

## Evaluation of Pyrolysis and Steam Gasification Processes of Sugarcane Bagasse in a Fixed Bed Reactor

Jaiver Efren Jaimes Figueroa\*, Yurany Camacho Ardila, Betania Hoss Lunelli, Ruben Maciel Filho, Maria Regina Wolf Maciel

Department of Process and Product Development. School of Chemical Engineering. Av. Albert Einstein, 500. Cidade Universitária "Zeferino Vaz", CEP 13083-862. State University of Campinas - UNICAMP. Campinas-SP, Brazil.  
[jaiverej@hotmail.com](mailto:jaiverej@hotmail.com)

Sugarcane bagasse is the main byproduct of sugarcane mill, readily available at the production site so that it may be a suitable raw material for the production of biofuels, chemicals and electricity. Among the methods that have been widely studied, there are thermochemical processes such as gasification, pyrolysis and direct combustion. The direct combustion is used to produce electricity while the pyrolysis and gasification are used to obtain high value-added products such as bio-oil and synthesis gas (Syngas). In this study, a comparison between the experimental results by pyrolysis and gasification reactions is performed. The pyrolysis and gasification of sugarcane bagasse was carried out, using a laboratory-scale fixed bed reactor in order to produce bio-oil (pyrolysis) and Syngas (gasification). The gasification and pyrolysis were studied and char, tar and gas productions were evaluated as well as the composition of the gas produced. For the pyrolysis, temperature was varied from 500 °C to 900 °C and a quite broad reaction time range was considered. In gasification, the reaction temperature equal to 900 °C, reaction time and steam/bagasse ratio equal 2.0 were evaluated. The behavior for both processes was presented. Moreover, A comparison of experimental results gasification at 900 °C and SB = 2 with their respective simulation done in Aspen Plus<sup>TM</sup>. The results show that had great concordance between the experimental results and simulated, obtaining relative errors of 0.907%, 7.196% and 3.197% for the H<sub>2</sub>, CO<sub>2</sub> and CO, respectively.

### 1. Introduction

Sugarcane bagasse is a kind of renewable resource that is not only abundant, but also has fewer amounts of contaminants such as sulfur and ash. The use of biomass is eco-friendly and safe and will not add contribution to the total amount of carbon circular in nature. As a result, research on the development and utilization of biomass resources has increased in recent years. Thermochemical processes, which are the main use of biomass resources for hydrogen-rich gas or gas of high heat value of fuel, have the following advantages: do not present strict limitations on the size and type of biomass used *in natura* (for example, municipal solid waste and agricultural and forestry waste residues); the proper use of gas arising from different applications; lesser pollution problems associated with downstream applications compared to combustion (Zhou et al., 2008).

The thermochemical processes such as pyrolysis and gasification produce, besides hydrogen, a gas mixture containing carbon monoxide (CO), carbon dioxide (CO<sub>2</sub>) and light hydrocarbons. This gas is used in many industrial applications such as production of methanol, hydrogen, ammonia, sulphuric acid, formaldehyde or like saturated steam gas turbine. The pyrolysis process at low temperatures (400 - 600 °C) liquid products (Tar) are produced, but gaseous products are produced from high temperature (900 °C). Gasification and pyrolysis are similar processes however the gasification takes place in the presence of oxygen in the form of air or steam whereas the pyrolysis occurs in the absence of oxygen (Zhou et al., 2008).

Gases and liquids produced in the pyrolysis and gasification processes can be used as energy, as heat and electricity or chemicals production. For example, gases with high contents of CO and H<sub>2</sub> can be a source of

synthesis gas (for methanol, DME or Fischer-Tropsch synthesis) or H<sub>2</sub> (fuel cells) (Baumlin et al., 2006). Products with high added value such as hydrogen or synthesis gas can be produced from pyrolysis of bagasse using a fixed bed reactor. The synthesis gas comprises a mixture of hydrogen and carbon monoxide (H<sub>2</sub>+CO). The pyrolysis of sugarcane bagasse can be accomplished in two ways, with or without carrier gas (nitrogen). The literature emphasizes that it is very difficult to perform this process without the use of carrier gas (N<sub>2</sub>); this occurs because the formation of soot. The presence of the carrier gas provide a uniform distribution of the reagent in the reactor bed (Skoulou & Zabaniotou, 2013).

The gasification process can be defined as a process of partial combustion of sugarcane bagasse because it uses an amount of air lesser than that required stoichiometrically. The gaseous product is obtained consisting of hydrogen (H<sub>2</sub>), carbon monoxide (CO) and carbon dioxide (CO<sub>2</sub>), comprising the synthesis gas (Lan et al., 2013). Unlike pyrolysis, gasification occurs in the presence of oxygen in the form of air, pure oxygen or steam, it is not necessary, therefore, to use a carrier gas. The gasification corresponds to a thermal conversion process of the biomass into reactive atmosphere (air, O<sub>2</sub>, steam). The goal is to produce a maximum fraction of gaseous products (mainly CO and H<sub>2</sub>) (Baumlin et al., 2006). Among different types of experimental apparatus to perform the gasification or pyrolysis have the fixed bed reactor. The fixed bed is formed by solid particles mixed with any inert solid through which the agent gasifier or carrier gas flows. This is the simplest type of gasifier and pyrolyzer, usually consisting of a cylindrical space with fuel (bagasse) and supply carrier gases, a system of product removal, both liquid and solid and some types of reactors have a system for removing char. Such reactors are simpler to construct and operate normally with high carbon conversion, the long residence time and gas velocity below which avoids the carryover ash (Puig-Arnavat et al., 2010).

Thus, this paper presents the use of a fixed bed reactor (property of Laboratory of Optimization, Design and Advanced Control - LOPCA/FEQ/UNICAMP) for production of synthesis gas from pyrolysis and gasification of sugarcane bagasse. The influence of the temperature, reaction time and steam on the final distribution of gas, tar and char as well as gas composition obtained were evaluated.

## 2. Materials and methods

### 2.1 Raw material and characterization

The experiments carried out with commercial silica and aluminum oxide, with a purity of 99%, were purchased by Sigma-Aldrich Chemical Company. Sodium chloride (Labsynth) necessary in the ice bath and the Argon, supplied by White Martins, was used as carrier gas.

Sugarcane bagasse previously milled (from Costa & Pinto mill located in the State of São Paulo - Brazil) with a particle size of about 0.36 mm was used as the raw material in this work. The ultimate and proximate analyzes and determination of heat value of sugarcane bagasse were performed. The values are presented in Table 1.

The heating value was determined using a bomb calorimeter and following the methodology of standard ASTM D 5868-10ae1 "Standard test method for gross calorific value of coal and coke".

Table 1: Heat value, proximate and ultimate analyses of sugarcane bagasse

Proximate analysis (wt %)	Ultimate analysis (dry and free of ashes wt %)	Heating value (MJ/kg)		
		Low	High	
Moisture content	2.00	C	44.6	
		H	5.9	
Ash content	6.52	O*	42.1	17.4
		N	0.2	18.7
Volatile matter	88.12	Cl	0.3	
Fixed carbon	3.36	S	0.1	

\*By difference

The proximate analysis was carried out using the technique of thermogravimetric analysis (TGA), according to the following methodology (Ottaway, 1982): 1. Heating of 5 mg of sample using a flow rate of 50 cm<sup>3</sup>/min of nitrogen and ramp of 99 °C/min to 127 °C, keeping the sample at this temperature for 10 minutes. 2. Heat to 927 °C, at a rate of 150 °C/min, and keeping the sample at this temperature for 6 minutes. 3. Cool to 927 °C using a rate of 150 °C/min when the temperature 927 °C, the exchange of air with a nitrogen flow rate of 50 cm<sup>3</sup>/min. Keep the sample at 927 °C for a minimum of 30 minutes. 4. Cooling using a flow rate of 50 cm<sup>3</sup>/min and a nitrogen rate of 150 °C/min to room temperature. Recording the weight loss in all stages.

The elemental analysis was performed on Elemental Analyzer Perkin-Elmer CHN 2400.

## 2.2 Pyrolysis and gasification system and reaction conditions

Figure 1 shows a schematic drawing of the plant for producing synthesis gas that was built up. This plant is proposed in laboratory scale, which allows optimization of process conditions with reduced costs. This plant is available in the Laboratory of Optimization, Design and Advanced Control - LOPCA. The experimental apparatus was built up by the company Termoquip Alternative Energy Ltda. The apparatus consists of a stain steel tubular reactor (200 mm long by 10.75 mm of internal diameter). The carrier gases enter the system through a pressure regulator that decreases the commercial cylinder pressure to atmospheric pressure. Water is fed to the reactor using a liquid chromatography pump, model Water 515). Due to the small dimensions of the reactor, it is necessary to externally heat it in order to compensate heat losses. Therefore, the reactor was equipped with electric furnace (100mm x 100mm x 163mm), ice bath, flow meter, valves and temperature controller (Peres et al., 2010). The liquid product, Tar, was collected in a steel tank of 200 ml. This tank has an outlet side of the gases leaving. The gas obtained was collected in Tedlar<sup>®</sup> bags of 5 L (with a polypropylene fitting for sampling) and the experimental apparatus is presented in Figure 1.

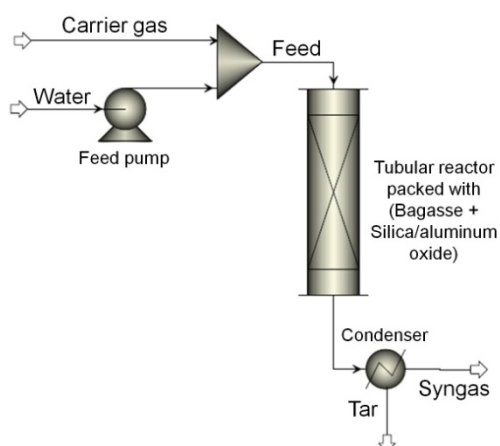


Figure 1: Syngas production flowsheet (system developed by LOPCA research group). Aluminum oxide and silica used in the pyrolysis and gasification, respectively.

The reaction conditions are reported in Table 2.

Table 2: Reactions conditions

	Pyrolysis	Gasification
Raw material	Bagasse (50 wt%)	Bagasse (50 wt%)
Packed material	Aluminum oxide (50 wt %)	Silica (50 wt%)
Carrier gas (mL/min)	Argon (77.5)	Argon (34)
Reactor purge time using carrier gas	20 min	20 min
Condenser temperature (°C)	0.0 -5.0 °C (Ice)	0.0 -5.0 °C (Ice)
Water (mL/min)	0	0.017
Reaction time (min)	135	180
Reaction temperature (°C)	500 - 900	900
Gaseous samples collected	3	9

## 2.3 Analytical methods for gases quantification

Gaseous product analyses were performed in a gas chromatograph (GC) Agilent Technologies, model 7890A, configured to analyze gases (inorganic and organic lights). The chromatograph has two columns: column 1: HP Plot U, 30 m length and diameter, 53 mm and column 2: HP - Molecular sieve, 30 m in length and diameter, 53 mm. The GC is equipped with a thermal conductivity detector (TCD) monofilament and flame ionization detector

(FID), with a detection limit of 0.10 %mol/mol for analyses. The columns, detector and sample circuit are connected to a 6-way valve with pneumatic actuator. The mobile phase used was Argon 5.0. Programming oven temperature: 4 min at 50 °C, 8 °C / min to 140 °C, 0.75 min at 140 °C with total analysis time of 16 min; spin valve set at 4.20 min. Elution order: H<sub>2</sub>, air, CO, CH<sub>4</sub>, turning valve, CO<sub>2</sub>, ethylene, ethane, propane and butane. Calibration of GC system was carried out using the standards at different concentration. Three standards gases were used, which contain gas that would possibly be produced during the reaction pyrolysis and gasification. The gases were purchased from Praxair company. The composition of these gases is reported in Table 3.

*Table 3 Composition of gases used in the calibration standard gas chromatograph*

Gas	% Molar composition		
	Standard 1	Standard 2	Standard 3
Carbon dioxide	51.0	15.0	5.0
Ethylene	5.0	0.0	3.0
Ethane	3.0	0.5	0.0
Propane	4.0	0.0	3.0
Butane	5.0	0.0	1.0
Hydrogen	6.0	35.0	60.0
Methane	11.0	4.5	3.0
Carbon monoxide	15.0	45.0	25.0

To perform the calibration, each standard was mixed with argon (carrier gas used for GC), so as to dilute the sample 10 times. All dilutions were performed using GC split. Each calibration sample was injected three times in order to check the analysis repeatability.

The correlation factor obtained after the calibration procedure was greater than 0.99 in all cases.

#### **2.4 Pyrolysis of sugarcane bagasse**

The pyrolysis process of bagasse is highly temperature dependent. When the pyrolysis is carried out at low temperatures (between 400 and 600 °C), most of the products are liquid, while at temperatures above 750 °C gaseous products are formed. Thus, the determination and control of the process temperature are very important because the desired products are temperature dependent.

The bagasse and aluminium oxide previously dried and weighed were placed into the reactor. Glass wool at the bottom and at the top of the reactor was used in order to support the fixed bed (bagasse-alumina) and improve the distribution of the carrier gas, respectively.

The reactor was sealed and placed inside the electric oven. The valve allowing the passage of the carrier gas was opened, allowing the purging of the system for about 15 min. After, the input and output valves were closed until the temperature reaction was reached. After reaching the reaction temperature, the carrier gas was allowed to pass. The flow rate of carrier gas was adjusted using a needle valve and monitored by a flow meter. The fixed bed occupies 54 % of the reactor, having a length of 70 mm. The reactor temperature is measured at the outer wall of the reactor by means of a thermocouple J.

The reactor product is condensed using an ice-bath with sodium chloride, then forms a liquid stream that is stored in the collector liquid and a gas stream which is collected using collectors type gas, specific for storage of light gases. The liquid product was withdrawn from the condenser and weighed. The gaseous product collected from time to time in the bags was analyzed according to the methodology described below.

At the end of this procedure, the reactor was cooled after the removal of a sample of material that was inside, for subsequent calcination and determination the char percentage (discounting in calculation the value of bagasse ash).

Following the procedure described above, several experiments were performed in which the reaction temperature ranged from 500 °C to 900 °C. Gas was collected three times at intervals of 45 min, thereby giving a reaction time equal to 135 min.

#### **2.5 Gasification of sugarcane bagasse using steam at 900 °C**

The operating procedure and sample collection in the gasification reaction was exactly like the pyrolysis process, the only difference was that when the reaction temperature was reached, it was allowed the passage of carrier gas and the water. Water was fed by means of a HPLC pump (Waters model 515 analytical pump) which controlled the flow of water throughout the reaction.

Water was supplied in liquid form, but when it enters the reactor, instantaneous vaporization occurs, which makes steam enter in the bed reaction.

Only one reaction was performed using a gasification relationship  $SB = 2$ . The relationship  $SB$  is defined in Eq. (1) and presented below:

$$SB = \frac{\text{Steam fed to the gasifier [kg/s]}}{\text{Bagasse fed to the gasifier [kg/s]}} \quad (1)$$

## 2.6 Pyrolysis mass balances

At the beginning of the pyrolysis reaction, the mass of bagasse ( $m_{\text{Bagasse}}$ ) and inert (Aluminum oxide) ( $m_{\text{inert}}$ ) placed in the bed were known. At the end of the reaction, it was possible to measure the mass of tar produced ( $m_{\text{Tar}}$ ) and the material that was inside the reactor ( $m_{\text{Residue}}$ ). Knowing the inert mass and the mass of the residue, which remained inside the reactor, it was possible to calculate the char produced using equation (2).

$$m_{\text{Char}} = m_{\text{Residue}} - m_{\text{inert}} \quad (2)$$

Once known Char using the overall mass balance equation (3) was calculated mass of gas produced.

$$m_{\text{Bagasse}} + m_{\text{inert}} = m_{\text{gas}} + m_{\text{Tar}} + m_{\text{Char}} \quad (3)$$

This, considering that the inert does not participate in the reaction, what is acceptable since the purity of the aluminum oxide was high.

## 2.7 Gasification mass balances

The mass balance in gasification is equal to the pyrolysis, but taking into account that in this case water enters. And as the amount of water pumped, it is possible to calculate the amount of water that had entered into the system.

At the beginning of the reaction, the water flow ( $F_{\text{Water}}$ ) was established such that, by the end of the reaction, had fed an amount of water that met with the ratio  $SB = 2$ .

Knowing the inert mass and the mass of the residue, which remained inside the reactor, it was possible to calculate the char produced using equation (2).

Once known Char using the overall mass balance equation (4), it was calculated mass of gas produced.

$$m_{\text{Bagasse}} + m_{\text{inert}} + F_{\text{Water}} * \text{Reaction time} = m_{\text{gas}} + m_{\text{Tar}} + m_{\text{Char}} \quad (4)$$

This, considering that the inert does not participate in the reaction, what is acceptable since the purity of the aluminum oxide was high. Another assumption is that the residue that remained inside the reactor was completely free of water and Tar.

## 3. Results and discussion

### 3.1 Pyrolysis: gas, tar and char distributions

Following, the results obtained from the pyrolysis process are presented, considering the influence of temperature on the amount of gas, tar and char produced as well as the composition of gases obtained in each reaction.

Figure 2 shows the percentages of gas, tar and char when used different reaction temperatures. Figure 2 shows clearly that the increase of temperature favours the production of gas. This increasing causes the amount of char decreased since the production of tar remained almost constant in all reactions.

The greatest increase was obtained in the temperature change of 700°C to 800°C, managing to increase the percentage of gas from 43.0 to 51.5%.

With those profiles (Figure 2), it can be concluded that the production of tar was approximately the same at all temperatures, 22.11 wt% average. This may have happened because the temperature range used greater-equal 500°C, range which was not favourable to the production of tar. This is in agreement with what is presented by other researchers; at high temperatures the conversion of tar increases (Mogohadam et al., 2013).

From the viewpoint of gas production, which is the main objective, it is concluded that the pyrolysis process needs to be improved. The amount of char is very high which says there is potential to crack this char and turn it into gas.

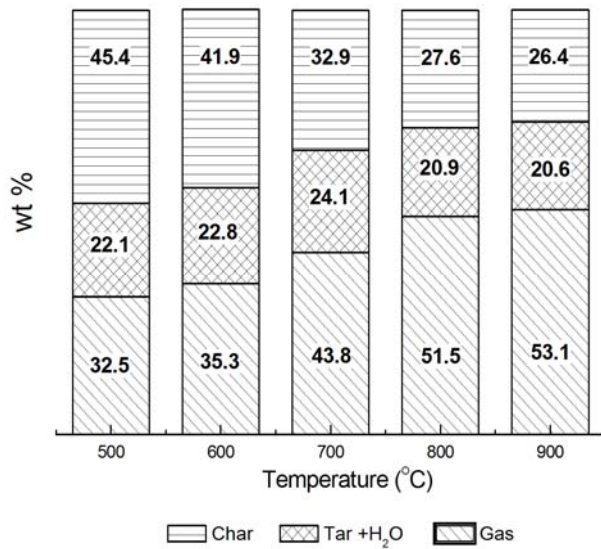


Figure 2: Weight percentage Gas, Tar and Char at different temperatures in the bagasse pyrolysis

### 3.2 Composition of pyrolysis gases

Subsequent to the distribution analyses of gas, tar and char, the gases produced at different temperatures were quantified. Figure 3 presents the mole composition percentages of the gas collected after 135 minutes of reaction. As can be appreciated in Figure 3, the mole composition percentages of the gas depends strongly on the reaction temperature, i.e., depending on the temperature some components are not produced.

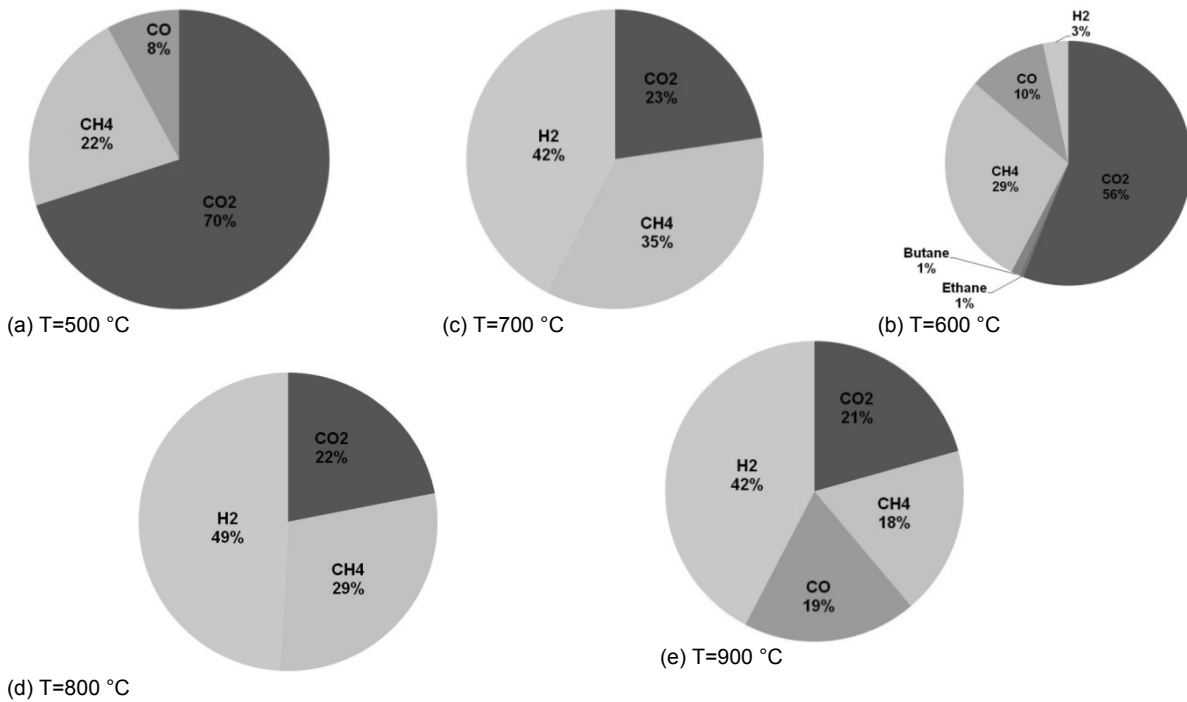


Figure 3: Influence of pyrolysis temperature on mole composition percentages of the gas obtained.

Based on these results it was concluded that:



- 1) The CO<sub>2</sub> and CH<sub>4</sub> gases which are produced at any temperature (Ardila et al., 2012). Have maximum values of 70 % (T = 500 °C) and 35 % (T = 700 °C), respectively. Minimum values of 20.66 % (CO<sub>2</sub>) and 18.14 % (CH<sub>4</sub>) at the temperature of 900 °C are found in 900°C.
- 2) The CO which is the component of interest is produced in only relatively low values at T = 600 °C and high values T = 800 °C and T = 900 °C. There is no production at intermediated temperatures.
- 3) The hydrogen is produced at temperatures exceeding 600 °C, and the maximum value (49.10 %) at 800 °C.
- 4) At temperature of 600 °C organic light gases were produced: butane (1.14 %) and ethane (0.51 %). In other experiments, were not detected by the chromatograph any other gas.

### 3.3 Composition variation of the pyrolysis gases with time and constant temperature

The experiment at 900 °C was selected to study the variation of the gas composition during the reaction time. The composition profiles are reported in Figure 4.

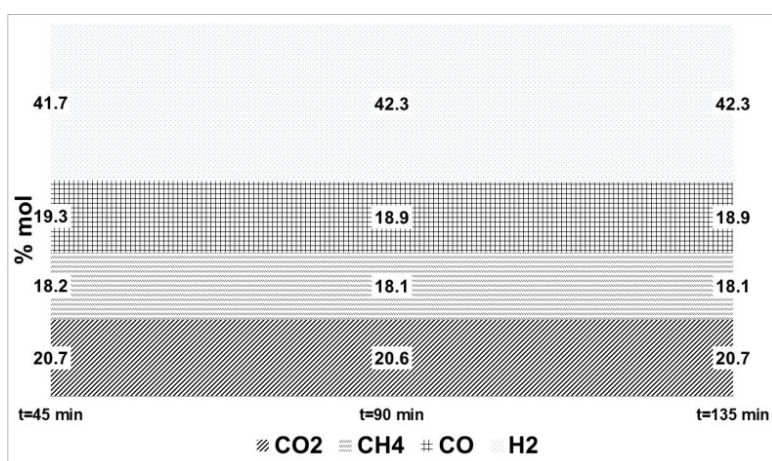


Figure 4: Mole composition percentages profiles of pyrolysis gases obtained at T = 900 °C

As can be appreciated from Figure 4, the gas composition does not vary with time. Coupling this with the information obtained from Figure 3, it can be concluded that the composition of the pyrolysis gases is independent of time and dependent of reaction temperature.

### 3.4 Bagasse gasification at 900 °C using steam

The gasification reaction at 900 °C using steam present a very different behaviour than that shown in the same pyrolysis temperature. The distribution of gas and char percentages changed significantly. In this temperature, the product distribution was char 7 wt%, tar 27 wt% and gas 66 wt% agreeing with the results obtained by Figueroa et al. (2012).

The amounts of tar and gas increased, which consequently led to decrease char. This type of behavior is highly favorable. Another important point was that the percentage of gas obtained was 66 wt%. The high gas production is the main objective of gasification, but it was also important to know what kind of gas had been produced. So, chromatographic analysis was done on gas samples collected from time to time, to be able to report on the final composition of the gases accumulated at each moment. Mole composition profiles of the gases versus time are shown in Figure 5.

In Figure 5 it was possible to appreciate that the compositions of CO<sub>2</sub> and CH<sub>4</sub> remain almost constants over time. The changes are more visible in the profiles of H<sub>2</sub> and CO in which the H<sub>2</sub> increases while that of CO decreases. This is the typical behaviour of the reaction Water-Shift.

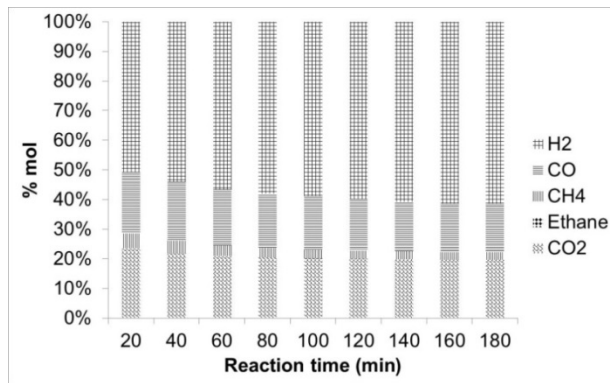


Figure 5: Mole composition percentage profiles obtained in the gasification gas ( $T = 900\text{ }^{\circ}\text{C}$  and  $SB = 2.0$ )

### 3.5 Modelling and simulation of pyrolysis and gasification.

To perform the modelling and simulation of the gasification process, it was necessary to divide the process at different stages: drying, pyrolysis and gasification. For this, it was necessary to model the process of pyrolysis which is presented below.

Using the data obtained in the previous items such as masses of char, tar and gases and the mole composition of gas, it was possible to determine correlations math to adjust the experimental data. The correlation obtained are presented in Table 4.

Table 4 Pyrolysis correlations

Correlations	Adj. R-square
$Y_{\text{Char}} = -1.4806 + 0.0096 * T - 1.5321 * 10^{-5} * T^2 + 7.5 * 10^{-9} * T^3$	0,9755
$Y_{\text{Gas}} = 3.3743 - 0.0146 * T + 2.2535 * 10^{-5} * T^2 - 1.0883 * 10^{-8} * T^3$	0.9961
$x_{\text{CO}_2} = 326.1783 - 0.7135 * T + 4,1478 * 10^{-4} * T^2$	0.8710
$x_{\text{H}_2} = -240.1154 + 0.6553 * T - 3.7449 * 10^{-4} * T^2$	0.6878
$x_{\text{CH}_4} = -126.2937 + 0.4634 * T - 3.3644 * 10^{-4} * T^2$	0.9137

$Y_i$  = Mass yield = kg produced of  $i$ /kg of bagasse

$x_i$  = mole composition

Using the commercial simulator Aspen Plus<sup>TM</sup> V7.3, there was a mass balance for each test at different pyrolysis temperatures. R-Yield reactor was used which had incorporated the mass balance equation in Fortran. The mass balance is presented in equations 5 and 6. With the results of the balances Tar yield and molar composition of CO were calculated, which along with the ultimate analysis of sugarcane bagasse, was calculated the ultimate analysis of the Char with the equation 7. The results of this step are presented in Table 5 and Figure 6.

$$Y_{\text{Tar}} = 1 - Y_{\text{Char}} - Y_{\text{Gas}} \quad (5)$$

$$Y_{\text{Tar}} = 1 - Y_{\text{Char}} - Y_{\text{Gas}} \quad (6)$$

$$\text{Element } i_{\text{Char}} = \text{Element } i_{\text{biomass}} - \sum_{\text{Element } i} \text{Gases} \quad ; \text{ Where the elements are Carbon, hydrogen and oxygen} \quad (7)$$

The assumptions made for the simulation of the pyrolysis were:

- 1) Process is in steady state and isothermal
- 2) The instantaneous drying and pyrolysis
- 3) In the pyrolysis or devolatilization the char and volatiles are formed.
- 4) The volatiles include non-condensable, such as  $\text{H}_2$ ,  $\text{CO}$ ,  $\text{CO}_2$ ,  $\text{CH}_4$ , condensable volatiles (Tar), and water.
- 5) Char contains carbon, hydrogen, oxygen and ash.
- 6) In order to avoid having a large variety of tar compounds, this group is represented only by Phenol.
- 7) The nitrogen was not considered.



Table 5 Mass balances of the pyrolysis

Temperature (°C)	Simulated values			Experimental values			Relative error		
	$Y_{Char}$	$Y_{Tar}$	$Y_{Gas}$	$Y_{Char}$	$Y_{Tar}$	$Y_{Gas}$	$Y_{Char}$	$Y_{Tar}$	$Y_{Gas}$
500	0.442	0.245	0.313	0.450	0.220	0.320	1.741	10.127	2.348
600	0.405	0.256	0.339	0.420	0.230	0.350	3.589	10.163	3.388
700	0.333	0.243	0.424	0.330	0.240	0.430	0.800	1.344	1.398
800	0.268	0.226	0.505	0.280	0.210	0.520	4.376	7.232	2.895
900	0.256	0.225	0.518	0.260	0.210	0.530	1.420	6.774	2.242

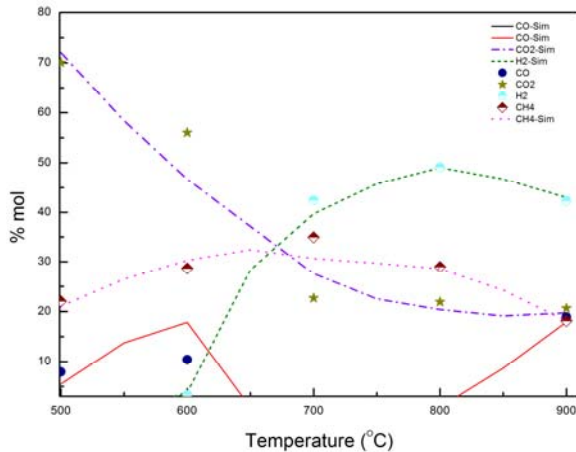


Figure 6: Mole composition percentages of pyrolysis gas: experimental and simulated values

As shown in Table 5 and in Figure 6, when comparing the experimental and simulated data obtained from modelling and simulation of the pyrolysis process, it can be appreciated that there is a high correlation between them, having the same profile and low error.

After pyrolysis correlated data and have entered these correlations to the simulator, was performed a simulation of the gasification step. A Gibbs reactor was considered and before enter with the products of this pyrolysis stage, it was necessary to decompose the compounds into elements, since this type of reactor (R-Gibbs) does not use non-conventional compounds. After simulation, gasification gas cleaning was performed using a cyclone, a condenser and finally a flash separator. The flowsheet is shown in Figure 7.

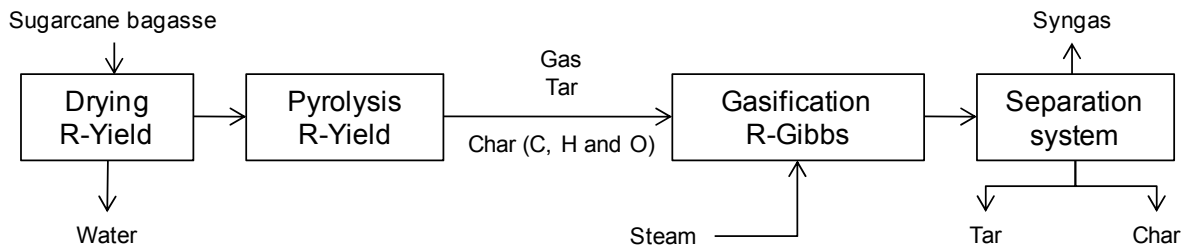


Figure 7: Flowsheet of gasification process

Table 6 shows the comparison of experimental data and results of sugarcane bagasse gasification at  $T = 900\text{ }^{\circ}\text{C}$  and using  $SB = 2$

Table 6 Comparison of the mole composition percentage of the gases obtained by gasification.

	$x_{CO}$	$x_{CO_2}$	$x_{CH_4}$	$x_{H_2}$
Experimental values	19.22	17.65	2.00	61.79
Simulated values	18.62	19.02	0.0012	62.36

As can be appreciated in Table 6, the simulation gave a satisfactory prediction of the composition of the gases produced. However the CH<sub>4</sub> had a considerably larger error which is common and it has been reported by other authors (Doherty et al., 2009). Relative errors obtained were 0.907%, 7.196% and 3.197% for the H<sub>2</sub>, CO<sub>2</sub> and CO, respectively.

#### 4. Conclusions

The pyrolysis and gasification processes have the potential to transform crushed sugarcane bagasse to gases, which are mainly composed of H<sub>2</sub>, CO, CO<sub>2</sub> and CH<sub>4</sub>.

In the tar production (bio-oil) were obtained values close in the experimental tests carried out at different temperatures, i.e. for each 100 g of bagasse used, approximately, 20 to 30 g of tar were produced. This behaviour may be due to the studied temperature range (T > 500 °C). According to the literature, at lower temperatures, the amount of tar always increases.

The use of a gasification agent, in this case steam, promotes increased quantity of gas produced, reaching almost 70 wt% and furthermore decreases the production of char, indeed highly desirable.

The fixed bed reactor is a recommended equipment to study the pyrolysis and gasification reactions at laboratory scale, since it allows to use small amounts of raw material and lower operating times.

The gasification process simulation has shown to be a powerful tool to predict the system behaviour, which has been shown to have low error when the results were compared with the experimental values

#### Acknowledgment

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