpy at the control volume input (kJ / kg); specific enthalpy at the control volume output (kJ / kg), net heat rate along the control volume boundaries (kW) and net work rate along the control volume boundaries (kW), respectively.

The electricity generations produced by the steam and gas turbines, were calculated using Eq. (2) and Eq. (3), respectively.

$$E_{ste} = (E_{st}) \,.\, \eta_e \quad (2)$$

$$E_{gte} = (E_{gt} - W_{ac}) \,.\, \eta_e \quad (3)$$

where E_{st} , E_{gt} and W_{ac} are the work produced by the steam turbine (kW), work produced by the gas turbine (kW) and work consumed by the air compressor (kW), respectively.

Also, it was necessary to calculate LHV of the syngas, LHV_{fg}, according to Eq. (4).

$$LHV_{fg} = \textstyle\sum_{i=1} \%m_i * LHV_i \quad (4)$$

when $\%m_i$ and LHV_i, are the mass fraction of component i of the gas mixture and LHV of component i of the gas mixture (kJ/kg), respectively.

According to Moran et al. (2013), the mass fraction, ($\%m_i$), of the components of a gas, can be determined through Eq. (5) and Eq. (6).

$$m_i = y_i * MM_i \quad (5)$$

$$\%m_i = \frac{m_i}{\sum_{i=1} m_i} \quad (6)$$

where m_i, y_i, MM_i, $\%m_i$ and $\sum_{i=1} m_i$, are the mixture mass (kg/kmol), molar fraction (%), mass fraction (%), of the component i of the gas mixture and the total mass of the mixture (kg/kmol), respectively.

Subsequently, performance analysis based on the First Law of Thermodynamics was performed by calculating the electricity generation efficiency, η_{ge}, and global efficiency, η_{gl} , of the CEST and BIG/GTCC technologies through Eq. (7) to (10).

$$\eta_{ge,CEST} = \frac{E_{ste} - W_p}{LHV_{wb,50} \,.\, \dot{m}_{wb,50}} \quad (7)$$

$$\eta_{ge,BIG/GTCC} = \frac{E_{gte} + E_{ste} - W_p - W_{fgc}}{LHV_{fg} \,.\, \dot{m}_{fg}} \quad (8)$$

$$\eta_{gl,CEST} = \frac{E_{ste} + Q_{proc} + W_{mec} - W_p}{LHV_{wb,50} \,.\, \dot{m}_{wb,50}} \quad (9)$$

$$\eta_{gl,BIG/GTCC} = \frac{E_{gte} + E_{ste} + Q_{proc} + W_{mec} - W_p - W_{fgc}}{LHV_{fg} \,.\, \dot{m}_{fg}} \quad (10)$$

where E_{ste} , E_{gte} , W_p and Q_{proc} are the electricity generate by the steam turbine (kWe), electricity generates by the gas turbine (kWe), work consumed by pump (kW) and thermal energy of consumed by the sugar production process (kW), respectively.

Exergy is defined as the maximum useful work that can be obtained when a system is brought to an equilibrium state with the environment (dead state), whose properties, temperature and pressure, are designated by the subscript zero, T_0 (K) e P_0 (kPa), respectively. Furthermore, it can be supplied or recovered in different amounts and forms, such as heat, work, enthalpy, kinetic energy, internal energy and potential energy (Moran et al., 2013).

In order to determine the performances based on the Second Law of Thermodynamics, it was first necessary to calculate the specific chemical exergy of bagasse at 50% moisture (kJ/kg), ${ex_{wb,50}}^Q$, and the syngas (kJ/kg), ${ex_{fg}}^Q$.

To calculate the specific bagasse exergy, the equation presented by Fiomari (2004 apud Szargut,1988) is used, according to Eq. (11).

$$ex_{wb,50} = \beta * (LHV_{wb,50} + L_{water} * Z_{water}) + ex_{water} * Z_{water} \quad (21)$$

Where:

$$\beta = \frac{1{,}0412 + 0{,}2160 * \left(\frac{Z_{H_2}}{Z_C}\right) - 0{,}2499 * \left(\frac{Z_{O_2}}{Z_C}\right) * \left[1 + 0{,}7884 * \frac{Z_{H_2}}{Z_C}\right] - 0{,}0450 * \left(\frac{Z_{N_2}}{Z_C}\right)}{1 - 0{,}3035 * \left(\frac{Z_{O_2}}{Z_C}\right)} \quad (12)$$

when β, Z_i, Z_{water}, L_{water} and ex_{water}, are the function of mass fractions of bagasse chemical components, mass fraction of different chemical elements (%), mass fraction of water in wet bagasse (%), enthalpy of water vaporization (2442 kJ/kg) and exergy chemistry of liquid water water (50 kJ/kg), respectively.

The chemical exergy of the syngas was determined according to Ferrarini et al. (2015), according to Eq. (13).

$${ex_{gc}}^Q = \frac{\sum_{i=1} y_i * \bar{e}_i{}^Q + \bar{R} * T_0 * \sum_{i=1} y_i * ln y_i}{MM_{fg}} \quad (13)$$

Where:

$$MM_{fg} = \sum_{i=1} MM_i * y_i \quad (34)$$

when y_i, $\bar{e}_i{}^Q$, MM_i and MM_{fg}, are the molar fraction of component i of the gas mixture (%), standard chemical exergy on molar basis of component i (kJ/kmol), molecular mass of component i of the gas mixture (kg/kmol) and molecular mass of sinter gas (kg / kmol), respectively.

Subsequently, the performance calculation was performed based on the Second Law of Thermodynamics for the generation of electrical energy, Eq. (15) and (16), and global, Eq. (17) and (18), of both configurations.

$$\psi_{ge,CEST} = \frac{E_{ste} - W_p}{{ex_{wb,50}}^Q \,.\, \dot{m}_{wb,50}} \quad (15)$$

$$\psi_{ge,BIG/GTCC} = \frac{E_{gte} + E_{ste} - W_p - W_{fgc}}{{ex_{fg}}^Q \,.\, \dot{m}_{fg}} \quad (16)$$

$$\psi_{gl,CEST} = \frac{E_{ste} + Q_{proc} + W_{mec} - W_p}{{ex_{wb,50}}^Q \,.\, \dot{m}_{wb,50}} \quad (17)$$

$$\psi_{gl,BIG/GTCC} = \frac{E_{gte} + E_{ste} + Q_{proc} + W_{mec} - W_p - W_{fgc}}{ex_{fg}{}^{Q} \cdot \dot{m}_{fg}} \tag{18}$$

7. RESULTS

The results obtained in this study are presented below.
Table 6, shows the results obtained for LHV and chemical exergy of the CEST and "pure" BIG/GTCC configurations.

Table 6. Results obtained for LHV and chemical exergy of CEST and "pure BIG/GTCC configurations.

Analysis on the energy basis				
CEST	$LHV_{wb,50}$ (kJ/kg)	7320	$E_{wb,50}$ (kW) (1)	143326
BIG/GTCC	LHV_{fg} (kJ/kg)	3574	E_{fg} (kW) (1)	415303
Exergy based analysis				
CEST	$ex_{wb,50}$ (kJ/kg)	9707	$Ex_{wb,50}$ (kW) (2)	190073
BIG/GTCC	$ex_{fg}{}^{Q}$ (kJ/kg)	4535	Ex_{fg} (kW) (2)	526994

(1) Energy supplied by the fuel to the system
(2) Exergy supplied by the fuel to the system

Table 7, shows the values obtained in the "pure" BIG/GTCC.

Table 7. Values obtained in the "pure" BIG/GTCC.

Configuration	E_{tve} (Kw_e)	E_{tge} (Kw_e)	E_{te} (Kw_e)
CEST	19085	-	19085
BIG/GTCC	19085	194804	213889

Table 8, shows a comparison of the calculated performances, between the CEST configuration and when the "pure" BIG/GTCC configuration is implemented.

Table 8. Results of the thermodynamic performances of CEST and BIG/GTCC configurations.

Technologic	η_{ge} (%)	η_{gl} (%)	ψ_{ge} (%)	ψ_{gl} (%)
CEST	12.87	77.5	9.705	58.44
"pure" BIG/GTCC	51.16	73.46	40.31	57.89

When comparing the results obtained for the two configurations studied, the feasibility of implementing gasification to increase electricity generation is observed, as it provides an increase of 37.29% and 30.605% in electricity generation efficiencies, based on the First and Second Law of Thermodynamics, respectively, when compared to the current configuration of the plant.

The increase in the efficiencies of electricity generation and exergetics, can be justified by the processing of wet biomass, through the use of the dryer, which evaporates much of the moisture of the bagasse to be gasified, thus not causing the drop in temperature inside the reactor, responsible for causing the desired reactions, for the maximum formation of energy carrier gases. In addition, the application of HRSG and the combination of Rankine and Brayton cycles, avoids the waste of exergy in the system, since the high energy of the hot exhaust gas, coming from the gas turbine, is recovered, producing more steam, to generate heat and mechanical energy for the process, as well as mechanical energy to generate electricity.

Thus, the plant, taken as a base, generated through the steam turbine 19085 Kw_e, while the plant with gasification generated 213889 Kw_e, through the sum of the power generated by the steam and gas turbines, which represents a 91.08% increase in the capacity to supply electricity. However, this increase in the production of electricity was only possible through a significant increase in fuel consumption, since, to ensure the functioning of the gasifier and meet the energy requirement of the plant, in addition to the gasification of all available bagasse (21.92 kg/s), it will still be necessary to purchase excess bagasse, which corresponds to 81.13% of the total volume of sugarcane residue required.

On the other hand, its global efficiency in terms of energy and exergy fell by 4.04% and 0.55%, respectively. This reduction is justified by the greater amount of fuel used in gasification, increasing the total energy supplied by biomass to the system. In addition, the need for a syngas compressor for conditioning the fuel to combustion chamber conditions also contributed to the decline in global performance.

According to Ferrarini et al. (2015), chemical exergy is an overvaluation of fuel capacity, given that this property corresponds to the greatest theoretical work possible to be achieved, while the system of interest reaches equilibrium when interacting with the reference environment. Thus, the decrease in exergy efficiency, when compared to energy efficiency, is justified, since the content based on exergy is higher, compared to the value of chemical exergy, it remains between the LHV and HHV.

Also, the implementation of the BIG/GTCC technology still presents, since most commercial reactors available on the market are not supplied to gasify the bagasse. In addition, these have a processing capacity lower than what is required for the system to function.

Furthermore, the size of the gas turbine, used in the BIG/GTCC, becomes another barrier for its implementation, given that the gases derived from biomass have low energy contents per unit of volume. Thus, it is necessary to use a gas turbine, capable of accommodating greater volumetric gas flows, to achieve a release of energy equivalent to that delivered by fuels with high energy content, such as natural gas, for which most commercial gas turbine combustors are designed.

8. CONCLUSION

Through this study, it was possible to carry out analyzes based on the First and Second Law of Thermodynamics, of two possible systems for cogeneration, used in a sugar-alcohol plant, which aim at the commercialization of the surplus of electric energy produced. For the first case, the conventional technology with an extraction and condensation steam turbine (CEST) was analyzed, in which wet bagasse is used as fuel to generate the plant's energy needs. The second one considers biomass gasification, instead of being burned directly as in the traditional cycle, replacing the conventional boiler with a Heat Recovery Steam Generator (HRSG), which interconnects the Brayton cycle to Rankine ("pure" BIG/GTCC).

The combination of bagasse drying, which provides an improvement in the physicochemical properties of the fuel, together with the bubbling fluidized bed gasifier, allows an increase in the efficiency of electrical generation based on the First and Second Laws of Thermodynamics, when compared to CEST. Thus, from the point of view of increasing electricity generation, in the BIG/GTCC configuration, it was presented as the most advantageous alternative, despite the reduction in the global efficiency of the plant. However, this increase in electricity production was only possible by increasing the total energy consumption of the system.

Furthermore, the need for excess bagasse, the size of the gas turbine required, as well as the dimensions of the gasification system required, can make the implementation cost more expensive and make the implementation of the "pure" BIG/GTCC unfeasible. Therefore, such technology can be an advantageous and easy-to-adapt alternative, when implemented in mills that have a larger sugarcane processing capacity, as they would not require the purchase of additional bagasse.

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10. RESPONSIBILITY NOTICE

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