Biomass Gasification

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Lignocellulosic gasification is a valid thermochemical approach for the conversion of organic solid matter into a gaseous mixture that is constituted of hydrogen, carbon monoxide, carbon dioxide and methane, named synthetic gas or syngas. Although about 55% of syngas is still produced from coal, biomass utilization, especially lignocellulose, is constantly growing. Indeed, gasification could be potentially applied to all different kinds of lignocellulosic biomass, unlike other conversion technologies. Moreover, in the last few decades, a wide range of applications of syngas have been intensively studied. Syngas can be directly used as a combustible substance in power plants for heat and power production (steam cycle, co-combustion, combustion in gas turbines or internal combustion engines, high temperature fuel cells), which represents the most common use of biomass-derived syngas. However, syngas also represents a platform that can be employed in a broad range of chemical and microbial processes, leading to gaseous and liquid fuels, as well as to chemicals. Chemical process research has mainly focused on transportation fuel production from syngas, such as Fischer–Tropsch liquid fuels, hydrogen, methanol, dimethyl ether (DME), mixed alcohols, and synthetic natural gas (SNG). Instead, the biochemical conversion route consists of syngas fermentation in which obligate anaerobic microorganisms convert syngas into organic acids, alcohols, and other chemicals. The most commonly used microorganisms are acetogens, which use the Wood–Ljungdahl metabolic pathway. Syngas fermentation is defined as an indirect fermentation process because biomass is not fed directly into the fermenter, but it is previously converted into syngas through gasification.

Keywords: biomass gasification ; syngas ; thermochemical process

1. Introduction

The gasification of carbonaceous feedstocks to syngas takes place inside a reactor, defined as a gasifier, at high temperatures (800–1500 °C). The feedstock is subjected to partial oxidation due to a lower concentration of oxygen than the stoichiometric requirement. Oxygen is supplied by a gasifying agent or carrier, such as air, pure oxygen, water steam, or their mixture. Although carbon dioxide can also be used as a gasifying agent, its use is less frequent. Moreover, the use of supercritical water is an innovative technology, without the need for pretreatment, which achieves a high H_2 yield and reduces tar and char production[1][2][3]. Compared with conventional methods, gasification is a more efficient process than combustion, which is the most common thermochemical route [4], and it can convert the entire carbon content in the biomass feedstock into gaseous compounds, unlike the biological or chemical hydrolysis that is adopted in biochemical processes [5]. According to the IEA Bioenergy Task 33, there are 114 working biomass gasification projects worldwide, 15 plants idle or on hold, and 13 are under construction or in planning (Figure 1) [6].

Figure 1. Geographical distribution of biomass gasification projects [6].

2. Syngas Characteristics By Biomass Type

At the end of the entire process, two main product mixtures are present: a solid mixture and a gaseous mixture. The solid mixture contains the unreacted organic fraction and inert materials, such as tars and ashes. Tars are classified into primary, secondary, and tertiary tars. Primary tars consist of both oxygenated compounds (alcohols, carboxylic acids, ketones, aldehydes, etc.) and substituted phenols (cresol, xylenol, etc.). Secondary tars are alkylated aromatics, such as toluene, ethylbenzene, xylenes, styrene, and hetero-aromatics, such as pyridine, furan, dioxin, and thiophene. Finally, tertiary tars consist of aromatics and polycyclic aromatic hydrocarbons (PAH), such as benzene, naphthalene, phenanthrene, pyrene, and benzopyrene. While primary tars are produced directly from the pyrolysis of cellulose, hemicellulose, and lignin, secondary and tertiary tars are the result of several complex reactions that have not been fully clarified yet[7]. On the other hand, the gaseous mixture contains syngas (H_2, CO, CO_2, and CH_4) and a small amount of impurities, such as light hydrocarbons (ethane, ethylene, acetylene), hydrogen sulfide (H_2S), sulfur dioxide (SO_2), hydrogen chloride (HCl), nitrogen oxides (NO_x), nitrogen (N_2), and ammonia (NH_3)[8]. The syngas's final composition and characteristics are related to the type of biomass, gasifying agent, gasifier type, and reactor's operational conditions, such as temperature, pressure, equivalence ratio (ER), residence time, and catalyst used [2][9][10][11][12][13]. For these reasons, in the last few decades, gasification has been intensively studied to investigate the effects of these factors, and thus, to identify the optimal conditions for the process. Regarding feedstock type, wood is the most commonly used feedstock in the gasification process. A representative component profile for syngas produced from several woody biomass types is shown in Table 1. In addition to woody biomass, other kinds of biomass have also been studied as gasification feedstocks. Agro-industrial residues and perennial herbaceous crops (Table 2) represent promising feedstocks that can be used in a thermochemical conversion process to obtain both energy and chemicals. The use of agricultural and industrial wastes, as well as herbaceous crops, instead of woody feedstocks, extends the seasonal availability of biomass. Syngas's composition is highly dependent on the used feedstocks, as well as the gasification technology applied (Tables 1 and 2). It is worth pointing out that nitrogen (N_2) can represent a main syngas component when air is used as a gasifying agent, in addition to H_2, CO, CO_2, and CH_4. Therefore, air gasification results in N_2-diluted syngas with low H_2 and CO concentrations. Instead, when gasification is carried out with steam or oxygen, the syngas shows higher H_2 and CO concentrations. One of the major challenges in biomass gasification is producing syngas with a low or absent impurities content.

Table 1. Syngas compositions that are obtained from the gasification of several woody biomass and their process characteristics.

Feedstock	Syngas Composition (% *v*/*v*)				Gasifier Type	Gasification Conditions	Reference
	H_2	**CO**	**CO_2**	**CH_4**			
Mesquite wood	1.6–3.0	13.0–21.0	11.0–25.0	1.0–1.5	Fixed bed gasifier	GA: air; T: 782 °C; ER: 2.70	[15]
Juniper wood	2.5–3.5	21.0–25.0	9.0–12.0	1.5–1.8	Fixed bed gasifier	GA: air; T: 713 °C; ER: 2.70	[15]
Pine wood	30.5	52.8	14.7	2.0	Downdraft fixed bed gasifier	GA: steam; T: 900 °C; ER: N.A.	[16]
Oak wood	18.0	21.0	12.0	2.0	Downdraft fixed bed gasifier	GA: air; T: N.A.; ER: N.A.	[17]
Poplar wood	45.5	23.1	20.8	8.6	Rotary kiln reactor	GA: steam; T: 1500 °C; ER: N.A.	[18]
Eucalyptus wood	10.7	20.2	9.1	8.6	Downdraft fixed bed gasifier	GA: air; T: 865 °C; ER: 0.31	[19]
Coffee wood	12.4	14.0	10.4	6.5	Downdraft fixed bed gasifier	GA: air; T: 813 °C; ER: 0.32	[19]
Rubber wood	6.0–8.0	10.0–14.0	16.0–18.0	N.A.	Bubbling fluidized bed gasifier	GA: air; T: 750–900 °C; ER: 0.38	[20]
Oil palm wood	60.0–70.0	10.0–30.0	20.0–50.0	5.0–10.0	N.A.	GA: steam; T: 800 °C; ER: N.A.	[21]
Spruce wood	10.7	25.9	9.7	3.8	Fixed bed reactor	GA: air; T: 800 °C; ER: N.A.	[22]

Wood residue	42.5	23.0	18.1	11.5	Fluidized bed gasifier	GA: air; T: 823 °C; ER: 0.17	[23]
Vermont wood [a]	28.6	23.5	24.0	15.5	Fluidized bed gasifier	GA: steam; T: 600–710 °C; ER: N.A.	[24]
Wood residue [b]	26.2–28.0	50.0–60.3	12.7–23.3	0.9–1.8	Entrained flow gasifier	GA: oxygen; T: 1200–1500 °C; ER: 0.44	[25]
SRF wood [c]	15.7–16.5	15.9–17.2	14.3–15.1	2.6–2.7	Downdraft fixed bed reactor	GA: air; T: 650–800 °C; ER: 0.25–0.26	[26]
Wood waste [d]	9.4–14.8	15.1–19.4	11.0–15.8	3.2–4.3	Bubbling fluidized bed gasifier	GA: air/air and steam mixture; T: 850 °C; ER: 0.20–0.29	[27]

GA: gasifying agent, T: temperature, ER: equivalence ratio, N.A.: data not available. [a] Vermont wood is a mixture of 25% red oak, 15% white pine, 15% maple, 15% ash, and 10% poplar, with the balance being cherry, birch, and cedar. [b] Wood residue is a mixture of 45% hardwood (birch) and 55% softwood (pine). [c] Solid recovered fuels (SRF) wood is composed of waste furniture and waste pallets from a waste collection site. [d] Wood waste that cannot be utilized to produce fuel for domestic heating because they come from potentially contaminated waste; it is made of sawdust from the wood packaging industry or it is obtained as a recycled product from furniture and from door and window frames.

Table 2. Syngas compositions obtained from the gasification of several agro-industrial residues and herbaceous crops and their process characteristics.

Feedstock	**Syngas Composition (% *v*/*v*)**				**Gasifier Type**	**Gasification Conditions**	**Ref.**
	H_2	**CO**	**CO_2**	**CH_4**			
Corn straw	48.5	33.9	12.2	5.3	N.A.	GA: N.A.; T: 750–900 °C; ER: N.A.	[28]
Wheat straw	25.4	27.5	22.0	16.3	Fluidized bed gasifier	GA: steam; T: 600–710 °C; ER: N.A.	[24]
Rice husk	5.0–8.0	16.0–21.0	15.0–16.0	46.0	Fluidized bed gasifier	GA: air; T: 700–800 °C; ER: 0.18–0.27	[29]
Coffee husk	6.6	13.8	12.1	14.8	Downdraft fixed bed gasifier	GA: air; T: 669 °C; ER: 0.12	[19]
Coconut coir	7.0–21.4	18.6–20.3	19.1–21.3	6.1–9.0	Entrained flow reactor	GA: air; T: 726–941 °C; ER: 0.21–0.30	[30]
Groundnut shells	13.8	13.0	13.5	5.7	Bubbling fluidized bed gasifier	GA: air; T: 714.4 °C; ER: 0.31	[31]
Almond shells	34.2–39.6	17.8–23.2	10.7–16.8	N.A.	Bubbling fluidized bed reactor	GA: N.A.; T: 820 °C; ER: N.A.	[32]

Hazelnut shells	11.1–14.7	8.6–20.7	9.5–16.3	1.4–2.5	Downdraft fixed bed gasifier	GA: air; T: 1000–1050 °C; ER: N.A.	[33]
Hay	8.8	19.7	14.4	3.0	Fixed bed reactor	GA: air; T: 800 °C; ER: N.A.	[22]
Corn stover	26.9	24.7	23.7	15.3	Fluidized bed gasifier	GA: steam; T: 600–710 °C; ER: N.A.	[24]
Olive kernels	5.4–9.3	6.9–8.6	19.0–21.7	1.8–3.0	Circulating fluidized bed gasifier	GA: air; T: 800 °C; ER: 0.4–0.7	[34]
Vine pruning	17.1–18.4	21.3–21.7	11.3–13.0	2.1–2.6	Downdraft fixed bed reactor	GA: air; T: N.A.; ER: 0.26	[35]
Corncobs	17.3	22.6	12.0	1.98	Downdraft fixed bed reactor	GA: air; T: N.A.; ER: 0.28	[36]
Citrus peels	60.0–65.0	15.0–25.0	15.0–23.0	<5.0	Fixed bed gasifier	GA: steam; T: 750 °C; ER: N.A.	[37]
Posidonia oceanica	11.8–24.9	4.1–12.7	14.1–20.0	2.0–3.0	Fluidized bed gasifier	GA: air; T: 750 °C; ER: 0.3	[38]
Empty fruit brunch	12.9–13.5	17.0–17.4	13.7–14.5	1.5–1.9	Downdraft fixed bed gasifier	GA: air; T: 650–825 °C; ER: N.A.	[39]
Sugarcane bagasse	7.4–8.0	8.0–12.9	15.9–18.7	1.4–2.5	Cyclone gasifier	GA: air; T: 600–950 °C; ER: 0.18–0.25	[40]
Sewage sludge	5.1–8.1	19.5–31.6	13.3–16.5	0.9–1.5	Fixed-bed gasifier	GA: air; T: 650–1100 °C; ER: 0.12–0.27	[41]
Miscanthus X giganteus	8.6	16.4	14.0	4.4	Bubbling fluidized bed reactor	GA: air; T: 800 °C; ER: 0.21	[42]
Switchgrass (*Panicum vigatum*)	23.5	33.2	19.4	17.0	Fluidized bed gasifier	GA: steam; T: 600–710 °C; ER: N.A.	[24]
Thistle (*Cynara cardunculus L.*)	36.6	8.5	50.4	4.5	Circulating fluidized bed gasifier	GA: steam and oxygen; T: 750 °C; ER: 0.3	[43]
Wheatgrass (*Elytrigia elongata*)	10.8	12.3	16.5	5.3	Bubbling fluidized bed gasifier	GA: oxygen-enriched air; T: 800 °C; ER: N.A.	[44]

GA: gasifying agent. T: temperature. ER: equivalence ratio. N.A.: not available data.

3. Syngas Final Uses

Syngas, depending on its composition and final quality, is used as (Figure 2):

1. combustible substance to produce heat and power

2. platform based on chemical synthesis of Fischer-Tropsch (FT) liquid fuels, hydrogen (H_2), methanol (MeOH), dimethyl ether (DME), mixed alcohols and synthetic natural gas (SNG)

3. platform based on biochemical fermentation to produce (bio)chemicals, (bio)fuels and (bio)materials.

Future investigation studies on biomass gasification will be strategic to achieve an ideal syngas composition, thereby making the syngas final use as efficient as possible[14].

Figure 2. Schematic representation of biomass gasification process and syngas final use.

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