

Sugarcane Bagasse Gasification – A Review

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Abstract

Biomass gasification processes are being widely researched due to increased global demand for energy. Sugarcane bagasse is one promising source for renewable energy since it is produced in high quantities due to agriculture. Sugarcane bagasse has low bulk density and a high content of moisture, but due to that, it can cause problems during the gasification. These problems can be partially solved with a pretreatment like torrefaction. In the industry, sugarcane bagasse is burned for energy production in a very inefficient process. Due to that, better ways to harness the energy of bagasse have been developed, from better standardization of the bagasse that will be burned to new energy production techniques, in which gasification is included. Gasification has a much higher energy efficiency than other techniques, like simply combustion, which is normally used to turn sugarcane bagasse in

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energy, or pyrolysis; and produces a gas, called syngas. This paper will be a review of the various pretreatment that can be used for sugarcane bagasse, the reactors that can be used for the gasification process, their main problems and the catalysts that can be used.

Keywords: Sugarcane bagasse; syngas; gasification; reactor; energy production

INTRODUCTION

In the current energy scenarium, biomass appears as an interesting alternative source of renewable energy, where fossil fuels are being replaced by more eco-friendly fuels (Jahirul et al. 2012). Biomass can be transformed to a bio-fuel via diverse ways like gasification to produce syngas (Graves et al. 2011), liquefaction to produce bio-oils, transesterification to produce biodiesel, etc (W. Huber, Iborra, and Corma 2006); and different feedstocks which included beech wood (Demirbas 2005), bagasse (Asadullah et al. 2007), wood pellets (Meijden et al. 2008), coffee grounds (Dong, Suda, and Murakami 2010), Cedar/white oak (Matsuoka et al. 2008), Pine sawdust (Wei et al. 2006), seedcakes (Karaosmanoğlu and Tetik 1999), straws (Aho et al. 2008), and municipal solid waste (Jensen, Sander, and Dam-Johansen 2001; Pütün, Uzun, and Pütün 2006). Commonly, biomass with high volatile matter produces more syngas (Jahirul et al. 2012) and feedstocks with low mineral are promoted for syngas production (Friedl et al. 2005).

Gasification and pyrolysis are two techniques to convert biomass that have been studied in the last decades. Both of them can generate more energy than combustion. In the gasification process, simple molecules are formed while biomass is transformed to gases (Graves et al. 2011) and pyrolysis allows to crack the polymeric structure of biomass fastly, transforming than to valuable material (Zandersons et al. 1999).

Syngas is mainly composed of H₂, CO and CO₂, its applications included several industrial products like bio-automotive fuels Fischer-Tropsch liquids (Lv et al. 2007). Since syngas can be obtained by gasification of biomass (Göransson et al. 2011) it can be produced with greater energy efficiency and environmental friendly integrated with

industries like agricultural, energy, and chemical. Gasification is a technique that changes the biomass structure at high temperatures (500-900 °C) in gasifying agent (air, O₂, steam, CO₂, etc.) presence (Wang et al. 2008).

Sugarcane bagasse is the major solid waste of the sugar cane industry and composed by approximately 50% cellulose, 25% hemicellulose, and 25% lignin (Ahmed and Gupta 2012). Bagasse consists of 2-4% of ash (Pandey et al. 2000; Munir et al. 2009). Sugarcane bagasse is generally applied as a source of fuel for steam turbines and sugar mills (Pellegrini and de Oliveira 2007; Ahmed and Gupta 2012).

Gasification and pyrolysis lead to an increase of tars during syngas production (over 30%) (Ahmed and Gupta 2012) and this formation is one of the main difficulty limiting commercialization of this technology (M. Yung, S. Jablonski, and A. Magrini-Bair 2009). Tars can be defined as a dark brown or black viscous liquid of hydrocarbons and free carbon, principally composed by toluene, benzene and naphthalene (Dayton 2002a; Devi, Ptasinski, and Janssen 2003). Tars can present various challenges in the process, like coking of catalysts and condensation on downstream on equipment (Dayton 2002a), and the tar removal costs can be similar to the ethanol production costs (Milne and Evans 1998).

The majority of tars in the syngas can be eliminated by thermal cracking, which is more efficient at high temperatures (> 1100 °C). Unfortunately, these temperatures are significantly higher than the typical gasification temperature, which increases the cost of the process (Dayton 2002a). Liquid scrubbing can also be used to eliminate contamination from syngas, but it generates a large amount of wastewater that needs treatment or recycle (M. Yung, S. Jablonski, and A. Magrini-Bair 2009). Syngas can be conditioned by catalytic hot gas cleanup too, which is more efficient than other process. The advantages include the improvement in the carbon capability to reform tars to produce more syngas and the absence of wastewater generated by the process. Catalytic tar cracking can be made by installing catalysts in the gasification unit (M. Yung, S. Jablonski, and A. Magrini-Bair 2009). The main limitation is catalyst deactivation (Sehested 2006) that occurs from chemical and physical processes combined with the

reaction conditions and contaminants in the feed stream (Bulushev and Ross 2011).

With this overview, the focus of this review is the gasification route to produce syngas based on sugarcane bagasse.

SUGARCANE BIOMASS

The sugarcane (*Saccharum officinarum*) is a grassland originating in Southeast Asia, but today it is grown in various regions around the world (Rosillo-Calle, Bajay, and Rothman 2005). Sugarcane bagasse is composed of cellulose (30 ± 5), hemicellulose (31 ± 4.8), lignin (18.3 ± 6.9) and others (8.65 ± 5.75) (Zhao et al. 2009; Canilha et al. 2011). Table 1 shows a more detailed analysis of the elementary components of the sugarcane bagasse.

Table 1 – Sugarcane bagasse elementary components

Reference	Carbon	Hydrogen	Nitrogen	Sulfur	Chlorine	Oxygen	Ashes
(Tsai, Lee, and Chang 2006)	58.14	6.05	0.69	0.19	0.36	34.57	4.34
(G. J. de M. Rocha et al. 2015)	44.90	6.10	0.27	-	-	48.74	2.84
(Munir et al. 2009)	45.48	5.96	0.15	-	-	45.21	3.20
(Pieter Willem; Poel, Schiweck, and Schwartz 1998)	47.20	6.30	0.30	0.10	-	44.50	2.50
(Gabra et al. 2001)	45.20	5.40	0.20	0.02	0.30	41.80	7.40
(Jenkin, Saunders, and Pilling 1997)	48.64	5.87	0.16	0.04	0.03	42.82	2.44
(S. Q.; Turn, Bain, and Kinoshita 2002)	48.19	5.67	0.14	0.08	-	42.35	3.61
(De Filippis et al. 2004)	42.90	5.90	0.20	-	-	49.00	0.20
(Manyà and Arauzo 2008)	43.60	5.52	0.25	0.07	-	50.63	-

Sugarcane bagasse comes from the broth extraction process, which is the main residue of sugarcane milling. It is composed of fibrous remains of the sugarcane after passing through the process of sugar extraction in sugar mills and distilleries. Usually, this residue is used in these

plants as fuel. This allows sugar-ethanol plants to become self-sufficient, which is not common in other industrial sectors (Reis 2001). Use the materials for energy objective, require the total knowledge of their properties to build different thermochemical conversion facilities, as well as for previous computational simulations (Geldart 1990). The characterization of sugarcane bagasse depends on various aspects such as plant species, season and type of harvest (manual or mechanized), soil type, the broth extraction process, type of fertilizer, etc (G. J. M. Rocha et al. 2012).

SUGARCANE BAGASSE MORPHOLOGY

Sugarcane bagasse is polydisperse biomass with a wide variety of diameters and sizes in its composition. No matter the process of extracting used, it will be composed of fibers, marrows, and powder. In both cases, the particles are very porous and hygroscopic with the most varied granulometry. Both the marrow and the fiber are in the cylindrical trunk format of different configurations between one and another particle. In the fiber, a high ratio of length was presented in relation to the ellipsoid base and, contrary to the bone marrow particles, the base was larger than the height (Nebra and Macedo 1988).

Obtain the shape and size of the particles in sugarcane bagasse is complex due to the diversity of particles that make up their agglomerate, therefore, obtaining their exact dimensions is not a simple task (Mohsenin 1986). The sphericity is one of the most important parameters during studies of fluid dynamics or computational simulations of particulate systems (Geldart 1990). The knowledge of this parameter helps in the study of fluidized bed reactors for several applications, especially biomass gasification. In the literature, there are different mechanism to determine the sphericity of a solid material, the most relevant is the surface diameter, which is the index of the sphere diameter equal to external surface area as the particle, both with the same volume (Hartman, Trnka, and Svoboda 1994). In cases where this determination is difficult and the models assume spherical particle, often imply errors (Xu and Di Guida 2003). In general, sugarcane bagasse has sphericity from 0.2 to 0.6 (Pérez et al. 2014).

PRE-TREATMENT OF SUGARCANE BAGASSE

Before sugarcane bagasse can be used in reactors, some challenges must be overcome to guarantee the efficiency of the biomass (Tumuluru et al. 2010). Biomass, in general, is hard to work in comparison to traditional fuels (Tallaksen 2011). In the case of sugarcane bagasse, some problems related to the fuel included the low energy and bulk density, high moisture, the presence of contaminants, the heterogeneous size, weight and shape (Anukam et al. 2014). To surpass these challenges some methods of pre-processing are developed and they can influence the gasification process (Tchapda and Pisupati 2014).

Problems associated to the size or shape of the biomass can affect directly the conversion process since the conversion of biomass in energy occurs at biomass material surface. Therefore, densification is one pre-processing technique commonly employed to rise the biomass materials densities and to reach uniform properties (Tumuluru et al. 2010). This makes biomass easy to handle and transport, and it makes the biomass more homogeneous (Tallaksen 2011). Methods frequently applied to obtain densification are pelleting or briquetting (Anukam et al. 2016). However, the employment of biomass pellets depends on conversion system adopted (Tumuluru et al. 2010). For fixed bed reactors, for example, feedstock for conversion must be uniformly sized from 7 ± 3 cm in length and 40 ± 10 mm in diameter, this is necessary to avoid blockage of the gasifier, which leads to poor gasification conditions (Mamphweli 2009). Even with the specifications, depending on how the biomass material will be used, these pellets have various shapes and composition (Tallaksen 2011).

Briquetting is a compaction technique applied to increase the biomass material density. After briquetting, the density of the biomass reaches to a maximum of 1500 kg/m^3 . Besides increasing density, briquetting leads to uniform biomass which improves combustion and reduces the emission of particulate material (Tumuluru et al. 2010). The technologies for briquetting are the screw extruder, the piston press, and the pellet mill (Anukam et al. 2016).

BIOMASS GASIFICATION FOR SYNGAS

Among the main methods to convert biomass, gasification is the one which generates the highest percentage of gas (85%), the products of the reaction include coal (10%) and liquid (5%) (T. Bridgwater 2001). The gasification modifies the structure of biomass in high temperatures (500 – 900 °C) (Wang et al. 2008) in the presence of a gasification agent, resulting in a gaseous products but in small amounts of other components too (Barman, Ghosh, and De 2012; Balat et al. 2009). It can be ranked depending on the agent of gasification: air, steam, water vapor and O₂, air enriched with O₂, etc (Gao et al. 2008). The gaseous product resulted of the biomass gasification or other solid fuels is known as synthesis gas (syngas). The syngas is a mix mainly of carbon monoxide (CO), hydrogen (H₂), and carbon dioxide (CO₂), but can also have CH₄, tars (like benzene or other aromatic hydrocarbons), H₂S, water vapor, and other trace species depending of the process conditions (S. Q. ; Turn, Bain, and Kinoshita 2002). Other inorganic compounds present in biomass (Si, Al, Ti, Fe, S, Cl, etc.) may also come in the gas phase (L. Bain et al. 2005). Syngas can be employed to produce electricity for direct combustion or the production of biofuels and chemical products (Lv et al. 2007).

Air gasification technology is the simplest and the most widely used because of the high cost of other gasification agents and problems in the safety of installations. In air gasification, a fuel gas of low calorific value (generally 4 to 7 MJ/Nm³) is generated. The gasification with O₂ and steam resulting in a gas with a calorific power between 10 and 18 MJ/Nm³ (Schuster et al. 2001). For biomass gasification, the use of pure O₂ is not indicated due to its high costs (Doherty, Reynolds, and Kennedy 2009).

The gasification is a process defined and limited to combustion and pyrolysis. Firstly, it occurs in an endothermic process that releases water and leads to the pyrolysis of the biomass. The pyrolysis generates pyrolytic coal and volatiles as hydrocarbons, H₂, CO, CO₂, pyrolytic tar, and water vapor. At the same time, the pyrolytic coal is oxidized and raises the reactions ranging from 800-1100 °C depending on the conditions and gasified agent used, this provides the energy for pyrolysis and gasification (combustion and reduction) of the remaining

coal. Table 2 summarizes most of the reactions of the gasification process.

Table 2 – Reactions of gasification process (Gómez-Barea and Leckner 2010; Franco et al. 2003; S. Turn et al. 1998; Doherty, Reynolds, and Kennedy 2009)

Stoichiometry	Equation
Biomass ? tar, ashes, coal, gas (CO + CO ₂ + H ₂ + H ₂ O + CH ₄ + ...)	(1)
Coalcombustion	
C + 0.5O ₂ ? CO	(2)
C + O ₂ ? CO ₂	(3)
Coalgasification	
C + CO ₂ ? 2CO	(4)
C + H ₂ O ? CO + H ₂	(5)
C + 2H ₂ O ? CO ₂ + 2H ₂	(6)
C + 2H ₂ ? CH ₄	(7)
Gaseousreactions	
CO + 0.5O ₂ ? CO ₂	(8)
H ₂ + 0.5O ₂ ? H ₂ O	(9)
CH ₄ + 2O ₂ ? CO ₂ + 2H ₂ O	(10)
CH ₄ + H ₂ O ? CO + 3H ₂	(11)
CO + H ₂ O ? CO ₂ + H ₂	(12)
H ₂ + S ? H ₂ S	(13)
N ₂ + 3H ₂ ? 2NH ₃	(14)
Tarreactions	
C _n H _m + (n/2)O ₂ ? nCO + (m/2)H ₂	(15)
C _n H _m + nCO ₂ ? (2n)CO + (m/2)H ₂	(16)
C _n H _m + nH ₂ O ? nCO ₂ + (m/2 + n)H ₂	(17)
C _n H _m + (2n – m/2)H ₂ ? nCH ₄	(18)
C _n H _m ? (n – m/4)C + (m/4)CH ₄	(19)

It is possible to note in Table 2 that the initial step of gasification occurs in equation (1), which is the decomposition of biomass or pyrolysis, generating coal and volatiles. After that, a variety of reactions occurs from these products, some of them specifically with the coal (equations 2 – 7) and the tar (equation 15 – 19), and some in a homogeneous phase (equation 8 – 14). Not all the reactions occur at the same time, for reactors like the fixed bed, there are different zones where four

fundamental processes occur (drying, pyrolysis, oxidation, and reduction) (Anukam et al. 2016).

The coal gasification reactions are the slower reactions of the gasification process and for this reason, are responsible for the total conversion rate of gases (Higman 2008). If all coal gasification reaches equilibrium, the carbon present in the char would be converted into gases. Yet, in general, the contact time between the char and the gaseous reagents for high temperature is insufficient for the equilibrium to be achieved, which leads to the appearance of char in the gasification products (Bain; and Broer 2011). Regarding this observation, conditioning the pyrolysis to supply a large amount of volatiles and a small amount of char is a means of improving the capacity of the gasifier (Di Blasi 2009).

Some of the gasification reactions are endothermic (equations 4 and 5), so they need a determined quantity of energy to occur. This energy comes mainly from combustion, but some gasification reactions are exothermic and contribute to the energy supply to the bed (7). However, the exothermic reactions in the coal gasification are usually negligible because of the small amount of hydrogen present in the gasifier bed (Bain and Broer 2011) and their low rate of reaction.

REACTORS FOR THE GASIFICATION PROCESS

Gasification can be executed in different reactors, like fixed bed (countercurrent and concurrent) and fluidized bed. The gasification techniques used in the industries of Europe and the USA use different configurations of reactors, of which 75% are fixed bed type, 20% are fluidized bed type, 2.5% are countercurrent fixed bed type and 2.5% are others types (Maniatis 2008).

Fixed bed reactors – This kind of reactors can be built at extremely low cost, which is one of its advantages (Basu 2010). However, the fact that fixed bed reactors operate only for small loads has encouraged studies to enable the fluidized bed and drag bed reactors, which are ideal for industrial-scale operations. Fixed bed reactors can be subdivided from the direction in which the fuel and oxidant streams flow, such as countercurrent reactors and co-current reactors.

Countercurrent gasifier is the oldest and simplest type to be built, so it has still been widely used for coal gasification and, to a lesser extent, for biomass gasification (CENBIO 2002). In the countercurrent gasifier, power is feeded at the top and the gasification agent (O_2 /air) is inserted into its base. A schematic of the operation, as well as an estimate of the temperature distribution along the reactor, are shown in Figure 1.

As the fuel moves in the contrary direction of the gas stream, the particles go through the stages of drying, pyrolysis, gasification, and combustion. Although in Figure 1 the regions in which each step occurs are well defined, in a real system, it does not follow. Therefore, it is possible that the interior of a particle is drying while its outer regions are being pyrolyzed (Souza-Santos 2004).

In these gasifiers, ash removal is commonly performed with the use of a rotating grid at the bottom, while the gases exit through the top of the reactor. The fact that the combustion region is located near the ash removal site reduces the possibility of the ashes to melt and cause tube clogging problems, damaging the gasifier operation, as in co-current reactors. In this way, countercurrent reactors can be considered practically insensitive to the ashes of the fuel (Siedlecki 2011). However, the produced gases do not reach near the hotter zones of the gasifier causes a very high tar production when compared to the other types of reactors (around $50,000 \text{ mg/m}^3$). In this way, the gases produced by these gasifiers must undergo tar removal processes for use in gas turbines and production of synthesis gas. For direct burning in boilers, this process is not necessary (Bain; and Broer 2011).

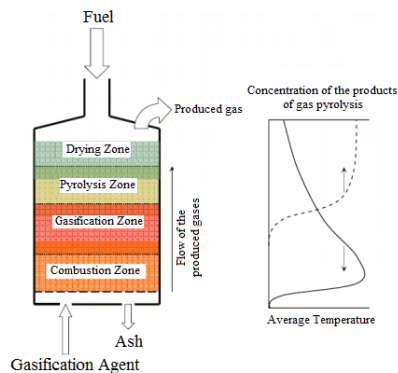


Figure 1 – Countercurrent fixed bed gasifier and the temperature distribution in the reactor (adapted from Siedlecki 2011).

In the concurrent gasifier, the feed is carried out from the top, while the gassing agent is added by side or top. Although the flow direction may be from the bottom up or from the top-down, most co-current reactors operate with the flow directed downward (Siedlecki 2011). The concurrent fixed bed gasifier has the benefit of the consumption of 99% of the tar generated, requiring a minimum tar removal in the gas stream produced (Speight 2014). The reactor scheme is presented in Figure 2.

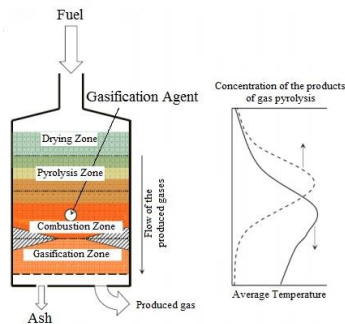


Figure 2 – Co-current fixed bed gasifier and the temperature distribution in the reactor (adapted from SIEDLECKI 2011).

In the scheme of Figure 2, the fuel is inserted through the top of the reactor and the gasifier in the middle of the reactor and, as the particles flow downward, they undergo the drying, pyrolysis, combustion, and gasification stages. In this scheme, both gases and ashes are withdrawn from the reactor by the lower region. It should be noted that, in this situation, the pyrolysis products cross the combustion zone of the reactor. This characteristic causes a large part of the produced tar to be burnt, which significantly reduces the tar concentration in the gasification products (Basu 2010; Gómez-Barea and Leckner 2010). However, these same characteristics make these gasifiers extremely dependent on the humidity content. If the biomass has a moisture content above 20%, it is possible that the drying and pyrolysis difficulties occur, causing an increment in the tar composition (CENBIO 2002).

The gas produced has less than 1% of tar, higher temperature (700 °C) and more particulate material than that obtained using a countercurrent gasifier. A model proposed for (Blasi 2000) to concurrent fixed bed gasifier indicates a composition of (v/v) 20.3-18.5%

CO; 16.8-9.8% H₂; 15.3-9.4% CO₂; 4.5-2.4% CH₄, and 43-60% N₂ (Blasi 2000). Experimental studies showed a gas composition of the products of (v/v) 24% CO; 12% H₂; 14% CO₂; 2% CH₄, and 45% N₂ (Blasi 2000). The great advantage of co-current gasifiers is their low tar content.

Fluidized bed reactors – Fluidized bed reactors operate in a way that the fuel particles are fluidized using a gas. A gas stream enters in the lower part of the reactor so that the particle bed has several typical characteristics of a fluid (GRACE et al. 2006).

Fluidized bed reactors can be classified in two types: bubbling fluid bed (BLB) and circulation fluid bed (CFB). The BLB reactors operate at moderate fluidization velocities and low particles residence time. In this kind of reactors, the gasification agent is inserted by the bottom region of the reactor with a speed lower than 2.0 m/s. The biomass is fed from a side entrance, located above a distributor plate, used to distribute the incoming gas evenly in the reactor. The gases leave by the upper region of the reactor, while the ashes are removed from the bottom. A scheme is presented in Figure 3.

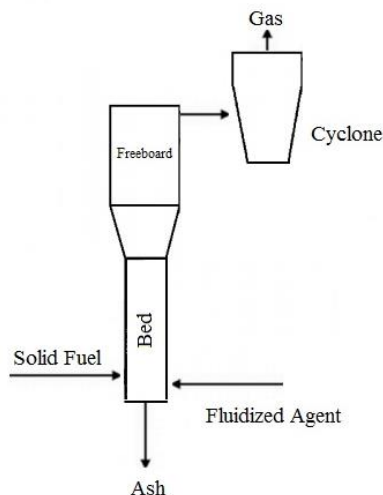


Figure 3 – Bubbling fluid bed reactor (Adapted from (Verissimo 2014))

The explosion of the bubbles near the top of the reactor (freeboard region) causes solid particles to be released into the region. Normally, the freeboard region has a larger cross-sectional area than the bed region, in order to return the particles to the bed (Bain; and Broer 2011). However, only the larger particles, with terminal velocities

below the superficial gas velocity of the ascending gas, return to the bed. However, most of the solid particles that reach the top region end up undergoing the elutriation process, which consists of dragging these particles out of the reactor, along with the stream of gases produced (Souza-Santos 2004).

The BLB reactors operational temperature is determined by the melting temperature of the ashes of the fuel used. Once the ashes begin to melt and form larger particles, even defluidization of the bed may occur. Thus, BLB gasifiers operate normally at temperatures below 900 °C (Siedlecki 2011).

The CFB operates at higher speeds and solids recirculation, as shown in Figure 4. CFB reactors are composed of a riser, where injection of fuel and oxidizing agent occurs, a cyclone separator, located at the outlet of the riser, the downcomer, which is a vessel that helps regulate the particle recirculation rate and the distribution plate present in the BLB reactors too (Fan and Zhu 1998). However, these reactors operate at higher speeds, usually between 3 and 10 m/s, with fast fluidization or pneumatic conveying patterns. Thus, much of the bed material, or even all of it, is dragged to the riser, where the cyclone separator causes the gases to leave the gasifier cycle, while the solids are inserted into the downcomer to be recirculated in the riser.

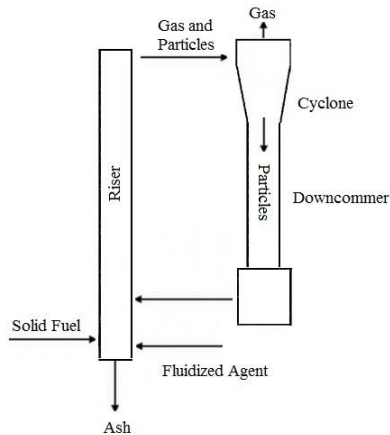


Figure 4 – Circulating fluid bed reactor (Adapted from Pinho 2012)

An experimental data and mathematical model for a fluidized bed reactor show a composition of the gas product of the gasification of (v/v) 17% CO; 5% H₂; 15% CO₂; 4% CH₄, and 59% N₂ (Li et al. 2004). Another

model in fluidized bed reactors for biomass considers two zones, a gasification zone (fluidization with steam) and a zone of combustion, in which the composition of the gas produced is estimated through an equilibrium model with the minimization of Gibbs free energy (Schuster et al. 2001).

When compared to fixed bed gasifiers, fluid bed gasifiers generally have the benefit of being capable to operate at higher loads. Furthermore, these gasifiers have a unique characteristic, due to the strong mixing rate in both BFB and CFB reactors, there is the possibility of using a large number of different fuels or a mixture between different fuels (Basu 2010). Another advantage is the possibility of using catalysts in the bed of fluidized reactors, with the objective of reducing tar and other pollutants like sulfur and rising the quantity of H₂ and CO in the gases produced (Gómez-Barea and Leckner 2010).

Comparing the CFB and BFB reactors, it is possible to note that CFB reactors have the advantage of working at higher flow rates and producing gas with a lower amount of tar and particulate matter (Bain; and Broer 2011). In addition, bubbles from BFB reactors facilitate homogeneous combustion reactions due to reduced oxygen diffusivity between the bubbles and the emulsion. Thus, heterogeneous combustion reactions are impaired, which reduces the conversion efficiency of the gasifier (Basu 2010). This problem does not exist for CFB reactors since it does not have bubbles. On the other hand, BFB reactors have the advantage of working with a substantially isothermal condition in the bed, due to the high rates of mixing of the particles and the transfer of heat and mass. This condition allows for greater control over the temperature of the gasification process. Furthermore, the need to use a cyclone separator with additional equipment to perform solids return to the reactor raises the investment costs of CFB reactors when compared to BFB reactors (Alimuddin et al. 2010).

Drag bed reactors – This type of reactor operates with the fuel stream and the gasifier stream being inserted at high speeds in the same location and flowing in the same direction. Figure 5 shows an illustration of the drag bed reactor with the injection of the reactants in the top of the reactor and the outlet of gases in the lower region. However, there are also reactors in which fuel and gasifiers are inserted in the lower region and leave the reactor by the upper region.

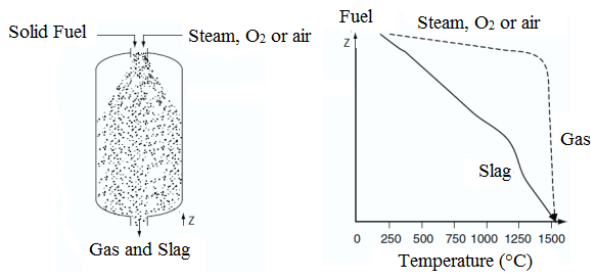


Figure 5 –Drag bed reactor and temperature profile in the reactor

Considering the high flow rates, particles residence time inside the reactor is very short. Therefore, there is a need to operate at high temperatures, usually superior the ashes melting temperature, and with extremely small fuel particles in order to guarantee a satisfactory conversion rate (Higman 2008).

The drag bed reactor is ideal for producing large amounts of gas since it is possible to work with a much larger load than other types of reactors. Another advantage is that the gas produced is practically free of tar due to the high temperatures inside the reactor higher than 1000 °C (Basu 2010). One of its disadvantages is the need to use materials that withstand high temperatures to build the gasifier, which ends up making the plant more expensive.

These gasifiers were developed initially to operate with coal (Siedlecki 2011) and present two main difficulties for its use with biomass. The first one is related to the difficulty of pulverizing certain biomasses to the required particle size due to its fibrous composition, and the second is the high aggressiveness of the biomass-fired ash compared to coal ash, which reduces the useful life of the gasifier. Due to these two limitations, its use has been much more common with coal than with biomass (Basu 2010).

Other types of reactors can be used too, Gabra et al. 2001 evaluated the efficiency of a two-stage cyclone gasifier to produce a gas which is adequate for a gas turbine. The authors produced gas in a stable way. The process showed a significant alkali separation at the cyclone, but the concentration of particles was higher than what is necessary to operate a gas turbine. Some conclusions of the authors are contradictory with theoretical calculation, for example, the fly ash

should be melted at 1200 °C but the experimental tests showed the opposite.

The gas stream composition of the products for different reactors using air is summarized in Table 3.

Table 3 – composition of the gas stream

Type of gasifier	Fixed bed reactor - countercurrent	Fixed bed reactor - concurrent	Fluidized bed - BLB	Fluidized bed - CFB
CO (%)	48	24	15	19.6
CO ₂ (%)	15	9	17	13.5
H ₂ (%)	32	11	5	20.2
CH ₄ (%)	2	3	6	3.8
N ₂ (%)	3	53	57	42.9
Reference	(A. V Bridgwater 1995)		(Datar et al. 2004)	(Subramani and Gangwal 2008)

CONDITIONS FOR BIOMASS GASIFICATION

Table 4 shows the conditions used for various authors to produce syngas, the composition of the syngas, tar content and cleaning process used are shown too.

Reference	Temperature (°C)	Catalyst	Process	Type of reactor	Bed material	Syngas composition (%)	Tar content (%)	Cleaning process
(Ahmed and Gupta 2012)	800, 900, 1000	-	Pyrolysis and gasification					
(Al Arni, Bosio, and Arato 2010)	700	-	Pyrolysis	Fixedbed				
(Danyanto et al. 2015)	Variable – 500 – 1000		gasification	Fixedbed				Cyclone
(Akay and Jordan 2011)	Variable – 300 – 1200		gasification	Fixedbed– counter-current		CO ₂ – 14 CO – 12 O ₂ – 3 H ₂ – 7 CH ₄ – 1	-	Two cyclones
(Gabra et al. 2001)	800	-	gasification	Two-stage combustor		CO ₂ – 17 CO – 10 H ₂ – 7.7 CH ₄ – 2 N ₂ – 58	0.4 – 0.6	Cyclone
(Sahoo and Ram 2015)	500 – 800		gasification	Fluidizedbed	Sand, mud and/or dolomite	CO ₂ – 11 CO – 47 H ₂ – 30 CH ₄ – 11 *	-	-

(Ebrahimi-nik et al. 2014)	400 – 800	Several	gasification	Batch autoclave reactors	-	CO ₂ – 10.1 – 25.3 CO – 0.37 – 10.1 H ₂ – 0.36 – 6.6 CH ₄ – 0.3 – 12.1	-	
(Cao et al. 2017)	600-750	Raney-Ni; K ₂ CO ₃ ; Na ₂ CO ₃	gasification	Batch reactor		H ₂ – 7.63 to 47.32; CO – 0.59 to 2.42; CH ₄ – 2.32 to 6.08; CO ₂ – 9.85 to 26.81		

* Composition showed on N₂ and S free basis

TREATMENTS FOR SYNGAS

The synthesis gas obtained by biomass gasification has several impurities such as tar, particles, nitrogen compounds, chlorine, sulfur, alkali, and heavy metals, that have to be removed or can generate operational problems (Villot et al. 2012). The necessity of cleaning the syngas relies on the the gas usage and is especially relevant when the syngas is to be transformed to synthetic liquid fuel. The gas cleaning is classified into conventional and dry hot gas cleaning (Göransson et al. 2011).

Conventional gas cleaning – The purification can be divided into four parts. (1) Particles, alkali metals, and HCl can be removed by cyclones, scrubbers, filters, and packed beds, the last one with adequate solvent. Once alkali metals can condense on the particulates (if the operation is above 550 °C), they can be removed in the cyclones with the particles (Göransson et al. 2011); (2) Acid gas and inorganic compounds can be removed by scrubbers and conventional systems with chemical solvents (like methyldiethanolamine (MDEAs)) and physical solvents (like Selexol process (Goransson et al. 2010)); H₂S and COS can be removed by an amine unit or a catalyst guard bed (Göransson et al. 2011); CO₂ can be removed by absorption, adsorption, or cryogenic membranes (Belgiorno et al. 2003; Zhang 2010; Goransson et al. 2010). The conventional gas cleaning is a thermally inefficient process and produces wastewater sludge (Sharma et al. 2008).

Dry hot gas cleaning – This technique has the possibility to be efficient, clean and safe (Göransson et al. 2011). The particulates are extracted in a hot gas cyclone and a sinter metal candle, H₂S is

eliminated by two-steps in ZnO and ZnO/CuO beds, chlorine is extracted in sodium promoted bed. Finally, a two-step tar reformer of dolomite and NiO beds is used to reform the tars (SCHWEIGER and HOHENWARTER, 2007 [102]). However, some authors suggest combining the particulate filter with a catalyst susceptible to sulfur components. The sorbent should be dissipated as a fine powder forward the filter and put on the filter elements with the fly ash. Moreover, it is suggested the conversion of tar and NH₃ in the syngas by a catalyst layer after the filter (Leibold, Hornung, and Seifert 2008).

Removal of particulate matter – Cyclones are widely used technique to remove particulate material. Among the various cleaning possibilities of gas, these devices have indicated the better equilibrium of separation and the cost of investment, operation, and maintenance. They can control any combination of gas temperature, pressure, and high solids loading, its development is tolerant, compared to the equipment in a more efficient separation (that is, filters of ceramic), while being much simpler and reliable (Cortés and Gil 2007).

In the gasification processes, after the gas passes through the cyclones, they cool it through a filter of sleeves to achieve maximum removal (Efren et al. 2014). These filters operate at 130 °C, under these conditions they can remove particulate material and tar. The reduction of particulate material reaches 70-95%(Hasler and Nussbaumer 1999).

Tar Removal – One of the biggest problems in the efficiency of gasification is the tar formation, which can condense and lead to corrosion in equipment and piping, besides that it can act as a poison for catalytic processes (Yung *et al.*, 2009). Tar presence also means a considerable loss of energy, which reduces the efficiency of the process (Nemanova et al. 2011).

Tar is differently defined by different research groups. Based on the ECN definition, tar includes all organic components that have molecular weight higher than benzene, but does not consider the benzene itself as a tar (Bergman, Van Paasen, and Boerrigter 2002). However, once benzene is one of the principal and more stable among the aromatic compounds and may be responsible for environmental or technical problems, a few researchers recognize benzene as a tar (Göransson et al. 2011). Otherwise, the tars can be categorized based on their physical properties (condensation or water solubility) (Bergman, Van Paasen, and Boerrigter 2002; van Paasen and Kiel

2004), or based on conditions of the process in which the compounds are produced (Milne and Evans 1998; Rabou et al. 2009).

Biomass syngas of tar concentration is in the order of 10 g/m³ for fluidized-bed gasifiers (Rabou et al. 2009). However, the fouling problems are not important if all the tar is current in the gas phase, so the tar problem is mainly not due to the tar quantity, but its properties and composition. Tar condensation and water solubility are significant parameters once the waste water pollution is associated to the tar composition in the syngas (Bergman, Van Paasen, and Boerrigter 2002).

The methods for tar removal can be classified as primary methods when the tar is removed in the gasifier itself, and secondary methods when the tar is removed after gasification (Devi, Ptasinski, and Janssen 2003). The primary method should be considered before the second method (Göransson et al. 2011). The primary methods are all measures taken in gasification in order to prevent or convert the tar produced in the gasifier (Lisý et al. 2012). To get better output gas quality, the gasifier operating conditions have to be optimized. Primary methods include appropriate choice of operational conditions, proper catalyst usage during gasification and appropriate design of the gasifier. To avoid the formation of tar, the temperature of gasification has a notable effect on amount of tar and its composition. Also rising the gas residence time in a hot zone has a similar result (Rabou et al. 2009). The secondary methods are the treatment of the gaseous product of the gasifier. These methods may be chemical, such as destruction at high temperature, above 1250 °C, or catalytic destruction at low temperature less than 950 °C (Devi et al. 2005; Zhang 2010), or physical, such as cyclones, rotary particle separators, filters (ceramic, electrostatic, deflectors, fabrics)(L. Bain et al. 2005), biodiesel scrubbing or the OLGA process (Zhang 2010).

CATALYSTS

The heterogeneous catalysts composition can be classified into (1) an active catalytic phase or metal, (2) a promoter, which rises activity and stability, and (3) a high surface area support that contributes to dispersion of the active phase (Bartholomew and Farrauto 2007). The most common catalyst is Ni but other metals can be used, such as Au,

Co, Cu, Fe, Ir, Pd, Pt, Rh, Zn, however, Ni based and Rh based catalysts presented the best performing activity (M. Yung, S. Jablonski, and A. Magrini-Bair 2009). These Ni catalysts have also demonstrated activity for tar removal, water-gas shift, hydrocarbon reforming, and NH₃ decomposition (Dayton 2002b).

The use of a promoter can affect catalyst activity, reducibility, renewability, and coke resistance. Promotion can also contribute to rise mechanical strength and attrition resistance, which is essential for catalysts employed in fluidized-bed reactors. The most common promoter are metals from Group VIII, other groups included the transition metal, alkalis and other groups (Yung *et al.*, 2009).

Ebrahimi-Nik et al. 2014 studied the consequence of the use of different catalysts in the sugarcane bagasse gasification. The studied was done in two batch autoclave reactors with constant pressure (25 MPa) and various temperatures (400 – 800 °C). The main objective was to find the maximum hydrogen production, which is observed at 800 °C and with KOH as a catalyst.

The biggest problem in the use of catalysts is the possibility of deactivation, which can be mechanical (particle failure, fouling), thermal (volatilization of the catalyst, phase changes, compound formation, sintering) and chemical (poison adsorption, coking) (Spencer and Twigg 2005). In general, all catalysts will reduce its initial performance, leading the process to slow down (Bartholomew 2001). The ways of deactivation modify the available surface area and chemical and physical nature of the active sites, changing the reaction rate (Spencer and Twigg 2005). The catalysts commonly employed for syngas are affected to deactivation, mainly by coking, sulfur poisoning and the presence of trace contaminants (L. Bain et al. 2005). The understanding of these processes is important for designing catalysts to reduce the degradation of long-term catalytic performance (M. Yung, S. Jablonski, and A. Magrini-Bair 2009).

Coke formation – Coke is a carbonaceous deposit that covers the catalyst surface and avoids reactants from reaching it (Aguayo et al. 2003). These carbon deposits can occur as crystalline graphitic sheets, amorphous films or fibers, and adsorbed carbides. Some of these carbon forms persist on the surface, while others diffuse into the catalyst. Due to all this variation, different methods of removal must be applied (Bartholomew 2001; Ginsburg et al. 2005). The hydrocarbons

type that interact with a catalyst influences the quantity of coke formed, in general, the susceptibility of hydrocarbon species for coke formation is aromatic > olefinic > paraffinic (Rostrup-Nielsen 1997; Rostrup-Nielsen, Sehested, and Nørskov 2002).

Sulfur Poisoning – Sulfur is recognized to produce metal sulfides on numerous materials. Ni catalysts deactivation due to sulfur poisoning has been evaluated by many authors (Ko, Chu, and Chaung 2005; Cheekatamarla and Lane 2006; Magrini-bair et al. 2007). The solution to sulfur poisoning includes the development of catalyst more sulfur-tolerant, the sulfur components (like H₂S) removal from the stream or the usage of a sulfur sorbent, like ZnO, that will adsorb H₂S leading to the formation of ZnS. However, the catalytic conditioning of syngas streams made of biomass directly occurs at temperatures that are high for ZnO sorbents (800 °C), which limited the efficient of H₂S adsorption, that occurs commonly at 500 °C (Jung et al. 2006; Slimane and Williams 2002).

Other contaminants than Sulfur – Beyond sulfur, natural contaminants present in biomass can also be responsible for the catalyst deactivation by poisoning. There are many inorganic species in biomass, like Si, Al, Ti, Fe, Ca, Mg, Na, K, P, S, and Cl (Elliott et al. 2004).

CONCLUSION

In the last decades, much research has been conducted and a lot of progress has been made in the fields of sugarcane bagasse gasification, especially in the pretreatment, like torrefaction, that is used to remove moisture and increase the bulk density. Gasification has a much higher energy efficiency than techniques like combustion or pyrolysis, producing a gas (named syngas) which consists of carbon monoxide, nitrogen, hydrogen, carbon dioxide, methane, and other compounds. Research on sugarcane bagasse gasification is ongoing and its future is promising.

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