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Chapter

Gasification of Biomass

Thanh Phong Mai and Dinh Quan Nguyen

Abstract

Gasification is an indirect combustion of solid and liquid biomass by converting them to combustive syngas. Gasification is an alternative process for the traditional combustion, in which the emission of dust and toxic gases can be minimized. In this chapter, a comparison of these two biomass-to-heat conversion processes applied on biomass is presented in term of environmental impacts and technological benefits with a hope to provide readers a basic view of choices. Gasification is classified as in term of gasification agents, non-catalytic and catalytic process, and plasma assisted process. Popular types of gasification equipment, aka gasifiers, are introduced with working principles, through which the advantages and weakness of technology are briefly discussed.

Keywords: gasification, gasifier, biomass, indirect combustion, direct combustion, syngas, plasma, updraft, downdraft, cross-draft, bridging, tar, charcoal, hydrogen, steam, carbon dioxide, flue gas

1. Introduction

For the last decades, the demand for renewable energy has been increasing intensively due to the crude-oil crisis and the alert of global warming. Among the alternatives for fossil fuels to generate heat, biomass is an abundant neutral carbon source, of which its conversion to heat does not break the balance of the atmosphere's air contents [1]. Combustion of biomass has been the most direct and simple process to produce energy. However, the traditional combustion of biomass, such as wood, charcoal, straw, husks, etc., often leads to the emission of smoke, dust, fumes, volatile compounds and toxic gases due to incomplete reactions and fine particles dragged out of the system by the flue gas [2]. Although several combustion methods were invented to increase efficiency and reduce emission of pollutants, such as fixed bed rocket type, and fluidized bed technology, the direct combustion of solid fuels is still one of the major causes of the industrial air pollutant in the world [3].

In contrast, gasification of biomass can minimize the emission of pollutants. Syngas produced from gasification of biomass can be optionally purified before being combusted. Ultimately, the combustion of gaseous fuels inherently has higher efficiency than that of solid matters. That is because the oxidation of a solid object in oxygen/air is gradually happening from its outer surface into the inner layers, which can be described as a heterogeneous process, while a combustive gas like syngas can be burned at a very high mass transfer rate in a homogeneous process. A comparison is presented in **Table 1**.

The gasification phenomenon of carbonaceous materials was possibly observed in the human history as very early as the invention of fire. Gasification was found as the ignition and combustion of smoke released from smoldering coal, wood, straw,

	Combustion of syngas from gasification of biomass	Direct combustion of solid biomass
Type of reactions	Homogeneous	Heterogeneous
Uniformity	Very high	None
Process nature	Simple	Complex
Mass transfer rate	Almost instant	Slow, depending on the solid surface – oxygen/air contact

Table 1.
Combustion of syngas vs. combustion of solid biomass.

Figure 1.
Gasification of oil-extracted cashew nut shell at Laboratory of Biofuel and Biomass Research, Ho chi Minh City University of Technology (HCMUT).

grass, or other organic substances in the lack of oxygen. In 1792, the first industrial gasification system to generate electricity was reported [4]. Gasification is a thermal decomposition process of solid or liquid substances to syngas in the presence of gasification agents through a series of chemical reactions mentioned in the following sections. This technology can help converting variable low-energy-density fuels to combustive gases. It attracts significant interests in both academic and industrial fields. **Figure 1** shows a very strong flame torch produced by gasification of oil-extracted cashew nut shell.

Gasification is an advanced technology to convert biomass to syngas fuel under different atmospheres (oxygen/air, steam, H_2, CO_2). The product syngas can also be used as precursors to synthesize valuable chemicals via Fischer-Tropsch (F-T) reactions [5]. **Table 2** highlights some key differences between gasification and direct combustion of biomass.

2. Biomass gasification reactions

The combustion of a solid fuel is a thermal and oxidation decomposition with the involvement of oxygen in air. Generally, for biomass, it can be simply expressed as:

$$C_aH_bO_cN_dS_e + O_2/\text{air} \rightarrow CO_2 + H_2O + N_xO_y + SO_z + \text{Heat} \tag{1}$$

This process can be observed with two visual phenomena: first, thermal decomposition on the outer surface of the solid phase to release volatile and combustive components, which join thermal reactions in the gas phase secondly, as the formation of flames [6]. Differing from direct combustion, gasification limits the process at the first step to produce syngas. Conventionally, oxygen/air is used as gasification agent in this case. However, other gasification agents also can be employed to enhance the conversion efficiency as presented followings.

	Gasification of biomass	Direct combustion of biomass
Input feedstock	Low-energy-density and wet biomass is still feasible	The biomass fuel must have acceptable moisture content and relatively flammable to guarantee a sustainable operation.
Output flame	Smokeless, free of dust and toxic gases if the syngas is purified.	Smoky and dusty with fly ash.
Impact to the heat exchangers' surface	Minimized	Silica fume, dusty aerosol, and corrosive gases can shorten the lifetime of equipment.
Applicability for internal combustion engines	Yes	No
Equipment design complexity	Complex	Simple
Heat receiver arrangement	Mobile	Fixed to the burner
Side product	Char, ash (solids), tar, bio-oil, wood vinegar (liquids)	Ash

Table 2.
A brief comparison between biomass gasification and combustion.

In this context, to simplify the theory, biomass can be formulated with its main general composition $C_aH_bO_c$ due to the much lower contents of other elements, such as N, S, P, and halogens. The involvement of inorganic compounds is not considered.

2.1 Oxygen/air as gasification agent

The thermal decomposition of biomass in insufficient presence of oxygen/air, known as incomplete combustion, is the most conventional gasification. Logically, the whole process can be described below as rearranged from theory [7].

Drying: firstly, once entering the reactor, the biomass is dried due to heat.

Combustion: secondly, a part of the solid biomass, which was ignited and in contact with locally excess oxygen/air, is combusted to generate heat as the energy source for later reactions to occur.

$$C_aH_bO_c\ (\text{biomass}) + O_2 \rightarrow CO_2 + H_2O + Q\ (\text{kJ/mol}) \tag{2}$$

Pyrolysis: heat from the combustion zone is transferred via radiation, conduction, and convective hot streams to the surrounding biomass where oxygen/air is not sufficient or absent. Due to the heat, pyrolysis occurs to form CO_2, CO, CH_4, C_2H_4, H_2O, char (C), and other organic solids and liquids as primary tar (2).

Reduction: after the above two steps, hot reactants react in situ with the biomass and with each other via a series of reactions.

$$\text{Water gas reaction}: C + H_2O + 118.5\ \text{kJ/mol} \rightarrow CO + H_2 \tag{3}$$

$$\text{Methanation reaction}: C + 2H_2 \rightarrow CH_4 + 87.5\ \text{kJ/mol} \tag{4}$$

$$\text{Steam reforming methanation}: CH_4 + H_2O + 206\ \text{kJ/mol} \rightarrow CO + 3H_2 \tag{5}$$

$$\text{Water gas shift reaction}: CO + H_2O \rightarrow CO_2 + H_2 + 40.9\ \text{kJ/mol} \tag{6}$$

$$\text{Boudouard reaction}: C + CO_2 + 159.9\ \text{kJ/mol} \rightarrow 2CO \tag{7}$$

$$\text{Reverse water gas shift reaction}: CO_2 + H_2 + 41.2\ \text{kJ/mol} \rightarrow H_2O + CO \tag{8}$$

The main weakness of gasification by oxygen/air is due to a large portion of inert nitrogen in the agent (79–80%), which makes the resulted syngas diluted. It can be roughly estimated that syngas from this type of gasification mainly contains around 30–60% of nitrogen and 10–15% of CO_2 since its heating value is typically between 4 and 6 MJ/m^3 (for comparison, HHV of H_2 = 12.76 MJ/m^3, CO = 12.63 MJ/m^3, CH_4 39.76 MJ/m^3 and CH_4 is commonly much less than CO and H_2) [7–9]. Low quality syngas is the main disadvantage of this technique for applications which require high temperature and steady operation, such as internal combustion engine, metallurgy, and melting glass industries.

Air-based gasification processes are sensitive and complex, which are influenced by a number of factors, such as biomass composition and particle geometry, gasification agent composition and flow rate, equipment design, etc. Among these, the ratio of actual air-fuel ratio to the stoichiometric air-fuel ratio (ER) is used as a parameter to calculate and to simulate the process [10].

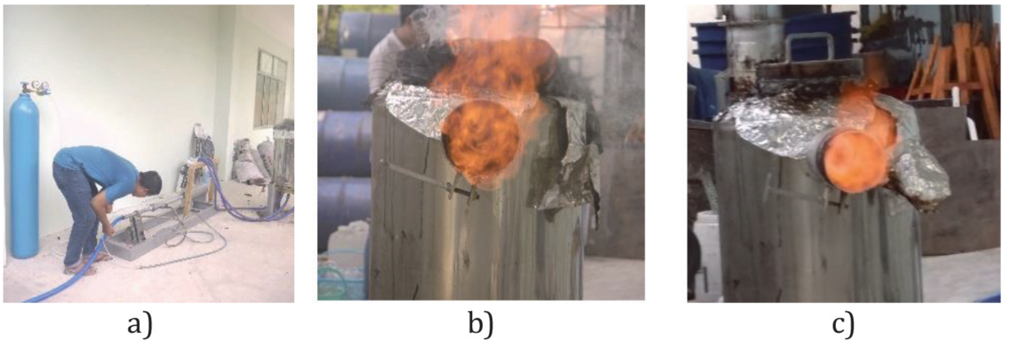
$$ER = \frac{Stoichiometric\ Air\ \left(Nm^3\right)}{Actual\ Air\ Supplied\ \left(Nm^3\right)} \text{ and ER} < 1.0 \tag{9}$$

Gasification ER is theoretically usually from 0.19 to 0.43, and a range of 0.25–0.29 was studied to be considered as the optimum ER in gasification of some popular biomass [11].

2.2 Oxygen-enriched air

To obtain more concentrated syngas, nitrogen must be limited from the gasification agent in air-based systems while sufficient oxygen is still guaranteed for combustion to generate heat [12]. This method does not change the nature of the gasification process since nitrogen is an inert gas not involved in the reactions. Several techniques were introduced to remove nitrogen, thus increase oxygen content in the input air stream, such as pressure swing adsorption (PSA) [13], temperature swing adsorption [14], carbon membranes [15], etc. Oxygen concentration in studies on gasification with oxygen- enriched air is found limited by less than 50%, and no study on 100% oxygen gasification, possibly because of a high risk of explosion [16–18].

Figure 2 shows the visual change in an air-based syngas flame (wood pellet as feedstock) when oxygen concentration in the gasifying agent increased from that of normal air to 30%. With normal air, the syngas flame is thinner with smoke, while oxygen-enriched air makes the flame stronger, thicker, and less smoke. The flame temperature was measured as 874 and 933°C, respectively.



a) b) c)

Figure 2.
Experimental gasification of wood pellet (a) showing the flame of syngas when using (b) normal air (21% vol. as O_2) and (c) oxygen-enriched air (30% vol. as O_2)

2.3 Saturated and superheated steam as gasification agent

Water gas (3) and water gas shift (6) reactions are the reasons steam can be introduced to oxygen/air gasification or wet biomass is accepted, of which moisture is more tolerated than that in direct combustion. Higher generation yields of H_2 and CO are obtained so the final syngas mixture gets higher heating value. However, these two reactions are endothermic while the vaporization enthalpy of water has a large value (at atmospheric pressure that is 40.65 kJ/mol) so saturated steam or water can make the pyrolysis zone lose heat, drop temperature, leading to lower conversion yield. Lower quantity becomes a contrast to higher quality of syngas formation in this case. Subsequently, the process even gets faded if sufficient heat is not guaranteed. To achieve both quantity and quality of syngas, heat should be redeemed by using superheated steam instead of saturated steam or water in wet biomass so that the gasification temperature is maintained above 750–800°C [19].

The ratio of steam to carbon content of the biomass fuel (SCR) is used as a crucial operating parameter in biomass gasification with steam feeding [20]:

$$SCR = \frac{Steam\ mass\ flow\ rate\ \left(\frac{kg}{s}\right)}{Carbon\ feed\ rate\ \left(\frac{kg}{s}\right)} \tag{10}$$

Steam flow rate (kg/s) to biomass (kg/s) ratio (S/B) is also used like SCR [21]. Steam feeding makes the ratio of hydrogen to carbon in the whole reaction mixture increase, which was found to yield more H_2, and increase the heating value of the syngas, while tar content decreases significantly [22]. This technique is positively meaningful in biomass gasification because it does not only increase the quality of the syngas but also reduce tar-clogging problems to sustain the process.

2.4 Other gasification agents: H_2 and CO_2

Not many studies on gasification by hydrogen and carbon dioxide were found although these two agents are reactants in methanation (4) and Boudouard (7) reactions.

Methanation reaction can be increased when more H_2 exists in the reaction zone of a gasifier. Since methanation is exothermic, hydrogen can be mixed with air in air-based gasification or can be used as the only gasification agents without slagging problems in the gasifiers like conventional oxygen/air gasification. Pure hydrogen gasification is expected to be able to run at lower temperature and milder conditions because less heat is generated from methanation reaction ($\Delta H = -87.5$ kJ/mol) than from combustion step in air-based gasification [23], which may lead to the absence of oils and tars [24]. However, catalysts are needed because the reaction rates are very low [25]. Otherwise, hydrogen gasification should be carried out in high H_2 pressure, which rises several safety concerns.

CO_2 is a Boudouard reactant, as well as it can react with H_2 in the mixture via reverse water gas shift reaction. Hot flue gas is a popular product in industry, which includes steam, CO_2, and heat from direct combustion of fuel, thus can be considered as a gasification agent [26]. This technique is available if a combustion process is combined with gasification because air-based gasification already has its combustion zone. CO_2 utilization and enhancement of CO formation can be the purposes of CO_2-gasification [27].

2.5 Catalysts

The reactions in gasification can proceed with higher yields and less energy input if appropriate catalysts are employed. Catalysts can facilitate the process by reducing slagging problems, by which in severe cases, gasifiers need to be shut down for maintenance. Together with slagging of low-melting-point inorganic compounds, tar and soot formation also interrupts the operation because matters can be vaporized at high temperature, then condense at cooler zones and clog the systems. Catalysis helps limit the formation of such undesired side-products or decompose them to workable substances by cracking reactions. The mechanism of tar catalytic cracking can be assumed as follows [28]:

- Organic and hydrocarbon compounds are dissociated from the biomass and absorbed on the catalytic sites.

- Catalytic dehydrogenation reactions happen.

- Water is hydroxylated to OH radicals, which oxidize the hydrocarbon fragments.

- Syngas, CH_4, and lighter hydrocarbons are formed then.

In contrast, catalytic gasification has some disadvantages, such as material costs and fading catalyst performance over reaction time. Theoretically, catalysts can be recovered after the process. But in fact, they are easily poisoned and contaminated by variable products, which are formed from the complex interactions in gasification.

Alkali metal salts seem to be the earliest catalysts to be examined for gasification [29]. Alkali elements were studied to catalyze gasification of char and biomass, and they were proved to reduce the formation of tar and soot [30, 31]. The employment of catalysts is preferred for entrained-flow gasifiers, which will be discussed later [32].

Natural minerals, precious metal and synthetic catalysts are also studied for their application in biomass gasification, as well as coal and syngas conversion [33–35].

2.6 Plasma gasification

Plasma, which can be produced by an electric arc discharged to a gas, is a very hot and highly ionized gaseous mixture. The initial gas interacts with the electric arc to become dissociated into electrons and ions at temperatures often exceeding thousands of Celsius degree. When biomass and a non-oxidizing gasifying agent are fed into a plasma reactor, the gasification can proceed at high temperatures without combustion to generate heat as in conventional process. Therefore, plasma gasification can convert organic substances to syngas that preserve all its chemical and heat energy, while converts inorganic mineral ash to inert vitrified glass or slag. As a result, contamination and dilution of syngas are minimized and the process control is easy to yield expected syngas composition [36, 37].

Microwave was also used to generate plasma in plasma gasification [38]. However, microwave plasma system is not easy to scale up for industrial purposes like electric arc type.

With the principle of supplying intensive heat for endothermic reactions, plasma gasification was used to produce hydrogen with steam injection as discussed in Section 2.3 [20]. Carbon dioxide gasification was studied with a various biomass feedstock to show input plasma energy was lowest while syngas formation yield was highest [39]. Experimental results showed that steam or catalysts added to plasma gasification can significantly reduce the formation of tars [40].

3. Gasifiers

Gasification is a complicated process, which is influenced by many factors, among which equipment design plays a very important role. Popular types of gasifiers are listed and briefly discussed as bellows.

3.1 Fixed-bed gasifiers

There are three ways of arrangement for biomass and gasifying agents entering to react with each other in the reactors: updraft, downdraft, and cross draft as illustrated in **Figure 2a–c**.

- Updraft gasifiers (**Figure 3a**): in this type of reactor, biomass is fed downward from the top and gasifying agents is fed upward from the bottom in a counter flow arrangement. Ash is collected at the bottom of the equipment with air-lock design. The biggest weakness of updraft gasifiers is the accumulation of tar, moisture, and soot on the top of the reactors, which becomes hard clogging blocks inside the equipment. **Figure 4** is the actual photo of a very thick and hard layer of tar and soot attached to the inner wall on the top of an updraft biomass gasification reactor (the photos were taken at the Laboratory of Biofuel and Biomass Research, Ho Chi Minh City University of Technology, HCMUT). This counter flow process also makes syngas from updraft gasifiers carries much contamination. In contrast, the operation of updraft gasifiers is the easiest among the three types of fix-bed gasifiers above. Its design is also simple and available for multi-feed stock purpose.

- Downdraft gasifiers (**Figure 3b**): a narrow throat at the combustion zone is the typical design of this type of equipment. Since syngas is obtained at the bottom of the reactor, biomass and gasifying agents move in a co-current direction and get in contact for combustion at the device throttle. The flow rate of the

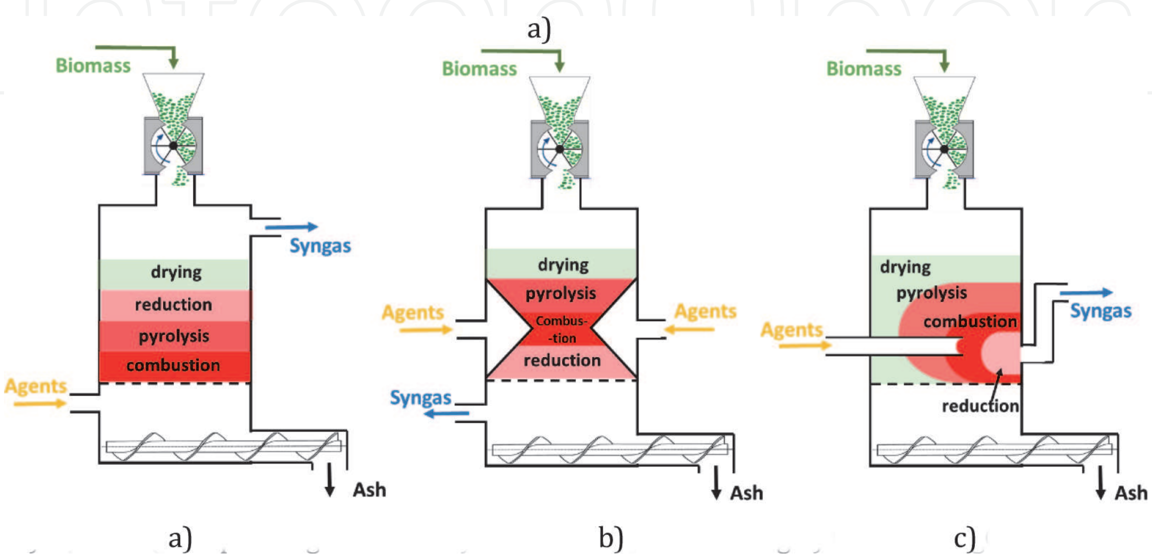


Figure 3.
Fix-bed gasifier types. (a) Updraft gasifier. (b) Downdraft gasifier. (c) Crossdraft gasifier.

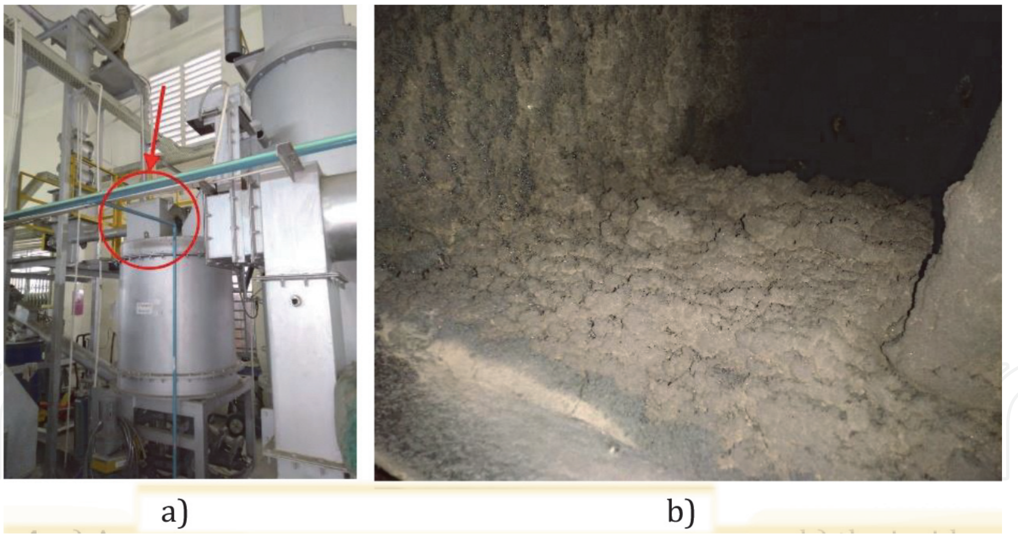


Figure 4.
(a) an updraft gasifier converting rice husk to syngas, (b) the inside wall of the top opening is clogged with a thick layer of condensed tar and soot.

gasifying agent gets maximum at this position due to the decreasing cross-sectional area of the orifice. As a result of this structure, the combustion increased sharply at the throttle while the amount of feeding agents is still. Downdraft gasifiers have higher conversion yield than that of their updraft models [41]. Syngas from downdraft gasifiers have much less tar and incomplete decomposed substances because they have to pass the combustion zone before exit with the syngas. However, downdraft gasifiers cannot be scaled up easily due to difficulties in controlling the movement of solid fuels through the throttle. Another difficulty in designing and fabricating downdraft gasifiers is "bridging problems" for feedstock with low densities [42]. The downward flow of the solid fuel is dictated by gravity while the pyrolysis zone is right above the narrow throat. The melting and adhesivity of lignin in biomass, as well as the local condensation of volatile substances, also facilitate the formation of stiff domes above the device throat, blocking the coming feedstock. It was observed that a rice husk downdraft gasifier kept stop working within some minutes of operation due to this problem and it was not an easy job to remove the bridging dome of "melting" rice husk inside the equipment (**Figure 5**).

- Crossdraft gasifiers (**Figure 3c**): as an intermediate between downdraft and updraft design, crossdraft gasifiers has the simplest design when biomass is fed from the top, gasifying agent from the rear side, and syngas is withdrawn from the other rear side of the reactor. Thanks to this arrangement, the pyrolysis zone is separated from reduction zone, where syngas is obtained, and between them is the combustion zone to reduce tar and soot. Bridging problem is not a concern in this case, and scaling up is feasible.

3.2 Fluidized bed gasifiers

Fluidization is an advance technique for solid fuel combustion. It is also applied for gasification. Inert materials (sand, dolomite, crushed stone, etc.) are employed to hold fluidization. The gasifying agents enter the reactor from the bottom upward to the top at velocities of 1–3 m/s through the biomass + inert material bed. Gasification reactions occur inside the bed then the resulted gases drag the particle before going up like "bubbling". This technique provides the mixture a uniformity for heat

Figure 5.
Fixing a downdraft gasifier after a bridging problem happened.

exchange. Cyclones are installed to collected solid particles and return them to the reactors. With high gasification efficiency, fluidized bed gasifiers are known for tar and char reduction [43].

The operating temperature of fluidized-bed gasifiers is limited to the melting point of the inert medium. The gasifying agents also play a role as fluidization fluids so the input flow rate must be high enough. Therefore, gasification agents in fluidized bed gasifiers are usually rather than only oxygen/air, which need to be at a limited mass ratio to the biomass [44, 45].

3.3 Entrained flow gasifiers

Entrained flow gasifiers are applied for biomass with small particle sizes so that the specific contact area with gasifying agents is large enough for suitable reaction rate. Simply described as illustrated in **Figure 6a**, the solid and the gas agents are fed co-currently to the reactor in the same downward direction. The agent surrounds the solid particles and react to convert the biomass to syngas. At the end of the falling routine to the bottom of the reactor of the feed, only ash and slag are expected to be remained solid collected in cyclone systems while syngas is passing through. The operation is carried out at high temperature and in high pressure. The

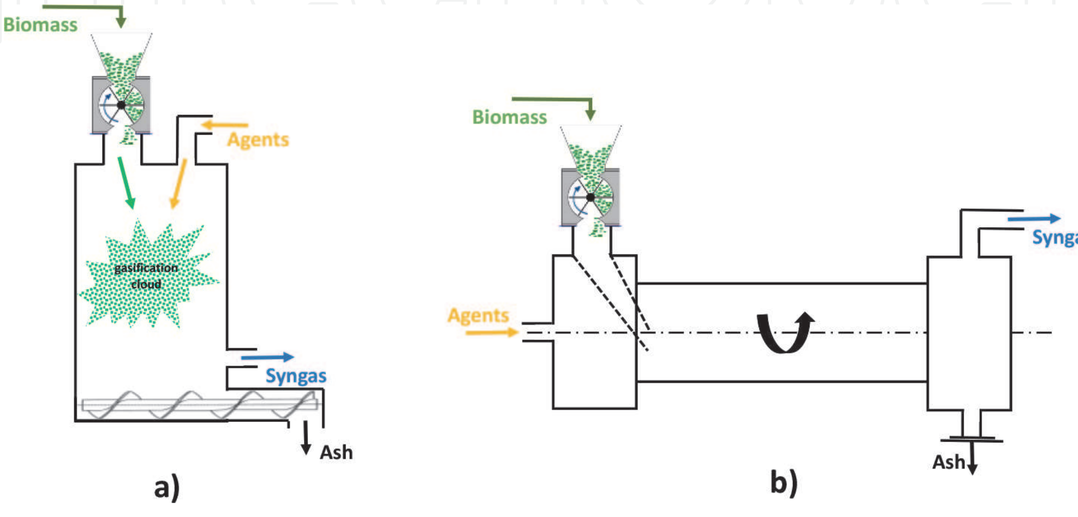


Figure 6.
(a) Entrained flow gasifier, (b) rotary drum gasifier.

extremely turbulent flow of the aerosol mixture causes rapid conversion and allows high throughput [46].

3.4 Rotary drum gasifiers

To reach uniformity of the biomass during gasification without combustion (using gasifying agents rather than oxygen/air), mechanical mixing can be applied as rotary kiln type reactor (**Figure 6b**). In this rotating cylinder, biomass is well mixed in contact with gasifying agents. Differing from fluidized bed and entrained flow equipment, the gasifying agents' flow rates can be at any value in rotary drum gasifiers.

4. Conclusion

Gasification is a big subject in biomass and chemical engineering. Among the renewable technologies converting biomass to fuels and energy with environmental preservation concern, gasification is superior over combustion with variable feasible application. Gasification process includes many reactions, which make it complex and sensitive to many factors. The diversity in the thermochemistry of gasification gives researchers and engineers a big space for creativity in R&D. This context introduced some brief theory and technical discussion on gasification technology with a humble hope to contribute to that vision.

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References

[1] Tran TTA, Le TKP, Mai TP, et al. Bioethanol Production from Lignocellulosic Biomass. In: Yun Y (ed) *Alcohol Fuels - Current Technologies and Future Prospect*. London, UK: IntechOpen, p. 1.

[2] Cormier SA, Lomnicki S, Backes W, et al. Origin and Health Impacts of Emissions of Toxic By-Products and Fine Particles from Combustion and Thermal Treatment of Hazardous Wastes and Materials. *Environ Health Perspect* 2006; 114: 810–817.

[3] Nussbaumer T, Hustad JE. Overview of Biomass Combustion. In: *Developments in Thermochemical Biomass Conversion*. Dordrecht: Springer Netherlands, pp. 1229–1243.

[4] Farzad S, Mandegari MA, Görgens JF. A critical review on biomass gasification, co-gasification, and their environmental assessments. *Biofuel Res J* 2016; 3: 483–495.

[5] Santos RG dos, Alencar AC. Biomass-derived syngas production via gasification process and its catalytic conversion into fuels by Fischer Tropsch synthesis: A review. *Int J Hydrogen Energy* 2020; 45: 18114–18132.

[6] Caillat S, Vakkilainen E. Large-scale biomass combustion plants: an overview. In: *Biomass Combustion Science, Technology and Engineering*. Elsevier, pp. 189–224.

[7] Ciferno JP, Marano JJ. Benchmarking biomass gasification technologies for fuels, chemicals and hydrogen production. *US Dep Energy Natl Energy* 2002; 58.

[8] Waldheim, L. Nilsson T. Heating value of gases from biomass gasification. *IEA Bioenergy Agreement, Task 20 - Therm Gasif Biomass* 2001; 61.

[9] Tran PNU, Vu LVK, Nguyen DQ, et al. Energy balance of small-scale biorefinery system. *Environ Sci* 2013; 26: 489–496.

[10] Rukshan J, Souman R. Numerical and Experimental Investigation of Equivalence Ratio (ER) and Feedstock Particle Size on Birchwood Gasification. *Energies* 2017; 10: 1232.

[11] James AM, Yuan W, Boyette MD, et al. The effect of air flow rate and biomass type on the performance of an updraft biomass gasifier. *BioResources* 2015; 10: 3615–3624.

[12] Cao Y, Wang Q, Du J, et al. Oxygen-enriched air gasification of biomass materials for high-quality syngas production. *Energy Convers Manag* 2019; 199: 111628.

[13] Reiss G. Oxygen Enrichment of Air With Molecular Sieve Zeolites Using The Psa/Vsa Technique. pp. 607–614.

[14] Eriksson T, Kiros Y. Temperature swing adsorption device for oxygen-enriched air. *J Clean Prod* 2014; 76: 174–179.

[15] Haider S, Lindbråthen A, Lie JA, et al. Carbon membranes for oxygen enriched air – Part II: Techno-economic analysis. *Sep Purif Technol* 2018; 205: 251–262.

[16] Liu L, Huang Y, Cao J, et al. Experimental study of biomass gasification with oxygen-enriched air in fluidized bed gasifier. *Sci Total Environ* 2018; 626: 423–433.

[17] Liu C, Huang Y, Niu M, et al. Influences of equivalence ratio, oxygen concentration and fluidization velocity on the characteristics of oxygen-enriched gasification products from biomass in a pilot-scale fluidized bed. *Int J Hydrogen Energy* 2018; 43: 14214–14225.

[18] Wang Z, He T, Qin J, et al. Gasification of biomass with oxygen-enriched air in a pilot scale two-stage gasifier. *Fuel* 2015; 150: 386–393.

[19] Kumar A, Jones DD, Hanna MA. Thermochemical biomass gasification: A review of the current status of the technology. *Energies* 2009; 2: 556–581.

[20] Favas J, Monteiro E, Rouboa A. Hydrogen production using plasma gasification with steam injection. *Int J Hydrogen Energy* 2017; 42: 10997–11005.

[21] Maschio G, Lucchesi A, Stoppato G. Production of syngas from biomass. *Bioresour Technol* 1994; 48: 119–126.

[22] Narváez I, Orío A, Aznar MP, et al. Biomass Gasification with Air in an Atmospheric Bubbling Fluidized Bed. Effect of Six Operational Variables on the Quality of the Produced Raw Gas. *Ind Eng Chem Res* 1996; 35: 2110–2120.

[23] Sheth AC, Sastry C, Yeboah YD, et al. Catalytic gasification of coal using eutectic salts: reaction kinetics for hydrogasification using binary and ternary eutectic catalysts. *Fuel* 2004; 83: 557–572.

[24] LEE S, LEE J, KIM J, et al. Hydrogasification characteristics of bituminous coals in an entrained-flow hydrogasifier. *Fuel* 2006; 85: 803– 806.

[25] Klinghoffer NB, Castaldi MJ, Nzihou A. Catalyst Properties and Catalytic Performance of Char from Biomass Gasification. *Ind Eng Chem Res* 2012; 51: 13113–13122.

[26] Maj I, Kudlek E, Ostrowski P, et al. Investigation of sewage sludge gasification with use of flue gas as a gasifying agent. *E3S Web Conf* 2017; 14: 02001.

[27] Sadhwani N, Adhikari S, Eden MR, et al. Aspen plus simulation to predict steady state performance of biomass-CO 2 gasification in a fluidized bed gasifier. *Biofuels, Bioprod Biorefining* 2018; 12: 379–389.

[28] Ren J, Cao J-P, Zhao X-Y, et al. Recent advances in syngas production from biomass catalytic gasification: A critical review on reactors, catalysts, catalytic mechanisms and mathematical models. *Renew Sustain Energy Rev* 2019; 116: 109426.

[29] Suzuki T, Ohme H, Watanabe Y. Mechanisms of Alkaline-Earth Metals Catalyzed CO2 Gasification of Carbon. *Energy & Fuels* 1994; 8: 649–658.

[30] Postma RS, Kersten SRA, van Rossum G. Potassium-Salt-Catalyzed Tar Reduction during Pyrolysis Oil Gasification. *Ind Eng Chem Res* 2016; 55: 7226–7230.

[31] Furusjö E, Ma C, Ji X, et al. Alkali enhanced biomass gasification with in situ S capture and novel syngas cleaning. Part 1: Gasifier performance. *Energy* 2018; 157: 96–105.

[32] Umeki K, Häggström G, Bach-Oller A, et al. Reduction of Tar and Soot Formation from Entrained-Flow Gasification of Woody Biomass by Alkali Impregnation. *Energy & Fuels* 2017; 31: 5104–5110.

[33] Yang Z, Cao J-P, Ren X-Y, et al. Preparation of hierarchical HZSM-5 based sulfated zirconium solid acid catalyst for catalytic upgrading of pyrolysis vapors from lignite pyrolysis. *Fuel* 2019; 237: 1079–1085.

[34] Park SY, Oh G, Kim K, et al. Deactivation characteristics of Ni and Ru catalysts in tar steam reforming. *Renew Energy* 2017; 105: 76–83.

[35] Zhao X-Y, Ren J, Cao J-P, et al. Catalytic Reforming of Volatiles from Biomass Pyrolysis for Hydrogen-Rich Gas Production over Limonite Ore. *Energy & Fuels* 2017; 31: 4054–4060.

[36] Hlina M, Hrabovsky M, Kavka T, et al. Production of high quality syngas from argon/water plasma gasification of biomass and waste. *Waste Manag* 2014; 34: 63–66.

[37] Rutberg PG, Bratsev AN, Kuznetsov VA, et al. On efficiency of plasma gasification of wood residues. *Biomass and Bioenergy* 2011; 35: 495–504.

[38] Delikonstantis E, Sturm G, Stankiewicz AI, et al. Biomass gasification in microwave plasma: An experimental feasibility study with a side stream from a fermentation reactor. *Chem Eng Process - Process Intensif* 2019; 141: 107538.

[39] Kuo P-C, Illathukandy B, Wu W, et al. Plasma gasification performances of various raw and torrefied biomass materials using different gasifying agents. *Bioresour Technol* 2020; 314: 123740.

[40] Mei D, Wang Y, Liu S, et al. Plasma reforming of biomass gasification tars using mixed naphthalene and toluene as model compounds. *Energy Convers Manag* 2019; 195: 409–419.

[41] Muthu Dinesh Kumar R, Anand R. Production of biofuel from biomass downdraft gasification and its applications. In: *Advanced Biofuels*. Elsevier, pp. 129–151.

[42] Guangul FM, Sulaiman SA. Mitigation of Bridging Problem in Biomass Gasification by a Novel Approach. *Asian J Sci Res* 2013; 6: 331–338.

[43] Gómez-Barea A, Ollero P, Leckner B. Optimization of char and tar conversion in fluidized bed biomass gasifiers. *Fuel* 2013; 103: 42–52.

[44] Udomsirichakorn J, Basu P, Salam PA, et al. Effect of CaO on tar reforming to hydrogen-enriched gas with in-process CO2 capture in a bubbling fluidized bed biomass steam gasifier. *Int J Hydrogen Energy* 2013; 38: 14495–14504.

[45] Kirnbauer F, Wilk V, Kitzler H, et al. The positive effects of bed material coating on tar reduction in a dual fluidized bed gasifier. *Fuel* 2012; 95: 553–562.

[46] Wu Y, Smith PJ, Zhang J, et al. Effects of Turbulent Mixing and Controlling Mechanisms in an Entrained Flow Coal Gasifier. *Energy & Fuels* 2010; 24: 1170–1175.