CHEMICAL ENGINEERING TRANSACTIONS

VOL. 37, 2014

A publication of AIDIC
The Italian Association of Chemical Engineering
www.aidic.it/cet

Guest Editors: Eliseo Ranzi, Katharina Kohse- Höinghaus

**ISBN** 978-88-95608-28-0; **ISSN** 2283-9216

DOI: 10.3303/CET1437039

# Fluidized Bed Reactor for Gasification of Sugarcane Bagasse: Distribution of Syngas, Bio-Tar and Char

Jaiver Efren Jaimes Figueroa*, Yurany Camacho Ardila, Rubens 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

A fluidized bed reactor to gasify sugarcane bagasse was designed and built in order to produce syngas. A study of the effect of two variables -- ER ratio (defined as the ratio between the air flow introduced into the gasifier and the air stoichiometric flow required for complete combustion of the bagasse) and reaction temperature -- on the product distribution (syngas, bio-tar and char) and syngas composition have been analyzed. The ER ratio has a positive effect on gas production, increasing production when a higher ER is used. The char yield decreased at higher temperatures and yield of bio-tar remained almost invariant regardless the value of ER. The amount of bio-tar in the syngas was very small, but it was found that the bio-tar was almost water (> 95 wt% of water). The highest ER promoted the production of larger quantities of hydrogen and carbon monoxide, while reducing the amount of carbon dioxide.

## 1. Introduction

Biomass processing has turned into a great source of study and breakthroughs in terms of new processes and products. One concept that has helped in this development was the biorefinery, which allows actual biomass to generate a wide range of products and moreover is energetically self-sufficient (Dias et al., 2013b). In general, the study of biomass has been fractionated trying to find ways to take advantage of each of its constituents. For example: sugarcane, from which first and second generation products, besides the production of electricity, can be obtained (Dias et al., 2013a).

In recent years, many studies and reviews are being directed to the processing of biomass to use in an integral manner. This route is the gasification of biomass, in which it is fully transformed to products with high added value such as: syngas (gaseous), bio-tar (liquid) and char (Jaimes Figueroa et al., 2013).

This paper presents the behavior of bagasse gasification of sugarcane in a fluidized bed reactor operating with continuous feed, and the effects of temperature and relative air / bagasse have been studied.

Fluidized beds offer many advantages when compared with other gasification reactors. Fluidized beds can be operated with biomass of different chemical compositions and different percentages of moisture. Additionally allows an excellent temperature distribution uniformity, high heat transfer rates, as well as the high conversion of biomass to gas.

## 2. Experimental procedure

### 2.1 Sugarcane bagasse

The bagasse used in this work was a donation from the São João plant located in the State of São Paulo - Brazil. The material was dried at room temperature and reduced in size using a hammer mill. Moisture equal to 7.8 wt% was determined using a moisture analyzer (Gehaka model IR 2000) and the average particle size measured was 0.3 mm.

The chemical composition of the bagasse was determined using three characterizations: a) Ultimate analysis was performed using an elemental analyzer (Perkin Elmer model 2400 CHN). b) Proximate analysis was performed using a thermogravimetric analyzer (TGA Mettler-Toledo, model TGA-DSC1) and

Please cite this article as: Jaimes Figueroa J.E., Camacho Ardila Y., Gimenez Peres A.P., 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 DOI: 10.3303/CET1437039

following the methodology proposed by Garcia et al. (2013). c) Lignocellulosic analysis was carried out and was based on published protocol (Sluiter et al, 2012). In addition to the above analyses, the particle density of the bagasse was determined using the technique of pycnometer with helium gas.
The report of the bagasse characterizations is shown in Table 1.

*Table 1: Characterization of sugarcane bagasse*

| Proximate analysis (wt%) | | Ultimate analysis (wt% free water) | | Lignocellulosic analysis (wt% free water) | |
|---|---|---|---|---|---|
| Moisture | 7.8±0.50 | C | 44.52±1.59 | Cellulose | 40.99±0.72 |
| Fixed carbon | 10.81±0.33 | H | 5.90±0.22 | Hemicellulose | 25.45±0.85 |
| Volatile matter | 83.97±0.36 | N | 0.32±0.08 | Acid insoluble lignin | 14.47±0.45 |
| Ash | 5.22±0.68 | S | 0.10 | Acid soluble lignin | 5.26±0.04 |
| | | Cl | 0.29 | Extractives | 4.86±1.09 |
| | | O* | 43.65 | | |
| Bagasse particle density (g/cm$^3$) | | | 1.49±0.01 | | |

* by difference

**2.2 Experimental apparatus**

The bagasse gasification was taken in a bench-scale equipment (Figure 1). The process began with dried and crushed bagasse, fed from storage silo (SS), by means of a screw conveyor (SC) cooled with water. The silo SS and SC are sealed using a low flow of inert gas (Argon) to prevent gas flow from the gasifier to the silo. The reactor is fluidized bed (FB) containing sand fluidized with air flow from the compressor (COM) and measured by rotameter (RO). The bagasse to be gasified also enters into the reactor. The height of the expanded bed is 300-400 mm. The reactor has externally installed electrical resistances (RC1 and RC2) in the plenum and in the bed to heat through the metal wall. Some char formed in the reactor (FB) is removed just above the sand bed expanded to a deposit (DC1) and stored for later disposal.
The gasification produces a gas (syngas + bio-tar) and a solid (char). The gas leaves the reactor dragging fine particles of char, ash, and sand (The particles decrease in size due to friction and material can be drawn pneumatically). This particulate material is retained in two cyclones (C1 and C2), which are heated with electric resistance and insulated with ceramic fiber, thereby preventing bio-condensation of bio-tar in line. After passing through the condensing bio-tar system and the sampling points, the syngas is sent to the catalytic combustor (CC), thus eliminating the combustible gases. After burning, the combustion gases are discharged into the atmosphere through the chimney (CH). The syngas is collected in a special bag (Tedlar bags of 5 L with a polypropylene fitting for sampling), to analyze them by gas chromatography. char and bio-tar condensate were collected quantitatively to determine their conversions.

**2.2.1. Gasifier design**

For this laboratory reactor, a system of electric heating for the air that enters the system to reach maximum temperature up to 800 °C in three stages of heating was adopted:
• Primary: with the heater (AE), provided with an electrical resistance, with power of 1 kW for the gas. Temperature at the entrance to the reactor at 350-400 °C.
• Secondary and tertiary: using two electrical resistances of 2 kW each, located in the plenum and the freeboard. External temperature up to 900 °C in a metal wall.
The data considered for sizing the gasifier:
• Specific Production 1 Gcal*h$^{-1}$*m$^{-2}$
• Diameter particle size <2 mm (dry material, milled and classified)
• Temperature: about 750 °C
• Capacity: 2 kg h$^{-1}$ (bagasse, moisture up to 25%)
• Flow of fluidizing gas: up to 3 Nm$^3$ h$^{-1}$
• Superficial velocity of the fluidizing gas: up to 0.5 m s$^{-1}$ at 750 °C
• Plenum (pipe 3" Sch 10 S) length 400 mm
• Fluidized Bed Reactor (Pipe 3" Sch 10 S) length 600 mm
• Freeboard (pipe 5" Sch 10S) length 600 mm
• Sandwich-type air distributor with ceramic fiber and perforated plates
• Material stainless steel 316 L
• All parts isolated with ceramic fiber blanket

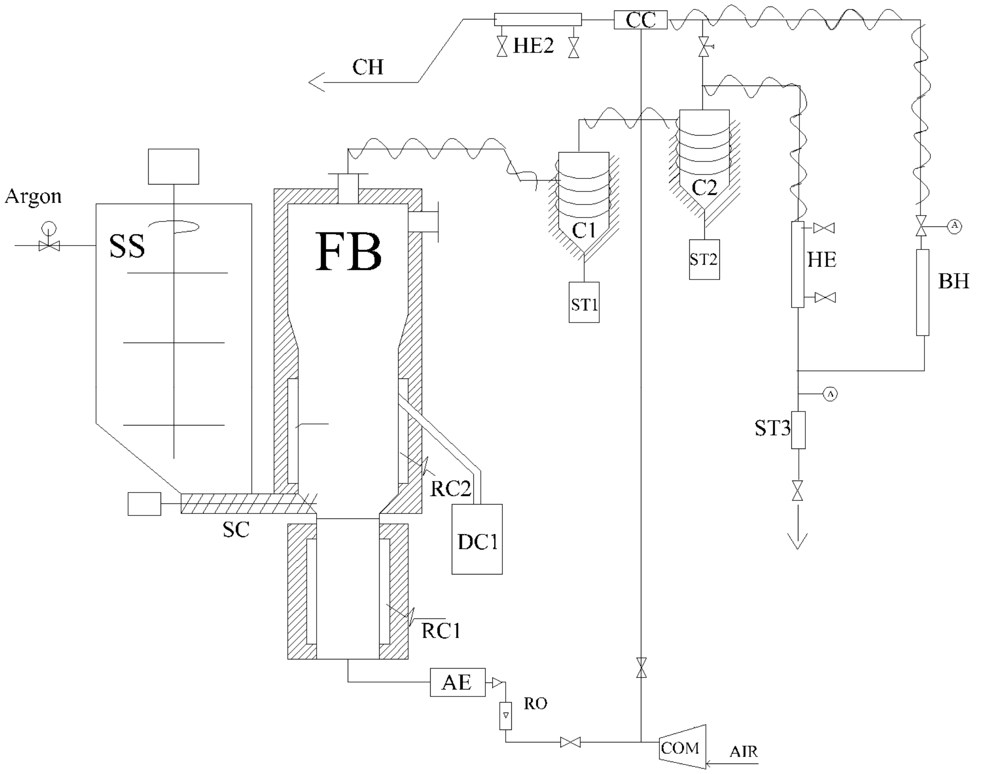


*Figure 1: Scheme of the bagasse gasification plant (description in text).*

**2.2.2. Continuous bagasse feeding**

The bagasse (crushed and dried) is stored in a cylindrical silo (L/D=2) with a capacity and volume of 12 kg and 0.08 $m^3$ approximately, respectively. L=750 mm and D=375 mm. Material: Carbon steel SAE 1010. Stirring with a vertical shaft and variable speed (5-30 rpm) with gearmotor and frequency inverter. The material of screw conveyor is stainless steel 316L, diameter 2 "Sch 10S and length 500 mm.

**2.2.3. Char separation system**

It was proposed that two Lapple type cyclones would be used in this work.. The first one with input tangential speed of 17 m $s^{-1}$, pipe 1/2 "Sch 10 S (Dc=pipe 2" Sch 10 S, Zc = Lc = 94 mm) and second one with input tangential speed of 25 m $s^{-1}$, tube 3/8" Sch 10 S ( Dc=pipe 1 1/2" Sch 10 S, Lc=Zc=80 mm). Material: 316L stainless steel, externally insulated with ceramic fiber blanket and heated to 450 - 500 °C with electrical resistance of 1 kW of power.

**2.2.4. Collection and sampling system of syngas and bio-tar**

The syngas and bio-tar produced in the gasifier after passing through the cyclones (each with their storage tank, ST1 and ST2) are directed to a vertical heat exchanger (HE) in which the bio-tar was condensed and stored in a storage tank (ST3). The tank has a side outlet, through which the syngas was sent to a baghouse (BH) to remove particulates before the sample collector of syngas. Subsequently the gases passes through a heat exchanger (HE2) before being released to the atmosphere.

**2.2.5. Catalytic combustor**

The catalytic combustor uses fixed bed copper catalyst, operating at 400 ° C and residence time of 0.1 sec. Pipe diameter 3 "Sch 10 S, length: 200 mm. Electric heating with power of 2 kW. Material: 316L stainless steel. Insulation: ceramic fiber.

**2.3 Experimental conditions**

Initially, the gasification reactor was charged with 680 g of sand (average particle diameter of 0.50 mm and a density of 2.69±0.01 g $cm^3$, values experimentally measured). This quantity of sand provided a bed height of 10 cm approx.

Before setting the amount of air that would enter the reactor, it was necessary to determine the minimum fluidization velocity of sand ($v_{mf-sand}$) as a function of reaction temperature.

If a velocity higher than $v_{mf-sand}$ is used, it is certain that sand is being fluidized, but it is also possible that sand-bagasse mixes (in any proportion) are as well.
If a velocity of more than 35 L min$^{-1}$ is used, it is possible to ensure that sand is being fluidized, but it is also possible to claim that mixes sand-bagasse (in any proportion) are also being fluidized (Paudel and Feng, 2013). To calculate the minimum fluidization velocity, Equation 1, proposed by Wen and Yu (1966), was used.

$$Re_{mf} = (1135.7 + 0.0408\,Ar)^{0.5} - 33.7 \quad (1)$$

Using the previous correlation, it was possible to calculate $v_{mf-sand}$ at different temperatures and hence the minimum fluidization flow (Figure 2). Since the gasification reactions are often conducted at temperatures higher than 500 ° C, 35 L min$^{-1}$ was defined as the minimum fluidization flow. It ensures that, when temperatures are higher than 500 °C, the bed is fluidized.

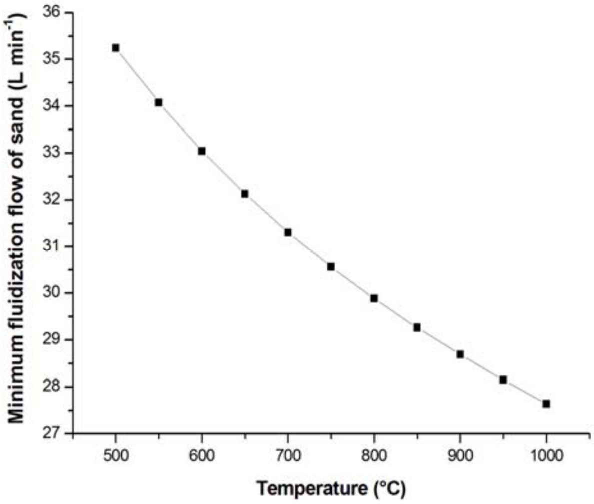


*Figure 2: Minimum fluidization flow of sand*

The gasification reactions proposed in this paper were performed using air as the gasification agent and the independent variable was the air/bagasse ratio (ER) defined in Equation 2.

$$ER = \frac{\left(\text{Liter of air}/\text{kilograms of Bagasse}\right)_{\text{used in the reaction}}}{\left(\text{Liter of air}/\text{kilograms of Bagasse}\right)_{\text{necessary for complete combustion}}} \quad (1)$$

Knowing the values of ER to be used (0.23 or 0.28. values were randomly chosen in a range between 0.20 and 0.40), the amount of air required for complete combustion (calculation based on elemental analysis of bagasse) and the minimum fluidization flow rate (35 L min$^{-1}$) as a restriction, were determined in air and flow of bagasse that had to be used in each experiment. Values are shown in Table 2.
The values of ER were chosen because these conditions bio-tar formed only a single stage (or the second phase was almost negligible). It has been proven that when used lower values of ER, the organic phase of bio-tar became more present.

*Table 2: Air and bagasse flows feeding to gasifier*

| Experiment | ER | Bagasse mass flow rate (kg h$^{-1}$) | Air volume flow rate at 25°C (L min$^{-1}$) |
|---|---|---|---|
| 1 | 0.23 | 2.20 | 34.21 |
| 2 | 0.28 | 1.86 | 34.99 |

Initially, heating plant tests varying only the air flow were made, finding the heating rate of system (data not shown). With these known values, a protocol for start-up of the gasification plant was defined as shown below:
- The air supply was turned to the value of 70 L min$^{-1}$.

- The temperatures were set at 700 °C for the air heater, plenum, freeboard. For cyclones and piping, the condenser, temperature was set at 400 °C. These temperatures are for the metal wall.
- After 30 min, the system reaches its highest temperature value. At this point the air flow rate was reduced to 37 L $min^{-1}$.
- After 50, min the system stabilizes completely, reaching 480 °C inside the gasifier (meeting point of air with bagasse), 310 °C inside the cyclone 1 and 200 in the pipe before the condenser.

The protocol explained above was performed; it began with the continuous feeding of bagasse to reactor, and an increase in the internal gasifier temperature (TG) was immediately observed. After stabilizing of TG (the gasification reactions are very fast, which makes them reach steady state quickly), the syngas was collected in different instances to make sure that the steady-state had been reached.

The reaction is performed for 20 min. At the end, the bagasse is turned off but the passage of air is allowed for 5 min more. After that, the system was thoroughly cooled. char and bio-tar were collected, weighed and analyzed. Finally, a sharp heating at 900 °C using air (50 L $min^{-1}$ for 2 h) was performed in order to completely clean the reactor.

### 2.4 Syngas, bio-tar analysis

The syngas was analyzed using gas chromatography according to the methodology described by Jaimes Figueroa et al. (2013).

The mass fraction of water in the bio-tar was measured by volumetric Karl Fischer titration using a Metrohm, model 841 Titrando, coupled with Tiamo software.

## 3. Results and discussion

### 3.1 Reaction temperature and products distribution

The gasification process is formed by several reactions: pyrolysis, Boudouard, cracking, water gas shift and combustion. These reactions are mostly endothermic, which causes high temperatures to promote them; therefore, manipulating the reaction temperature indirectly manipulates the types of products being produced. The gasification temperature depends basically on two points: the reactor and the ER ratio. Figure 3 shows the products distribution at different ER (and temperatures). It can be seen that, an increase in the ER causes an increase of reaction temperature. Two temperatures, T1 and T2, measured at the contact point of bagasse with air and outlet of the gasifier, respectively, are presented. The increased temperature promotes the increased production of syngas from conversion of bio-tar and char.

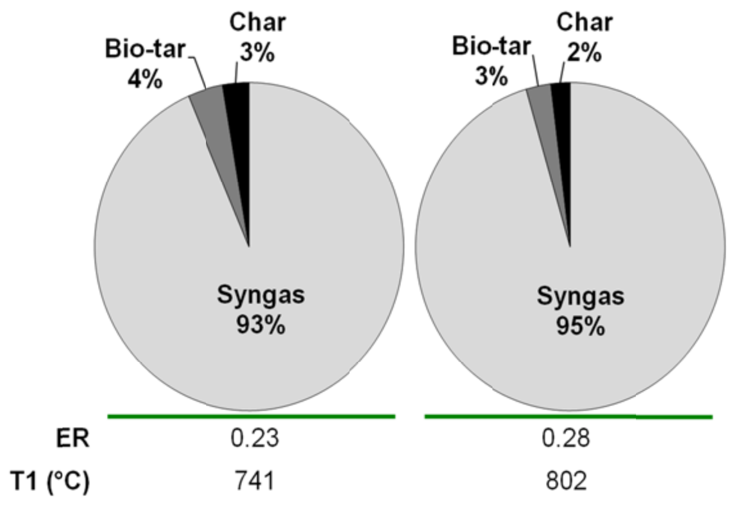


*Figure 3: Impact of the ER on products distribution*

The syngas yield ranged from 1.61 to 1.85 m3 $kg^{-1}$ of bagasse, for ER equal to 0.23 and 0.28, respectively. Another important effect of increased ER was increased yield char (g of char per 100 g bagasse), which had decreased from 5.56 to 4.50. The amount of bio-tar in syngas remained almost unchanged, with values of 48.18 and 50.15 g bio-tar $m^{-3}$ of syngas when T1 was increased from 741 to 802 °C.

The analysis determined that the amounts of water in the bio-tar, when using ER equal to 741 and 801 °C, were 95.45 and 97.69%. The indicates that, although there is a significant amount of bio-tar in syngas, this is mostly water. The composition of syngas obtained for each test is shown in Table 3.

*Table 3: Syngas composition*

| | Syngas mole percentage (%) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | $CO_2$ | $C_2H_4$ - Ethylene | $C_2H_6$ - Ethane | $C_3H_8$ - Propane | $C_4H_{10}$ - Butane | $CH_4$ | CO | $H_2$ |
| ER=0.23 ; T1=741°C | 12.48 | 0.87 | 0.05 | 0.05 | 0.02 | 2.21 | 8.14 | 3.39 |
| ER=0.28 ; T1=802°C | 12.12 | 1.03 | 0.11 | 0.13 | 0.02 | 2.48 | 9.68 | 4.79 |

The increases in temperature promote compounds of high interest, such as $H_2$ and CO, and reduce $CO_2$ (Akay and Jordan, 2011). This is one of the major potentials of the process, in which, from biomass, the syngas is produced, which is a building block of high value to the industry. But one can also appreciate that there are minor amounts of other gases such as ethylene, ethane, methane, etc.; suggesting the use of a subsequent stage to convert them to CO and $H_2$.
Is important to emphasize that these resultss are only valid in the range of ER (studied here ER=0.23 or 0.28..

## 4. Conclusions

The fluidized bed reactor has great potential for continuous gasification of sugarcane bagasse, having the capacity to operate with low air flow and bagasse. An increment of ER and therefore the reaction temperature improves the efficiency of the process in terms of conversion to syngas. Using an ER of 0.28, it was found that 95 wt % of the product is syngas. Furthermore, the increase in ER also led to an increased production of $H_2$ and CO, reaching approximately 15 % mole and with a $H_2$/CO molar ratio of 0.49 %. With this process, it was produced syngas with maximum 50.15 g bio-tar $m^{-3}$ and a yield of 4.50 g of char/100 g Bagasse was produced when the reactor was operated at 802 °C. The syngas obtained presented small quantities of gases such as ethylene, ethane, propane, butane and methane, which are susceptible to conversion to increase the production of $H_2$ and CO. A possible solution would be to work with lower values of ER or add another step after the gasification.

## Acknowledgment

The authors gratefully acknowledge the Brazilian financial support from FAPESP/ Bioen – Fundação de amparo à pesquisa de estado de São Paulo (Process 2008/57873-8), CNPq – Conselho Nacional de Desenvolvimento Científico e Tecnológico (Process 143070/2011-8) and support and technical assistance with the gasification plant from TERMOQUIP Energia Alternativa LTDA.

### References

Akay, G., Jordan, C. A., 2011, Gasification of Fuel Cane Bagasse in a Downdraft Gasifier: Influence of Lignocellulosic Composition and Fuel Particle Size on Syngas Composition and Yield, *Energy & Fuels,* 25**,** 2274-2283.

Dias, M. O. S., Junqueira, T. L., Cavalett, O., Cunha, M. P., Jesus, C. D. F., Mantelatto, P. E., Rossell, C. E. V., Maciel Filho, R., Bonomi, A., 2013a, Cogeneration in integrated first and second generation ethanol from sugarcane, *Chemical Engineering Research and Design,* 91**,** 1411-1417.

Dias, M. O. S., Junqueira, T. L., Cavalett, O., Pavanello, L. G., Cunha, M. P., Jesus, C. D. F., Maciel Filho, R., Bonomi, A., 2013b, Biorefineries for the production of first and second generation ethanol and electricity from sugarcane, *Applied Energy,* 109**,** 72-78.

Jaimes Figueroa, J. E., Ardila, Y. C., Hoss Lunelli, B., Maciel Filho, R., Wolf Maciel, M. R., 2013, Evaluation of pyrolysis and steam gasification processes of sugarcane bagasse in a fixed bed reactor, *Chemical Engineering Transactions,* 32, 925-930, DOI: 10.3303/CET1332155

Paudel, B., Feng, Z.-G., 2013, Prediction of minimum fluidization velocity for binary mixtures of biomass and inert particles, *Powder Technology,* 237**,** 134-140.

Sluiter, A., Hames, B., Ruiz, R., Scarlata, C., Sluiter, J., Templeton, D., Crocker, D., 2008, Determination of structural carbohydrates and lignin in biomass, Laboratory Analytical Procedure (LAP), NREL/TP-510-42618, revised July 2012.

Wen, C. Y., Yu, Y. H., 1966, A generalized method for predicting the minimum fluidization velocity, *AIChE Journal,* 12**,** 610-612.