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Original Research Article

Thermodynamic analysis of sugarcane bagasse plasma gasification

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ABSTRACT

Plasma thermal gasification can be one of the most relevant and environmentally friendly technologies for waste treatment and has gained interest for its use in the thermos-conversion of biomass. From this perspective, the objective of this study is to evaluate the gasification of sugarcane bagasse by studying the effective areas of operation of this process and to establish a comparison with conventional autothermal gasification. A thermochemical equilibrium model was used to calculate the indicators that characterize the performance of the process on its own and integrated with a combined cycle. As a result, it was obtained that plasma and gasification of bagasse are technically feasible for the specific net electrical production of 4 MJ with 30% electrical efficiency, producing gas with a higher calorific value than autothermal gasification. The operating points where the electrical energy production and the cold gas efficiency reach their highest values were determined; then the effects of the operational parameters on these performance indicators were analyzed.

Keywords: Plasma Gasification; Equilibrium Model; Thermodynamic Analysis; Sugar Cane Bagasse Gasification

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1. Introduction

Global energy consumption has grown steadily for a number of reasons, mainly due to industrialization, the rapid growth of developing countries and their populations, the increased quality of life, and the increased transportation of people and goods. To meet these needs, the extensive use of fossil fuels has proven to be unsustainable and a major cause of greenhouse gas emissions. The need for renewable sources of energy that provide low emissions of such gases is more necessary than ever. Biomass is expected to be one of the predominant options within renewable energy resources, mainly due to its abundance and manageability. At present, significant amounts of biomass are mainly converted into heat. It is estimated that 13% of the global primary energy used worldwide is biomass, most of which is very inefficient when burned outdoors[1].

In some countries such as Brazil and Cuba, biomass as a primary source is used to obtain electricity in sugar mills by burning bagasse. This process can be improved from an efficiency point of view if other forms of thermal conversion such as gasification are used[2]. However, gasification is a complicated process, which is subjects to the influence of multiple factors and faces strict technological requirements, so this technology has not yet been introduced in the sugar sector.

One of the ways to gasify biomass is through the use of thermal plasma as a source of the heat necessary for the essentially endothermic gasification reactions to occur. This technique has been tested primarily for the treatment of municipal solid waste[3], coal[4], and other biomasses[5]. Through plasma gasification, it is possible to obtain a clean gas suitable for use in gas turbine systems that allow gasifiers integrated into a combined cycle (IGCC)[6]. The use of IGCC is recognized as the way to obtain more electrical energy from gasification, but in the case of plasma gasification, there is a decrease in net energy due to the electrical consumption of the gasifier[7]. That is why thermodynamic studies are required to improve the performance of the process.

In this paper, thermodynamic analysis is addressed through the evaluation of the performance criteria of plasma gasification as an individual process and of the IGCC operation. As a method of analysis, the use of models is proposed to explore the effective areas of operation in search of the zones where the performance criteria are maximum, as well as the effects of the operational parameters.

2. Methods used and experimental conditions

A thermochemical equilibrium model was used to perform the calculations and estimates of bagasse gasification performance in this study. This type of model is very popular because it is relatively simple and allows obtaining results close to reality, mainly in gasifiers operating at high temperatures and with gas residence times in which states close to the theoretical equilibrium are reached. However, it does not take into account important aspects such as chemical kinetics and fluid dynamics, which are incorporated in other types of more complex models[8].

Model inputs include: the elemental composition of the biomass and its moisture, the amount of air involved in the process, the enthalpy contributed to the reaction by the thermal plasma, and the ratio of unconverted carbon. The final syngas composition is the main output of the model and constitutes a basic element to calculate the performance criteria.

The thermal plasma energy is taken into account in the energy balance as in the work of Mountouris, Voutsas, Tassios[9] and is shown in Equation 1.

$$\begin{aligned}\Delta H^{\circ}_{f\,biomasa} + w\left(\Delta H^{\circ}_{fH_2O} + H_{(vap)}\right) + m\left(\Delta H^{\circ}_{fO_2} + 3.76\Delta H^{\circ}_{fN_2}\right) + QPlasma \\ = x_{CO}\Delta H^{\circ}_{fCO} + x_{CO_2}\Delta H^{\circ}_{fCO_2} + x_{H_2O}\Delta H^{\circ}_{fH_2O} + x_{CH_4}\Delta H^{\circ}_{fCH_4} \\ + \Delta T\left(x_{H_2}Cp_{mH_2} + x_{CO}Cp_{mCO} + x_{CO_2}Cp_{mCO_2} + x_{H_2O}Cp_{mH_2O}\right. \\ \left. + x_{CH_4}Cp_{mCH_4} + (3.76m + bN)Cp_{N_2}\right) + ncC \cdot Cp_{mC}\end{aligned} \tag{1}$$

Where:

H°_{fi}: the enthalpy of formation of substance *i* [kJ/kmol]

w: water content in the biomass [mol]

m: amount of air involved in the reaction [mol]

Qplasma: enthalpy contributed by the thermal plasma [kJ]

x_i: amount of substance *i* present in the products [mol]

Cp_{mi}: average specific heat of substance *i* [kJ/(kmol·K)]

ΔT: temperature difference between the gasification temperature and 298 K° [K°]

ncC: fraction of unconverted carbon [mol]

H(*vap*): enthalpy of vaporization of water [kJ/kmol].

Other equations in the model are the mass balance of carbon, hydrogen, and oxygen as stated in some literature[10].

$$bC = x_{CO} + x_{CO_2} + x_{CH_4} + ncC \tag{2}$$

$$2w + bH = 2x_{H_2} + 2x_{H_2O} + 4x_{CH_4} \quad (3)$$

$$w + bO + 2m = x_{CO} + 2x_{CO_2} + x_{H_2O} \quad (4)$$

Where *bC, bH*, and *BO* are the hydrogen, oxygen and nitrogen atoms in the simplified form of the biomass molecule.

The equilibrium constants of the methane formation reaction K_1 and the gas shift reaction K_2 were posed[10].

$$K_1 = \frac{x_5}{x_1^2} \quad (5)$$

$$K_2 = \frac{x_1 x_3}{x_2 x_4} \quad (6)$$

The elemental composition of bagasse on a dry basis for this study was as follows: C = 47.5%, H = 5.9%, O = 40.7%, N = 0.29%, moisture = 20%, Ash = 5.6%[11].

The model was validated with the experimental results for autothermal air gasification described[12], air plasma gasification[13], and steam plasma gasification[14] (see **Table 1**). The root means square error (rmse) in the prediction of the percentage composition of syngas was less than 3.5 and in the prediction of the calorific value of syngas less than 0.85 MJ/m^3.

Table 1. Comparison of model results with experimental results of other authors

Criterion	**Ref.[12]**	**Ref.[13]**	**Ref.[14]**
rmse composition	2.80	3.48	1.08
Rmse PCI MJ/m^{3}*	0.39	0.45	0.84

* At standard pressure and temperature

Carbon conversion in a real gasifier depends on many factors: thermodynamics, chemical kinetics, hydrodynamics, heat and mass transfer, residence time, and even particle size distribution, in this research a carbon conversion value of 100% is assumed.

There are several criteria for evaluating the performance of a gasifier. Depending on the use of the syngas, some are more relevant than others. For energy production, the most relevant is the lower heating value of the gas produced (LHV), the cold gas efficiency (CGE), and the specific output of the syngas.

The calorific value of syngas gives the measure of the total amount of heat released in the complete combustion of a unit mass or volume without counting the part corresponding to the latent heat of the water vapor generated in the combustion. The following Equation 7 is used for its calculation:

$$PCI_g = 0.108 \cdot X_{H_2} + 0.126 \cdot X_{CO} + 0.358 \cdot X_{CH_4} \qquad [MJ/\mathrm{m}^3] \quad (7)$$

One of the most widely used efficiency indicators is the cold gas efficiency, which measures the energy efficiency of the gasification process considering the gas produced at ambient temperature and its equation for plasma gasification is taken from the literature of Zhang[15] and expressed in terms of one mole of biomass. See Equation 8 below:

$$CGE = \frac{PCI'_g}{PCI'_{Biomass} + Q_{plasma}} \cdot 100 \quad (8)$$

Where PCI'_g is the lower calorific value of the syngas produced by converting one mole of biomass, $PCI'_{Biomass}$ is the lower calorific value of one mole of biomass.

The specific syngas production can be approximately calculated by assuming a value of 22.4 as the volume of one mole of ideal gas in dm^3 at standard temperature and pressure (see Equation 9).

$$y = 22.4 \cdot x_{tatao} / (12 \cdot \mathrm{bC} + \mathrm{bH} + 16 \cdot \mathrm{bO} + 14 \cdot b\mathrm{N} + 18 \cdot \mathrm{w} + \mathrm{Am}) \;\; [\mathrm{dm^3/kg}] \tag{9}$$

Where x_{tatao} is the total number of moles of gas produced and Am is the ash content in one mole of biomass.

The data to analyze the performance of sugarcane bagasse gasification were taken from works by other authors (see **Table 2**). In them, it is possible to observe PCI values lower than 6 MJ/m^3 and CGE lower than 75% for the autothermal gasification of bagasse. While in plasma gasification the CGE is between 80–85%.

Table 2. Performance of sugarcane bagasse gasification

	Ref.[16]	Ref.[17]	Ref.[18]	
Process type	**Autothermal**	**Autothermal**	**PerPlasma (T = 1227 ℃)**	
Agent Gasf.	Air	Air + steam	Air	Air + steam
CGE	73	68	80	85
PCK(MJ/m^3)	5.98	5.23	n.a.	n.a.

3. Results and discussion

In order to study the effective areas of operation of biomass plasma gasification, experimental results in the literature were consulted, which allowed defining the approximate values of the fundamental operational parameters: equivalent ratio (defined by Equation 10) and the plasma energy ratio (defined by Equation 11) as well as the reaction temperature (See **Table 3**).

$$ER = \frac{actual\ amount\ of\ oxygen}{theoretical\ amount\ of\ oxygen\ for\ complete\ combustion} \tag{10}$$

$$PER = E_{th,plasma} / PCI_{Biomass} \tag{11}$$

Table 3. Operational parameters for plasma gasification

Reaction temperature ºC	ER	PER
920–1,220[13]	0.04–0.18[20]	0.08–0.11[20]
1,122–1,281[3]	0.20–0.25 < 0.25[13]	0–0.20[13]
	0.43–0.52[3]	

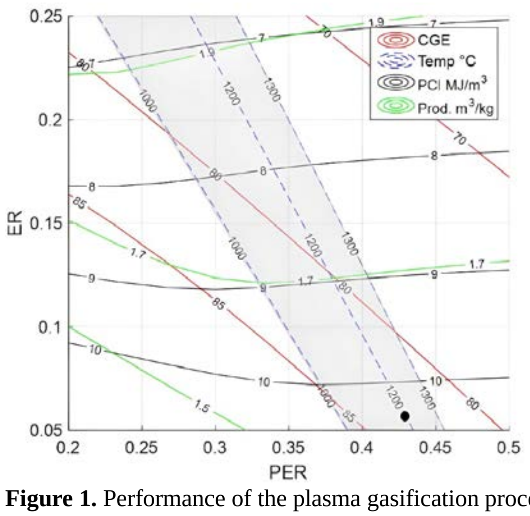

Figure 1. Performance of the plasma gasification process of bagasse with 20% moisture and 100% conversion.

In this study, it is proposed to use a graphical method of analysis using isolines since these allow to study of the influence of the independent variables on a set of different performance indicators in the same figure. **Figure 1** shows the effective operating area between 1,000 °C and 1,300 °C, with an ER higher than 0.05 and lower than 0.25 where the isolines of gasification temperature, cold gas efficiency, the lower calorific value of syngas, and specific syngas production are illustrated.

The ER strongly affects the gasification process; it determines the temperature of the system, the availability of oxygen, the production of syngas, and therefore the composition of the syngas and its calorific value. An increase in RE leads to a higher specific syngas production and at the same time to a higher oxidation which implies a higher production of carbon dioxide, to this is added the dilution effect of the incorporated nitrogen which reduces the PCI of the syngas and therefore also reduces the efficiency of the cold gas.

The PER is a characteristic parameter of plasma gasification with a weak influence on the PCI of the syngas, in the effective area of operation the isolines of the PCI are almost parallel to the axis of the PER. Its greatest influence is seen on the cold gas efficiency, since an increase in PER implies a decrease in efficiency.

Temperature also has a great impact on thermos-conversion, as it modifies the composition of the chemical species produced in the process. In practice, temperature is an important operational parameter at laboratory scale, but in plants it is very difficult to control and measure accurately, since it depends on ER, PER, gasifying agent flows, biomass flow and thermal losses. That is why in this work it is rather considered a constraint, being PER and ER the manipulated variables.

Following the 1,200 °C isoline, corresponding to a typical value for this type of gasifier, it is possible to move the operating point by increasing the PER while decreasing the ER or vice versa. Above this line, in **Figure 1**, a black dot is highlighted corresponding to an operation where the PCI of the syngas is higher than 10 MJ/m3 at standard pressure and temperatures and where the CGE reaches a value of 82%. This CGE result is in agreement with that published by de Souza-Santos[16] (See **Table 2**). In addition, they show the superiority of plasma gasification compared to autothermal gasification in terms of syngas calorific value and cold gas efficiency.

To perform the thermodynamic analysis of the integration of plasma gasification to a combined cycle with efficiency, the approach of Rutberg, Bratsev, Kuznetsovet *et al*.[13] depicted in **Figure 2** was assumed.

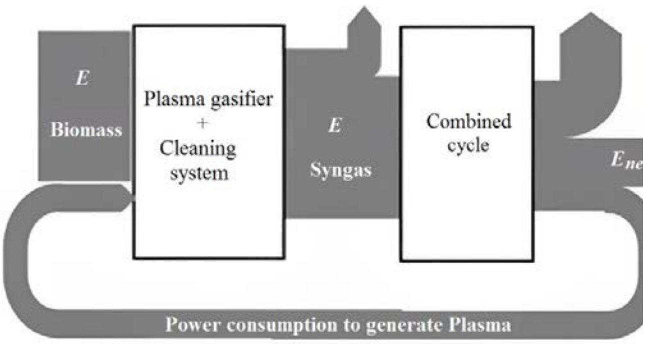

Figure 2. Energy flow in integrated plasma gasifier and combined cycle system.

Equation 12 can be used to calculate the electrical energy produced for each kilogram of gasified biomass:

$$E_{net} = m_{gas} \cdot PCI_g \cdot \eta_{cycle} - E_{plasma} \quad (12)$$

Where E_{plasma} is the electrical energy consumed by the plasma torches to convert one kilogram of biomass.

$$E_{plasma} = Q_{plasma}/\eta_{antorcha} \quad (13)$$

$$Q_{plasma} = PER \cdot PCI_{Biomasa} \quad (14)$$

Substituting Equations 9 and 10 into 8 leaves:

$$E_{net} = m_{gas} \cdot PCI_g \cdot \eta_{ciclo} - PER \cdot PCI_{Biomasa}/\eta_{antorcha} \quad (15)$$

From Equation 15, it can be deduced that if the electrical production is to be increased, the first summand must be increased and the second one decreased, but the first summand depends on PCI_g and these are interrelated because the gasification temperature also depends on them, so optimizing the electrical production is not trivial.

In this work, we propose to use the graphical method to find the operating point that maximizes the electrical production for which an exploration of the entire area of operation was carried out (see **Figure 3**).

Figure 3 shows the performance indicators related to the integration to a combined cycle of a plasma gasifier of bagasse with 20% humidity, i.e. net electricity produced and electrical efficiency. In this simulation $\eta_{cycle} = 0.6$ values of $\eta_{torch} = 0.6$ were assumed as in the work of Rutberg, *et al*[13].

The dependence of the net electricity produced on the operational parameters PER and ER can be seen in **Figure 3**. An increase in PER corresponds to a higher consumption in plasma generation and therefore lower net electricity produced and an increase in ER deteriorates the gas quality and leads to lower electricity generation. The black point represents an operating point above 1,200 °C where the electrical generation is slightly higher than 4 MJ/kg. As can be seen, this point of higher generation does not coincide with the point of higher CGE, but shifts towards higher ER where PER is lower.

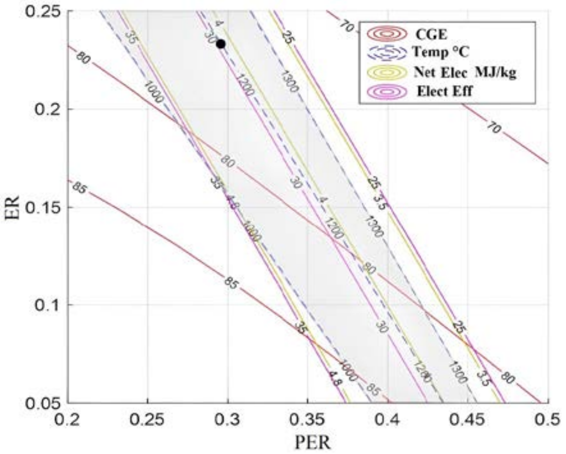

Figure 3. Performance of integration to a combined cycle with cycle efficiency of 60%.

The net electrical efficiency for the system studied reaches 30%, which is undoubtedly higher than the electrical efficiency achieved in plants where bagasse is burned in Rankine cycles with 20% electrical efficiency[17].

4. Conclusions

The plasma gasification process can be modeled by a thermochemical equilibrium approach with a good degree of approximation to the actual results studied, less than 3.5% in the prediction of the percentage composition of the syngas.

The CGE for plasma gasification of sugarcane bagasse (82%) is higher than the reported autothermal CGE studied (68%, 73%). Similarly, the PCI of syngas for plasma gasification of sugarcane bagasse (10 MJ/m^3) is higher than the PCI of the reported autothermal gasification studied (5.98 MJ/m^3, 5.23 MJ/m^3).

For each application of the produced gas, ER and PER must be adjusted to achieve optimal performance. The areas where CEM and net electricity produced are maximized are not coincident; the latter is shifted towards a lower PER and a higher ER with respect to the former. Reaching a net electricity produced in the integration to a combined cycle of 4 MJ/kg of bagasse with 30% electrical efficiency.

According to the scientific literature reviewed, although the net electricity obtained in plasma gasification is lower than the theoretical autothermal, this is a viable option to increase electricity production in the sugar sector, since it is a flexible method, with facilities for process control and produces a syngas with low tar content suitable for integration into combined cycles.

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Conflict of interest

The authors declare that they have no interest of conflict.

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