Biomass Gasification Optimization: Semi-Pilot Scale 2 kg/h of Bagasse in Fluidized Bed Reactor

Jaiver Efren Jaimes Figueroa*[a], Yurany Camacho Ardila[b], Rubens Maciel Filho[b], Maria Regina Wolf Maciel[b]

[a]School of Chemical Engineering. Av. do Portugueses, 1966. Cidade Universitária "Dom Delgado", CEP 65080-805. Federal University of Maranhão. São Luis-MA, Brazil
[b]Department of Process and Product Development. School of Chemical Engineering. Av. Albert Einstein, 500. Cidade Universitária "Zeferino Vaz", CEP 13083-862. University of Campinas - UNICAMP. Campinas-SP,Brazil
*jaiver.figueroa@ufma.br

The gasification process may be utilized to transform the lignocellulosic material, in this case bagasse sugarcane, in three major products: coal, tar and gas (mixture of hydrogen, carbon monoxide, carbon dioxide and methane, mainly). The products have high potential as raw material for added-value fuels; among these fuels the hydrogen, which has lower capacity of environmental contamination (Anukam et al., 2016).

In literature, most of the work covers two scale kinds of biomass gasification processes:

a) Small-scale processes processing mass flow rate of the order of 10-1 kg / h, the most largely used kinetic data are the result of work done in this range.

b) Large-scale processes, processing 102 - 103 kg / h of biomass.

This fact has led to some phenomena, presented on the large-scale processing, which are not explained, because the kinetic in which the process is based on was conducted in a completely different scale and sometimes even the regime is not the kinetic one, mass transfer and heat phenomena are scale dependent and hence with completely different behaviours (Shen et al., 2017). In this context, this work presents a semi-pilot scale reactor, 2 kg of biomass/h as platform for investigation the main phenomena taking place in the process. Such a rig scale developed in house allows the collection of data in different operating conditions, combining ease of operation and more accurate measurements, typical of small scale, with the phenomenology of large-scale equipment.

Taking this into consideration, the reactions that occur in the biomass gasification process in a reactor with a processing capacity of 2 kg / h biomass were evaluated. The operability of the equipment, heating rates and cooling the reactor, start-up time, evaluation of the collection system and quantification of samples were identified and evaluated. After setting the operability of the equipment, optimizing the gasification process with the objective of maximizing the gaseous fraction obtained was carried out through changes in the air / biomass ratio used with respect to the same relationship required for complete combustion; this ratio is defined as ER. Varying the ER ratio, gas fractions, tar and char obtained, as well as gas composition and the amount of water in the tar were determined, allowing to identify suitable operational policies.

1. Flowchart of gasification plant

Gasification plant essentially consists of a feed silo, a fluidized bed reactor, cyclones, steam reforming reactor, condenser, filter and burner (Figure 1). The process begins with dry and milled biomass, fed from stirred Feed Silo (SAA) using a cooling Screw Conveyor (RT). Silo (SAA) was sealed with low argon flow (although it is expensive, the amount used was small) to prevent reactor gases flow into the silo.

The reactor is a Fluidized Bed (LF) containing sand that utilizes air from the compressor. Air flow fed to the system was measured with a rotameter connected to the line (RO1). Before being injected into the fluidized bed (LF) the air flow is heated up to 350-400 °C with electric heater (RC1).

The reactor has external electrical resistance (RC1 and RC2) for heating through the metal wall. Coal formed in the reactor (LF) is removed just above the sand bed expanded into a Coal Deposit (DC1) for subsequent storage and quantification.

Gas and tar produced in LF pull coal, ash and fine sand (by sand weighing after the process, it was found that fine sand was approximately zero). This particulate material was retained in two cyclones (C1 and C2) insulated with ceramic fibre and heated with electrical resistance (RC3), in order to avoid tar condensation inside the equipment. Charcoal fractions from the cyclones was collected in storage for coal (DC2 and DC3) and stored for later measurement.

When the mixture of gases and condensable leaves the second cyclone (C2) there are two trajectory options:

a) It is sent to the burner (CC) that works at temperatures greater than 700 °C in order to transform it to CO2 and H_2O, released to atmosphere.

b) It is sent to the steam reforming reactor (RFC) heated in a controlled way between 600 and 900 °C with the aid of electrical resistance (RC4), installed on the outer wall. In this reactor there is also a steam stream, which is obtained by heating the water reservoir using an electrical resistance (RC5). The water entering the reservoir is pumped by a peristaltic pump (BO).

After gases leave the reforming reactor they are sent to a condenser, which works with a water bath with ethylene glycol (operating at -5 °C). At the condenser output, tar is collected in the trap (TP) and the gases are sent to the bag filter (FM). There are gas sampling points before and after bag filters. After passing through the filter, the gases enter the CC burner and are released to the atmosphere.
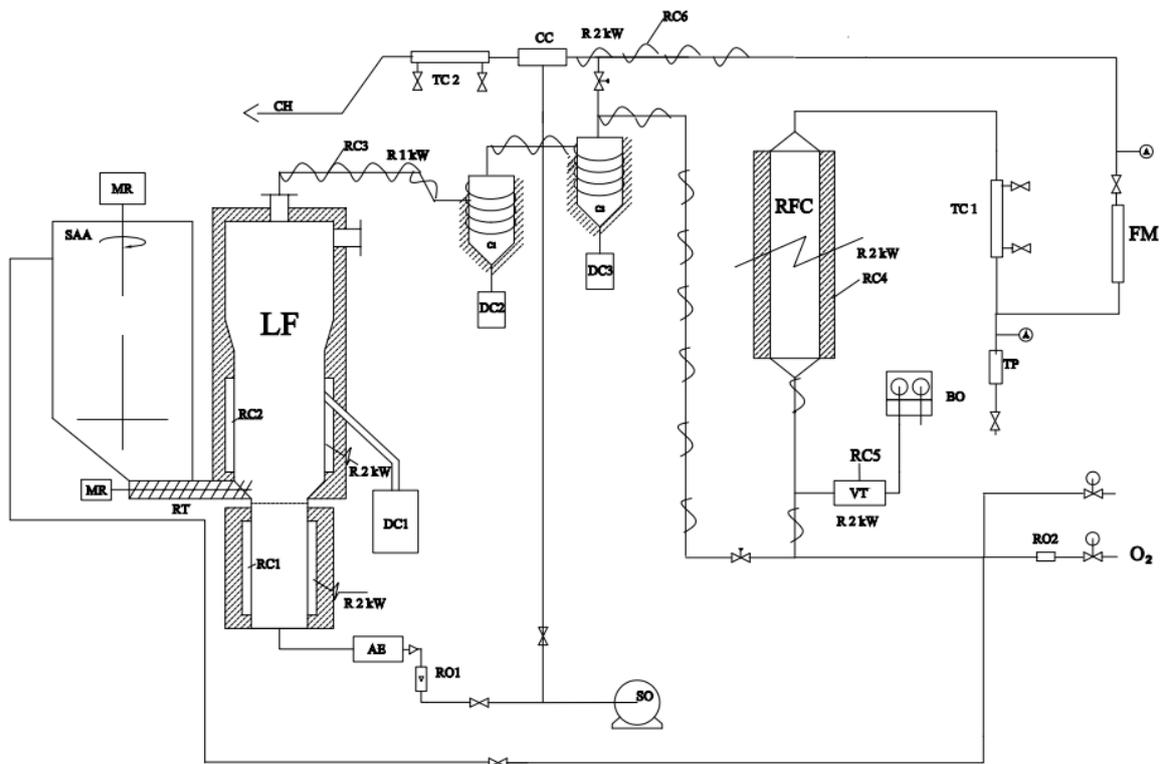

Figure 1: Flowchart of gasification plant and reforming reactor processes (Modified from Jaimes Figueroa et al., 2014).

In the two previously explained trajectories: in the case a) gasification and collection of coal was carried out; in the case b) gasification, steam reforming, gases cleaning, tar collection and sampling of gases were performed. In the case b without the need for steam reforming, the procedure was the same. The reforming reactor (RFC) operating at maximum temperatures of 400 °C was only change, thus ensuring that there were no reforming reactions and that the tar would not condense inside the RFC. This latter procedure was developed in this chapter. When performing steam reforming, the catalyst loses activity due to carbon particles that are deposited on its surface, making it regeneration necessary. For catalyst regeneration, a mixture of oxygen and argon is fed into the reformer by burning thus all the material deposited on the catalyst and recovering its activity. Gas concentration was about 5% (v/v) avoiding too rapid reactions.

2. Installation and start-up of gasification plant

The purpose of this session was to present the installation and conditioning procedures of the plant for proper operation, taking into account: operating conditions (T = 500 - 900 °C and P = 1 atm) and safety in the laboratory. With these procedures a working methodology was created to be followed whenever starting a reaction.

For a better plant installation presentation, the procedure was divided into the following items:

- Mechanical mounting of equipment;
- Installation of water and electricity services;
- Monitoring possible leaks;
- Installation of electrical resistances at points where the process needs external power supply;
- Thermal insulation.

2.1 Mechanical mounting

The plant was installed on a 9 m^2 area (3 m length x 3 m wide) and 15 m height. A 60 cm space was left around it to free movement.

The plant has several connections; therefore there are different points of possible leaks. All plant flanges were tightening crosswise, and asbestos was used to improve the seal. In initial tests, as air was used, additional care was not required. For gasification tests a CO detector (Spygas CO) was obtained, which had an audible alarm, allowing monitoring leakages of this toxic gas.

2.2 Water and electricity services

Water services were necessary due to heat exchangers. Water was the coolant liquid. The plant has three heat exchangers:

- Exchanger in the feed screw: it is necessary because due to screw friction, the system heats and may affect the engine that drives the system.

- Exchanger at the reforming reactor exit, in order to condense all the tar. Early in the project, water was used at room temperature/ however, the heat exchange was not enough, making it necessary to install a thermostatic bath, using water and ethylene glycol as coolant liquid.

- Exchanger in the burner output (CC). Before being sent into the atmosphere the gases are burned and subsequently cooled.

Three-phase power was connected to the main panel of central control from which are triggered: electrical resistances for system heating, bagasse feed screw, bagasse silo mixer, air compressor and the gas mass flow meter.

2.3 Leakage Monitoring

To check for leakages, the system was fed with ambient temperature air through the compressor using the highest flow rate (70 L/min). After one hour the complete filling of the reactor occurred. Later, a special solution was sprinkled throughout the plant (Snoop® of Swagelok®) for leak detection. Thus, leakage spots were identified and then eliminated. Among the most common points were the flanges screws and places where asbestos fabric was not centered or glued to the metal.

2.4 Electrical resistances

The plant has a heating system by means of electrical resistances. In total 6 resistances were installed, which are located:

1) In the air entrance of the gasification reactor, ensuring proper temperature to initiate the reaction (T ≥ 400 °C).

2) In the gasifier, to perform the reactor heating to temperature above 450 °C, allowing bagasse ignition.

3) In the cyclones and reformer-cyclones piping, assisting the gasification products do not condense in the line (T = 300 °C).

4) In the steam reforming reactor, to raise gas and tar temperature, allowing the catalyst activation (T = 800 °C).

5) In the water tank to evaporation (T = 150 °C at the wall).

6) In the gas burner to ensure complete combustion and release of CO_2 and H_2O to the atmosphere.

Each electrical resistance works with a thermocouple and a panel, closing a control loop.

In addition to the six thermocouples previously mentioned, the plant has five additional thermocouples:

1) Within the gasification reactor (FB), 2 cm above the bagasse entry point to the reactor.

2) In the gas entrance in the first cyclone (C1).

3) Inside the steam reforming reactor (SRR), 10 cm from the base of the reactor.

4) Within the steam tank (VT).
5) Within the burner (CC).

2.5 Thermal insulation

Ceramic fibre was the thermal insulation used, which is light, non-combustible, rot resistant and low thermal conductivity (about 0.035 W/mK). Insulation was done from the air heater (EH) to the burner (CC), except in the tar condenser and bag filter. In parts of the system as the reactors, where they would be at very high temperatures, before ceramic fibre, a blanket of asbestos was used.

3. Gasification reactions

The air/bagasse ratio, ER (Jaimes Figueroa et al., 2014), range between 0.18 and 0.32, intermediate values were chosen to be held gasification reactions. Table 1 shows the conditions used.

The reactions started with start-up protocol (method for connecting the plant and set it to bagasse feeding conditions), explained earlier; after reaching 400 °C inside the gasifier, the air and bagasse feed systems were set according to the experiment requirement (Table 1). Since the system was already completely filled with air and at temperatures of starting the reaction, when the bagasse inlet was set, the temperature inside the gasification reactor began to increase and quickly stabilized, which may be considered that the system reached steady state.

Before starting feeding, a gas collection was made, which came out of the plant (at the sampling point after the bag filter). Once the reaction started, gas samples were taken from 5 in 5 minutes. The tar was collected in the reservoir, which was periodically emptied (every 10 minutes), using a peristaltic pump. The reaction time was 20 min. After this period, bagasse feed was turned off, but the air passage was permitted for a further 5 minutes.

After the system was cooled by natural convection (about 8 hours), collecting, weighing and tar storage were performed. The storage was made in a freezer and protected from light.

Table 1. Experimental conditions of gasification reactions.

Experiment	ER	Bagasse mass flow (kg/h)	Air volumetric flow at 25 °C (L/min)
1	0.18	2.78	33.69
2	0.20	2.55	34.32
3	0.23	2.20	34.21
4	0.25	1.97	33.15
5	0.27	1.86	33.69
6	0.28	1.86	34.99
7	0.30	1.74	35.10
8	0.32	1.62	34.94

Coal collection requires plant opening (open Coal reservoir 1 and remove Coal reservoir 2 and 3) (Figure 1). Coal collected was weighed and stored separately, considering the place where it was obtained.

Subsequent to collection of products, the plant was again heated at 900 °C using 50 L/min air for 2 hours, in order to remove any impurities that have remained and could influence the next reaction results.

4. Results and discussion

4.1 Reaction temperature and distribution of products

As shown previously, the gasification process consists of several stages formed by various reactions: pyrolysis, *Boudouard*, cracking, *Water Gas Shift* and combustion, among others. These reactions are mostly endothermic; they continuously require a power supply that is directly related to the temperature. Thus, manipulating reaction temperature indirectly manipulates the types of products to be produced.

Gasification temperature depends primarily on two factors: the type of reactor and ER relationship. Figure2 shows the distribution of products when two ER values were used, and as a consequence the reaction temperature reached different values. It can be seen that an increase in ER causes an increase in reaction temperature, values represented by T1 (temperature inside the gasifier, point where the air comes into contact with the bagasse) and T2 (temperature of gases in the gasifier exit).
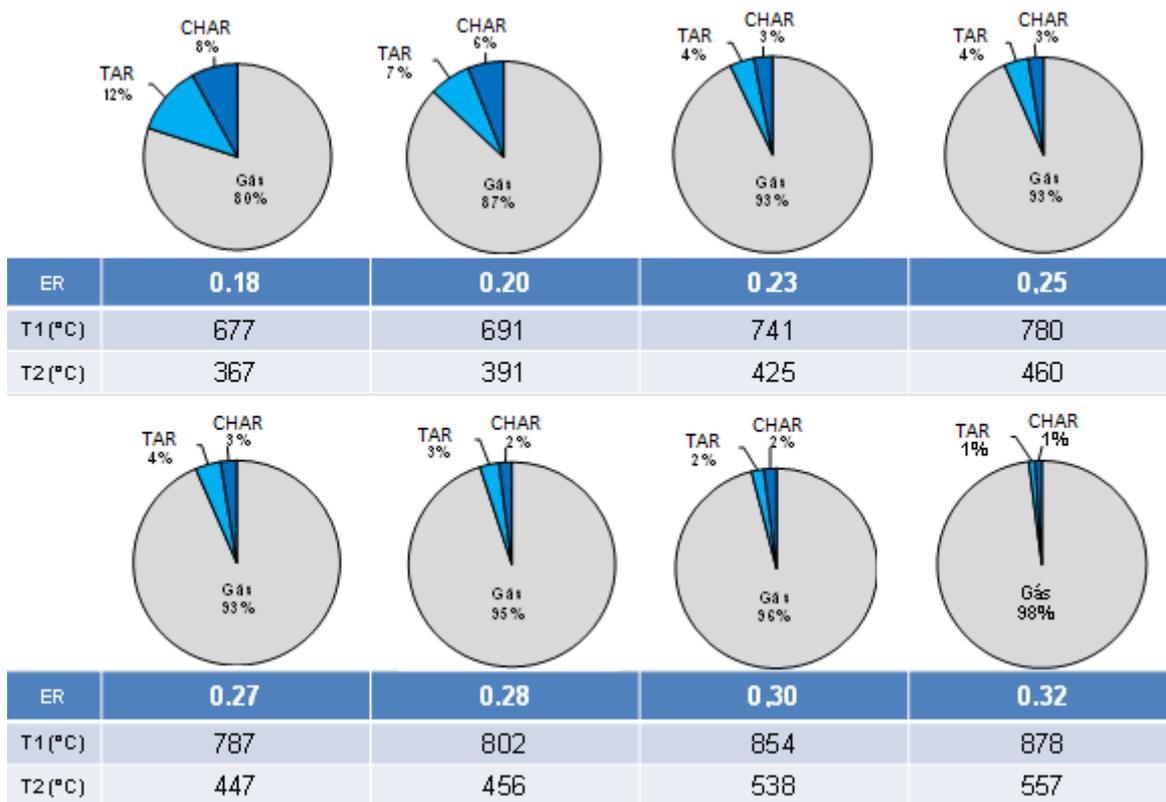
Figure2: Effect of ER relationship on the distribution of products and reaction temperature.

The difference between T1 and T2 temperatures is due to the fact that the gasification and pyrolysis reactions are endothermic, thus the heat released in the combustion (hence, T1 temperature has a high value) is rapidly consumed, decreasing the gas temperature in the reactor outlet (T2).

The distribution of products, in temperatures studied, clearly shows a gas production trend, obtaining lower tar and coal values, and the percentage of tar was always higher than coal percentage. At higher temperatures, an increase in cracking of primary pyrolysis products occurs, increasing the percentage of gases from the disappearance of tar. The same process occurs with coal: at high temperatures, it reacts to produce gas. It can thus be concluded that if the objective is the production of gases, high temperatures should be prioritized; however, understanding the composition of the gases is necessary.

Conducting mass balances for each reaction, one can trace a profile of some variables, regarding the ER reason used. **Errore. L'origine riferimento non è stata trovata.** shows the most common relationships found in thermochemical processes, variables that relate the products (gas, tar and coal) with feed (sugarcane bagasse).

Table 2. Evaluation variables of gasification performance.

ER	T1	m³ gas/kg fed bagasse	g coal/100 g bagasse	g tar/m³ gas
0.18	677	1.26	14.98	178.35
0.20	691	1.44	11.81	95.67
0.23	741	1.67	5.56	46.46
0.25	780	1.74	5.53	50.87
0.27	787	1.82	5.30	46.80
0.28	802	1.93	4.50	50.15
0.30	854	1.98	4.90	24.77
0.32	878	2.10	2.55	12.13

In table 2, as in Figure 2, it can be observed that gas production increases, due to temperature increase, causing the processing reactions of coal into gas to be completed. Analysing the amount of tar present in the produced gas it is concluded that temperature promotes tar disappearance, but aiming at the production of a

clean gas (raw material of other process), the amount of tar in the gas is still quite significant. Therefore, the system needs a subsequent process of gas cleaning to prepare it for a next stage.

4.2 Tar produced during gasification

The amount of tar present in the gas defines which cleaning stage must be coupled to condition the gas to a posterior process. Therefore, tar was condensed and characterized. After condensation tar separates into two phases, an aqueous phase (aqueous tar) and another phase called insoluble tar. The amount of aqueous phase increases with increase of reaction temperature, since temperature promotes tar decomposition. Such decomposition occurs by different routes, one of the most important is Water Gas Shift reaction, which is favoured at high temperatures and because it is reversible it can increase the amount of water produced. Furthermore, the concentration of water (Karl Fischer analysis) of the obtained aqueous phase was determined, finding it is almost completely composed of water. Water percentages, in tar aqueous phase, are presented in Table 3.

Table 3. Percentage of water in the aqueous phase of tar.

ER	T1	Percentage of water in aqueous tar
0.18	677	92.35
0.2	691	93.32
0.23	741	95.45
0.25	780	95.97
0.27	787	97.21
0.28	802	97.69
0.3	854	98.24
0.32	878	99.02

5. Conclusions

The fluidized bed reactor presented in this study has great potential for continuous gasification of sugarcane bagasse, capable of operating with low air flow and low bagasse pressure, allowing the use of the plant in a wide range of experiments with no large consumption of raw materials.

A relative increase in ER, and hence the reaction temperature, increases the process efficiency in terms of conversion to gases. Using ER = 0.30, it was found that 96% mass of reactor outputs are gases, and of these, 12.95 %mol were CO and 5.50 %mol per hydrogen, resulting in a CO/H_2 ratio equal to 2.35. The other main compound was CO2 with about 11.78 %mol.

Due to the presence of other gases such as ethylene, ethane, propane, butane and methane (adding about 3.6 %mol), the use of a process subsequent to gasification is recommended to continue the cracking of these components, and therefore, their transformation into high-value gases such as H_2 and CO.

The process yield for tar production was low, fulfilling the objective of this study, bagasse gasification aiming at producing gases. It was determined that the higher content of produced tar is water, component easy to manipulate and diluents of other contaminants which belong to tar.

Acknowledgments

Reference

Anukam, A., mamphweli, S., Reddy, P., Meyer, E., Okoh, O. 2016, Pre-processing of sugarcane bagasse for gasification in a downdraft biomass gasifier system: A comprehensive review, Renewable and Sustainable Enery Reviews, 66, 775-801.

Jaimes Figueroa, J. E., Ardila, Y. C., Maciel Filho, R., Wolf Maciel, M. R. 2014, Fluidized bed reactor for gasification of sugarcane bagasse: distribution of syngas, bio-tar and char, Chemical Engineering Transactions, 37, 229-234.

Shen, Y., Yu, S., G, S., Chen, X., Chen, M. 2017, Hydrothermal carbonization of medical wastes and lignocellulosic biomass for solid fuel production from lab-scale to pilot-scale, Energy, 118, 312-323.