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## Review of Biomass Thermal Gasification

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Additional information is available at the end of the chapter

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### Abstract

Gasification of biomass is one of the most attractive methods for producing hydrogen rich gas. Syngas production from biomass is an attractive solution for energy crisis. The production of energy from biomass reduces the dependence of developing countries on fossil fuels, as ample biomass is available in the developing countries and is renewable. Downdraft gasifiers are fixed bed gasifiers where the gasifying agent and biomass are flowing downwards, developed for high-volatile fuels such as wood or biomass gasification. Cocurrent flow regime throughout the oxidation and reduction zones reduces the tars and particulates in syngas, which will reduce the necessity of complicated cleaning methods compared to updraft gasifiers especially if the gas is used as a burnable gas in a small community. It is important to ensure homogenous distribution of gasifying agent at the downdraft gasifier throat. This chapter presents latest trends in gasification of biomass using downdraft gasification.

**Keywords:** gasification, hydrogen, agriculture waste, catalysts, downdraft gasifier

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### 1. Introduction

Gasification of biomass is one of the most attractive methods for producing hydrogen rich gas. Syngas production from biomass is an attractive solution for energy crisis. The production of energy from biomass reduces the dependence of developing countries on fossil fuels; as ample biomass is available in the developing countries and is renewable. Downdraft gasifiers are fixed bed gasifiers where the gasifying agent and biomass are flowing downwards, developed for high volatile fuels like wood or biomass gasification. Cocurrent flow regime throughout the oxidation and reduction zones reduces the tars and particulates in syngas, which will reduce the necessity of complicated cleaning methods compared to updraft gasifiers especially if the gas is used as a burnable gas in a small

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community. It is important to ensure homogenous distribution of gasifying agent at the downdraft gasifier throat [1–3].

Gasification is a process under development to utilize the energy conserved in biomass. Gasification can be used as a source of energy in rural and off-grid areas to fill the power gaps. The limited supply and the increasing demands of fossil fuels have led the world to investigate alternative energy sources. Renewable energy sources have been studied widely, and biomass appears as the most promising renewable energy source. Biomass can be used to overcome the depletion of fossil fuels and to reduce the environmental impact of the conventional fuels such as greenhouse gas emissions using one of these four technologies: direct combustion, thermochemical processes, biochemical processes, and agrochemical processes. Biomass is the third energy source after coal and oil. Biomass covers 35% of the energy demand of the developing countries corresponding to 13% of the world energy demand. Biomass is widely available in quantities enough to meet the world energy demand [1–7].

The oldest way to generate energy is to burn biomass. Due to environmental and technical difficulties associated with burning biomass, innovative processes should be developed to utilize biomass [5, 8–10]. Developing more effective techniques to utilize biomass will reduce the disposal problem and create profits. Hydrolysis, pyrolysis, gasification, and hydrogenation are the principal processes for biomass conversion in the literature [7, 11]. Gasification represents efficient and environmentally friendly method for producing the syngas as a bio-fuel from different sources of biomass [12–14], and to produce second-generation biofuels such as methanol, ethanol, and hydrogen [8, 10, 12, 15]. Gasification can be defined as the partial (incomplete) combustion of biomass, and gasification could extract up to 60–90% of the energy stored in biomass [16, 17]. To develop second-generation biofuels, economical and Feasible clean technologies of syngas are required. [15]. However, economical gasification of biomass may produce burnable gases, which can be used to provide heat requirements instead of LPG [12]. Gasifiers were developed to replace biomass burners. Gasifiers will prevent the necessity of on-site power generation [18, 19]. Gasification is the conversion of biomass into a combustible gas and charcoal by partial oxidation of biomass at temperature range of 800–900°C [6, 19, 20].

The charcoal is finally reduced to  $H_2$ ,  $CO$ ,  $CO_2$ ,  $O_2$ ,  $N_2$ , and  $CH_4$  [6, 8–10, 21]. Char gasification starts at temperatures above 350°C [7]. The products of gasification consist of the following components: ash, volatile alkali metals, tars, and syngas. Tars represent a challenge for the commercialization of gasification product as an alternative fuel [22]. Frequently using tar may result in complete shutdown and repair of the industrial unit [18, 22]. Tars set and amount vary considerably based on reaction conditions and gasifier type [18]. Gas produced from gasifier can be cleaned by removing tars either physically or chemically [18]. Physical removal can be achieved using bag filters or wet scrubbers. Chemical removal methods depend on converting tars to lighter hydrocarbons either using thermal conversion or catalytic conversion processes [18, 22].

Gasification of such material may help in reducing the gap between electricity requirements and available energy sources. Decentralized power regeneration units will help to fill power gap in rural and off-grid locations [4]. Yet, it is still difficult to develop a decentralized power

generation unit based on biomass energy which can be used to fill the gap in energy needs in rural areas and farms [4]. Technical difficulties prevent further commercialization of gasification units in accordance to lower conversion efficiency [23, 24]. Leung et al. [25] proposed a governmental support to accomplish faster steps toward gasification units commercialization. However, all over the world, biomass energy has been widely incorporated in the power generation system; U.S. started partial and full conversion of conventional power plants to biomass [24]. Throughout this chapter, we will discuss the latest trends in agricultural waste gasification. Our goal is to provide a full description of the process starting from basic understanding and ending by design of a gasification unit.

## 2. Chemistry of gasification

The reactions taking place in the gasifier can be summarized as indicated below [3, 4, 21]:

Partial oxidation:



Complete oxidation:



Water gas phase reaction:

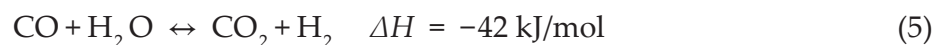


Boudouard reaction:

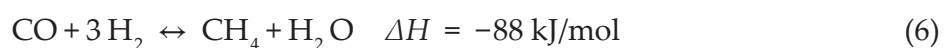


The heat required for water gas phase and Boudouard reactions is provided by complete and partial oxidation reactions, and complete oxidation provides around 60% of the heat requirements during gasification [3, 17]. In addition to the previous reactions that are common in combustion and gasification, hydrogen, steam, and carbon monoxide undergo further reactions as shown below [3, 24]:

Water gas shift reaction:



Methane formation:



The water gas shift and methane formation reactions are in equilibrium and the governing parameters are: pressure, temperature, and concentration of reaction species.

### 3. Gasifier design

The unit design is a very important factor in determining the syngas quality and heating value [15]. The gasifier will hold two processes: conversion of biomass to charcoal and then conversion of charcoal to hydrogen and carbon monoxide. The mixture of hydrogen and carbon monoxide can be used for direct heating in rural areas [16]. Leung et al. [25] identified four types of gasifiers: updraft, open core, downdraft, and circulating fluidized bed (CFB) gasifiers. The maximum efficiency of the updraft, downdraft, and CFB gasifiers may reach to 75%, the maximum energy output is 10E6, 4E6, and 40E6 kJ/h, respectively. According to Chopra and Jain [13], the fixed bed gasifiers can be further divided into: updraft, Imbert downdraft, throatless downdraft, cross draft, and two-stage gasifiers. The fixed-bed gasifier is suitable for producing low heating value gas for small and medium applications [13, 26]. The downdraft gasifier is distinguished by a simple design, high carbon conversion, long residence time, low cost, low pressure, relatively clean gas, and low gas velocity. The downdraft gasifier is suitable for producing low heating value burnable gas or for generating electricity of small-scale systems in the range of 10 kW up to 1 MW [12, 26–28].

#### 3.1. Design of downdraft gasifiers

Downdraft gasifiers are fixed bed gasifiers where the gasifying agent and biomass are flowing downwards, developed for high volatile fuels like wood or biomass gasification. Cocurrent flow regime throughout the oxidation and reduction zones reduces the tars and particulates in syngas, which will reduce the necessity of complicated cleaning methods compared to updraft gasifiers especially if the gas is used as a burnable gas in a small community [12, 17]. It is important to ensure homogenous distribution of gasifying agent at the downdraft gasifier throat.

Bhavanam and Sastry [24] provided design procedures for different types of downdraft gasifiers. The gasification reaction in a downdraft gasifier undergoes several steps, starting with drying step at 100°C, followed by pyrolysis step between 200 and 300°C resulting in release of around 70% of biomass weight as volatile matter and tars [16, 24]. After pyrolysis, the remaining biomass and volatile matter react with the incoming oxygen in the combustion step. Finally, various reactions take place in the reduction zone including carbon and steam reaction to produce CO and hydrogen, water-gas shift reaction, and CO and steam to form methane and carbon dioxide [24]. The four gasification reaction steps are illustrated in **Figure 1**. However, a limited experience has been gained in the field of biomass gasification while it represents an attractive renewable energy route [16]. **Table 1** illustrates the design specifications for two types of downdraft gasifiers: Imbert and stratified downdraft gasifiers. **Table 1** is developed based on extensive discussion in Bhavanam and Sastry [24].

Imbert downdraft gasifier is a cylindrical chamber of varying inner diameter across chamber length. The upper part of the cylindrical chamber is loaded with biomass according to

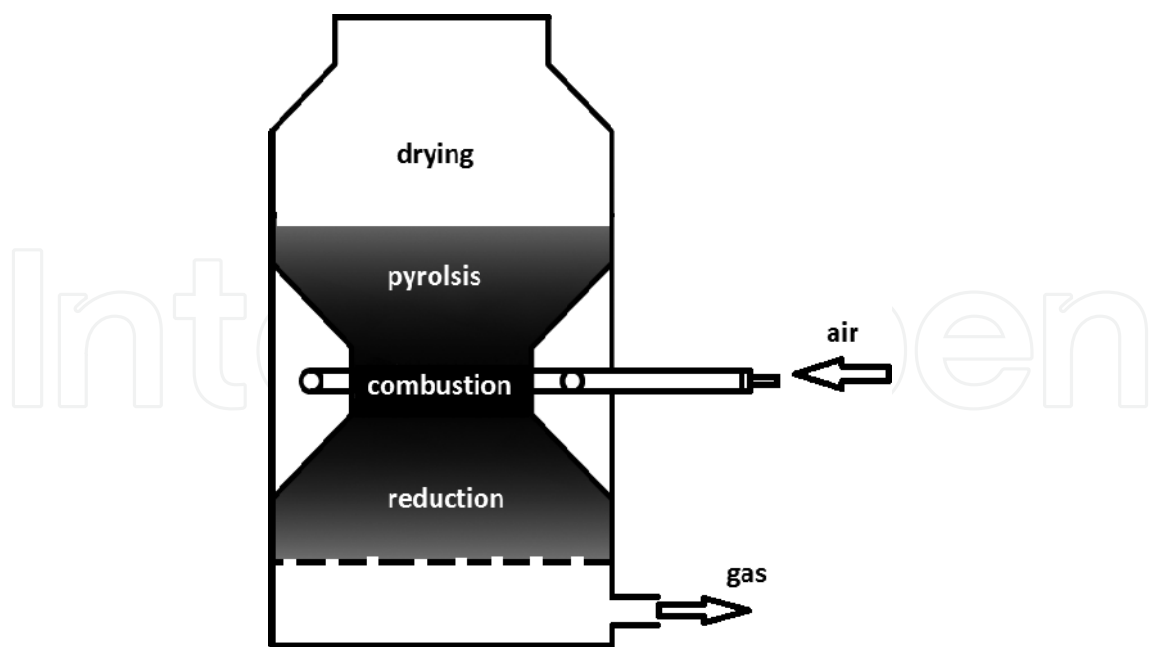


Figure 1. Different reaction zones in downdraft gasifier.

Design considerations		Imbert	Stratified
Biomass	Material	Uniform woody	Small size
	Moisture content	<20%	<20%
	Ash content	<5%	–
Reactor type		Packed bed supported on a throat	No-throat cylindrical packed bed with open top
Biomass feeding		Hopper	Open top
Gas feeding		Nozzle in the combustion zone	Enters from top mixed with biomass
Produced gas		Tar oils <1% $T = 700^{\circ}\text{C}$	Less tar
Maximum capacity		500 kW	Easy to scale up

Table 1. Design consideration for Imbert and stratified downdraft gasifiers.

requirement. Air nozzles, attached to distribution manifold, permit air to be drawn into biomass to improve mixing of gasifying agent and biomass. A charcoal balance is established around the nozzles. Below the air nozzles, a classical Imbert hearth forms the reduction part. Insulating the reduction hearth reduces the amount of tars in the produced syngas and increases gasification efficiency. The hot gases are forced to go through the hot zone due to hearth constriction. The char bed on the grate removes the dust, which should be cleaned eventually to prevent clogging, and dropping in airflow or channeling [17].

*Stratified or open-top downdraft gasifier* is a uniform diameter gasifier, usually made of a cylindrical vessel with a hearth near the bottom. The stratified gasifier is an improved, easy to

design gasifier compared to Imbert downdraft gasifier. The open-top helps in maintaining uniform access of gasifying agent to the pyrolysis zone, which prevents localized heating. Biomass is added through the open-top to the top layer of gasifier. The length of the gasifier can be divided into four reaction zones: unreacted biomass zone at which air enters, the flaming pyrolysis zone at which air reacts with biomass, adiabatic char gasification zone at which gases from flaming pyrolysis zone reacts with charcoal, and finally the unreacted charcoal zone that is located just above the grate which acts as a buffer for ash and charcoal. The stratified downdraft gasifier can be mathematically modeled easily as a plug flow reactor at which air and biomass are uniformly mixed. With such simple design, it is expected that stratified downdraft gasifier will replace the Imbert downdraft gasifier in commercial applications [17].

Wander et al. [29] illustrated the design of 12 kg/h downdraft stratified gasifier for sawmill dust gasification. The reactor is a cylindrical body of 270 mm internal diameter and 1100 mm of height made of SAE 1020 steel. Internal rods are used to mix the sawdust in the reduction zone. Ash box is used to reduce the ash content of the produced syngas. The reactor is insulated using 50 mm of rock wall. Air was introduced from the open top as a gasifying agent and a secondary air was used to provide air required for internal burner. A gas chromatography was used to analyze the gas samples and three water condensers in an ice bath were used to measure tars and humidity content.

Zainal et al. [30] developed a downdraft gasifier for the gasification using around 50 kg/h of wood chips. The temperature in the combustion zone may reach 1000°C, which reduces the tar content of produced syngas. The gasifier is made of mild steel pipe with a diameter of 0.6 m and a height of 2.5 m. A cone structure is used inside the gasifier above the combustion zone with an inclination of 60° to facilitate the wood material movement. The air supply was accomplished using a 40 mm diameter stainless-steel pipe with eight 10 mm diameter nozzles. The air is preheated by positioning the supply tube inside the gasifier. The heating value of the produced syngas was in the range of 4.65–5.62 MJ/Nm<sup>3</sup> depending on operating conditions.

Panwar et al. [31] developed an open-top downdraft gasifier for wood gasification to provide the heat requirement for the food processing industry. The downdraft gasifier was lined with ceramic and designed for a wood input of 60 kg/h equivalent to 180 kW. The gasifier body is made of mild steel. The air distribution system consists of six air tuyeres of 20 mm in diameter. A cyclone was used to remove solid particulates from produced syngas. The complete combustion of the syngas is achieved in a premixed burner to provide heat needed for the food processing industry unit. Note that 30 kg of charcoal and 10 kg of wood were used to provide heat required for gasifier start up.

Sheth and Babu [1] showed a design of an Imbert downdraft gasifier for wood waste gasification with a total height of 1.1 m. The diameter of pyrolysis zone and reduction zone are 0.31 and 0.15 m, respectively. The gasifier has throated combustion zone, a bed of char supported by a grate follows the combustion zone. The air is supplied through two nozzles in the oxidation zone. The high temperature in the combustion zone ensures cracking of tars into volatiles and water. The diameter of pyrolysis, reduction, and oxidation zones is 310, 150, and 53 mm, respectively. The grate is movable to unclog it for removing ash.

Vervaeke et al. [32] illustrated the design of a small-scale pilot plant downdraft gasifier equivalent to 100 kW of electricity generation. The downdraft unit used in this study is a pilot scale of the Xylowatt gasifier. The downdraft gasifier is a batch gasifier with a capacity of 90–105 kg. The gasification system consists of downdraft gasifier and inside it are ash collection container, cyclone, filter, and a scrubber.

Lv et al. [33] developed a downdraft gasifier to produce hydrogen from biomass using air and oxygen/steam as gasifying agents. Total 5 kg of char were supported on the grate to reduce tar content and to act as a catalyst to upgrade syngas. Biomass is pine wood blocks used in cubes cut into 3 cm × 3 cm × 3 cm. The gasifier height is 1.3 m and the diameter is 35 cm. The gasifying agent is preheated in a chamber inside the gasifier. Gas is cleaned using triple-stage spray shower filled with steel wire rings. The internal diameter of the gasifier is calculated according to the power output. The height is calculated based on batch operation time. The internal diameter is calculated in meters using the following equation [26]:

$$D = \left( \frac{1.27 * FCR}{SGR} \right)^{0.5} \quad (7)$$

where FCR is the fuel consumption rate (kg/h) and SGR is the specific gasification rate (kg/h/m<sup>2</sup>). The height can be determined in meter using the following equation [26]:

$$H = \frac{SGR * t}{\rho} \quad (8)$$

where  $t$  is the operation time (h) and  $\rho$  is the feedstock bulk density (kg/m<sup>3</sup>).

The power output  $P_0$  can be calculated in kW from the following equation [26]:

$$P_0 = \frac{FCR * HHV * \eta}{3.6} \quad (9)$$

where HHV is the higher heating value of the feedstock in MJ/kg and  $\eta$  is the efficiency of the gasifier usually around 0.7. The amount of air needed during operation can be calculated in Nm<sup>3</sup>/h from the following equation [26]:

$$AFR = \frac{\varepsilon * FCR * SA}{\rho_a} \quad (10)$$

where  $\varepsilon$  is the equivalence ratio, FCR is the fuel consumption rate, SA is the stoichiometric amount of air required for chemical reaction, and  $\rho_a$  is the density of air (1.18 kg/m<sup>3</sup>). Finally, the size of the air nozzle, which is required for uniform air distribution, can be calculated in mm<sup>2</sup> from the following equation [26]:

$$A = \frac{AFR * 10^3}{v * 3.6} \quad (11)$$

where  $v$  is the inlet velocity of air (m/s).

#### 4. Factors affecting on the gasification process

Zhou et al. [34] discussed the ongoing gasification projects taking place in China. The biomass gasification units were divided based on scale: small-, medium-, and large-scale biomass gasification and power generation units. Pretreatment of biomass includes size reduction, size screening, separation of magnetic materials, and storing as wet biomass. Then prior to gasification, drying and storing as dry material are accomplished to reduce the moisture content to 10–15% [35]. Feedstock type and feedstock preparation are important factors affecting the yield and quality of produced syngas. Shredding and drying are two processes conducted to prepare the biomass raw material for gasification process [14]. The main parameters affecting the gasification are clarified below:

*Equivalence ratio (ER):* The equivalence ratio is the air/biomass ratio divided by the theoretical air/biomass ratio. Increasing ER will decrease the heating value of the produced gas due to decreasing  $H_2$  and CO concentration and increasing  $CO_2$  concentration. Higher ER helps in reducing tars and provides more  $O_2$  to react with volatiles. Typical values of ER ranges between 0.2 and 0.4 [24]. Guo et al. [36] reported that increasing ER decreases the concentration of combustible gases ( $H_2$ , CO,  $CH_4$ , and  $C_nH_m$ ). The heating value was higher than 4 MJ/Nm<sup>3</sup> when ER is kept lower than 0.4. Increasing ER improves the reaction temperature and carbon conversion, and reduces the tar yield. For a downdraft stratified gasifier, Wander et al. [29] suggested an equivalence ratio of 0.3:0.35 kg- $O_2$ /kg-wood. A higher ratio is required when higher heat loss is expected, an equivalence ratio of 2:2.4 kg-air/kg-wood is optimum for producing a syngas with low heating value of 4–6 MJ/Nm<sup>3</sup>. For woody material in a downdraft gasifier, Zainal et al. [30] suggested an equivalence ratio of 0.268–0.43 with 0.38 showed optimum value (corresponding to a heating value of 5.62 MJ/Nm<sup>3</sup>). While Sheth and Babu [1] defined that the optimum equivalence ratio for wood gasification in Imbert downdraft gasifier is 0.205.

*Effect of biomass characteristics:* Biomass characteristic is a major factor affecting produced syngas quality. The physical properties that may have major effect are: absolute and bulk density, and particulate size. The chemical composition parameters that are of major importance to define the syngas [17] quality including volatile matter, moisture content, fixed carbon, ash content, and gross calorific value and the ultimate analysis comprises the carbon, oxygen, nitrogen, and sulfur of the dry biomass on a weight% [19].

*Moisture content:* The moisture content can be determined by complete drying of biomass sample. The moisture content is calculated by subtracting the sample weight after drying from fresh sample weight. Maximum allowable moisture content in downdraft gasifier is 40% on dry weight basis. Updraft gasifier can handle biomass with higher moisture content. The higher moisture content in biomass will increase the consumed energy for drying, and will reduce the pyrolysis of biomass. As a general rule, increasing moisture content decreases the conversion [1, 24].

*Superficial velocity:* The superficial velocity is the ratio of the syngas production rate at normal conditions and the narrowest cross-sectional area of gasifier. Lower superficial velocity is linked with high yield of char, and large quantities of unburned tars, which may deactivate catalyst, plug lines, and destroy compressors. On the other hand, higher superficial velocity results in reduced amount of char and low overall process efficiency [24].

*Operating temperature:* Operating temperature affects conversion, tar content, gas composition, gas heating value, and char conversion. To select the optimum temperature, gasifier type, and biomass source should be considered. Usually, temperature higher than 800°C should be used to obtain high conversion and low tar content in the produced syngas [24]. Low temperature is associated with low tar content, low H<sub>2</sub> and CO content in the produced syngas [12]. Increasing temperature will increase gas yield, hydrogen, heating value, and ash agglomeration. To overcome the ash agglomeration problem, practical temperature does not exceed 750°C [24].

*Gasifying agent:* Gasifying agents in use are air, steam, steam/oxygen mixture, and CO<sub>2</sub>. Gasifying agent affects the heating value of the produced syngas. The heating value increases with increasing steam content of the gasifying agent, while heating value decreases as air increases in the gasifying agent [24]. The steam/oxygen mixture represents a zero nitrogen-gasifying agent which increase heating value and allow liquefying the produced gas after proper treatment [37]. Using almond shells, the lower heating value was 5.9–6.7, 6.3–8.4, and 10.9–11.7 MJ/Nm<sup>3</sup> using the gasifying agent: 35 wt.% O<sub>2</sub> enriched air, 50 wt.% O<sub>2</sub> enriched air, and steam/oxygen mixture, respectively. Campoy et al. [38] reported a heat value of syngas produced from gasification to have an average value of 4–6 and 9–13 MJ/Nm<sup>3</sup> using air and oxygen/steam mixture, respectively. In addition to lower efficiency compared to air/steam mixture, enriched oxygen-air requires high capital cost for oxygen [38]. The addition of steam will shift toward the reforming reaction and heterogeneous gasification reactions.

*Residence time:* Residence time has a remarkable impact on the composition and produced tars. Increasing residence time decreases the fraction of oxygen-containing compounds, decreases yield of one and two atomic ring compounds, and increases three and four ring compounds [24].

*Pressure:* Atmospheric and higher pressures are commonly used in gasification process. Selecting the optimum pressure depends on the application of the produced syngas. If the syngas is used for producing methanol or synthetic auto-fuels, higher pressures are preferred to improve the process yield and to reduce tar content. For generating burnable gases, atmospheric pressure should be used [12]. High pressure applications are recommended for large-scale gasification, while atmospheric pressure is recommended for small-scale gasification [35]. High pressure gasification is still not well developed and further research is needed to further commercialize such process [39].

*Catalyst:* Catalyst type is a very important factor affecting gasification quality and produced syngas. Catalyst affects the composition of the syngas by manipulating the percentage volume of hydrogen, carbon dioxide, methane, and carbon monoxide. Optimum catalyst should play a role in minimizing the gas content of carbon dioxide and maximizing the gas content of hydrogen, carbon monoxide, and methane [40]. The catalyst type and loading on the gasification of cotton stalks and saw dust were studied. The catalysts selected are USY zeolite, dolomite, CaO, granulated slag, red brick clay, olivine, and cement kiln dust. The results demonstrate that the cement kiln dust and calcium hydroxide are more effective for increasing the gas yield and decreasing the char yield [8, 10].

*Effect of biomass/steam ratio:* Biomass/steam ratio affects hydrogen content in the produced syngas. Contradictory reports are found in literature, while Lv et al. [41] reported a positive effect on hydrogen content when biomass/steam ratio increases. Lv et al. [33] reported a negative effect of biomass/steam ratio increase on syngas hydrogen content. This variation can be understood by considering that biomass/steam ratio effect is altered according to the entire system configuration.

Lower values of biomass/steam ratio shift the reaction to produce more solid carbon and methane, since number of moles of steam increases in the feed. While at higher values of biomass/steam ratio, CO and H<sub>2</sub> are increased in the syngas as carbon and methane produced are decreased consequently.

## 5. Cost of biomass gasification process

The cost of any industrial process is governed by the capital cost and the running cost. Selection of best gasifier type depends on cost of fabrication, ease of manufacture, tar content, lower heating value, feedstock elasticity, and application of syngas [26]. The fixed bed gasifiers are more suitable for small- and medium-scale applications, while fluidized bed gasifiers are suitable for large-scale applications (equivalent to >15 MW) [25]. For example in China rice hulls, fluidized bed gasifiers are used in a production scale equivalent to 1–1.2 MW while downdraft gasifiers are used in a production scale equivalent to 60–200 kW [42]. The capital cost of the gasifier is divided into three items: gasifier and gas cleaning system cost, fuel gas utilization equipment cost, and fitting and system construction cost [25]. Cleaning systems and removing tars will add a significant cost to the produced syngas, which reduce the feasibility of using syngas in internal combustion engines [12]. Optimizing tar content can be achieved by varying the operating conditions and feedstock [43].

Upgrading using catalytic treatment represents the most economical and efficient method for syngas upgrading since it provides a way for removing tars and other particulates and converting tars to hydrocarbons [12]. Downdraft gasifier represents a reasonable cost production method for generating syngas with low tar content [29]. Especially small gasifiers that has proven economic feasibility [27]. Wu et al. [44] recommended implementing biomass gasification depending on the low biomass price. By comparing different technologies to generate electricity based on 1 MW scale, Wu et al. [44] mentioned that the capital cost of fluidized bed gasifier system for biomass gasification-power generation system is 60–70% of the capital cost of coal power station and much lower compared to the capital cost of conventional power station. For producing combustible gases, Bridgwater et al. [45] reported that for syngas produced from fluidized bed, updraft, and downdraft gasifiers: hydrogen volume percentage is 9, 11, and 17%, respectively; CO volume percentage is 14, 24, and 21%, respectively; and a heating value of 5.4, 5.5, and 5.7 MJ/Nm<sup>3</sup>, respectively. The downdraft represents the ideal solution to produce combustible (burnable) gases for household uses.

Biomass gasification economics are very sensitive to the scale of produced MW [44]. Leung et al. [25] mentioned two disadvantages of small- and medium-size gasifiers: capital cost

limitation that may prevent incorporating important processes like tar removal, and the environmental demands imposed by new regulations which is difficult to be met by different biomass gasification technologies. Wu et al. [44] identified 160 kW as a critical scale of biomass gasification unit, less than 160 kW biomass gasification units loses the economical attraction. Note that 1–5 MW was recommended as the most competitive size for biomass gasification unit. Lower than a unit capacity of 160 kW, the price of kWh increases sharply from 0.4 to 1.8 Yuan RMB/kWh for very small capacities. For unit with capacities higher than 160 Wh, the price will decrease gradually as the unit size increases. At the 600 kW capacity, the price will be around 0.3 Yuan RMB/kWh; while the price may reach 0.25 for a unit capacity of 1000 kW [44].

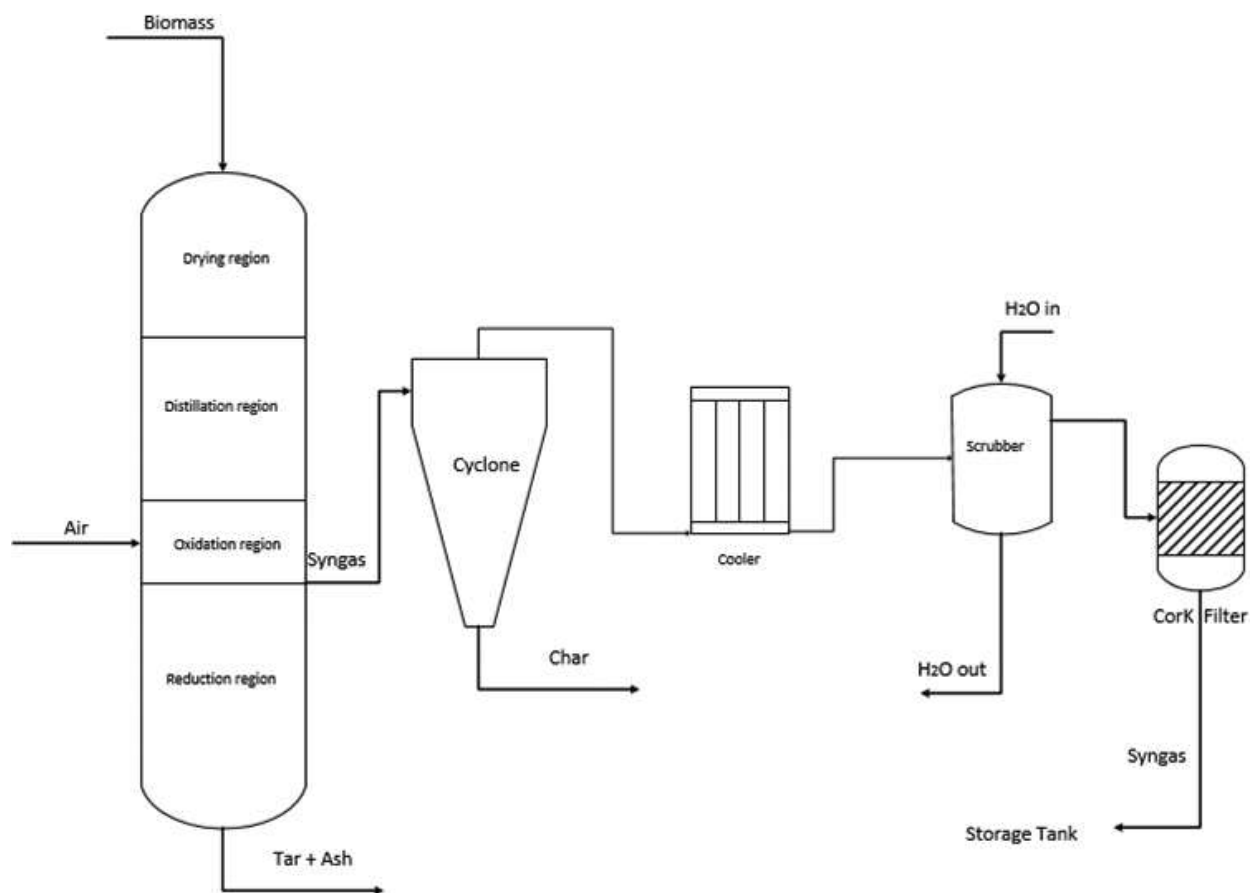
It is recommended to conduct gasification at pilot plant scale to mimic large scale to figure out the approximate industrial process scale economics [38]. The steam enhances the reforming and heterogeneous gasification reactions, the temperature inside the gasifier should be kept enough to support such reactions [38]. Combining gasification unit with heat and power generation systems will improve the economics of the process [3]. Gasification units combined with heat and power generation systems are expected to have an overall efficiency of 85% compared to a maximum efficiency of 35–55% for conventional power station, in addition to a substantial saving in carbon emissions. Total 1000 kg/year of carbon are saved for each MW when gasification units hybrid with heat and power generation systems [3].

Downdraft gasifiers are economically competitive even to conventional LPG heating unit. Panwar et al. [31] found that replacing LPG heating system with a downdraft wood gasification system could save \$13,850 US for 3000 h of operation. The payback period of the gasification system was only 1100 h. According to the extensive study of literature, the recommended gasification process consists of the following steps [13, 17, 19]:

1. Straw collection and preparation (milling and pelletization of straws).
2. Belt conveyor for feeding of the gasifier.
3. Downdraft gasifier.
4. Blower for suction of air and gas produced.
5. Gas cleaning and separation of tars.
6. Gas holder for storage of gas.
7. Gas distribution net.
8. Gas application devices.
9. Gas metering devices.

## 6. Preliminary techno-economic studies of downdraft gasifier

The aim of this chapter is to illustrate a detailed design of biomass gasification system to generate syngas for household applications. The stratified gasifier is selected based on the



**Figure 2.** Gasification system for producing burnable gas.

following parameters: easiness in design and scaling up, and production of syngas with tar content lower than that of Imbert gasifier [16–18, 26]. The gasification system comprises of a downdraft burnable syngas gasifier followed by a gas cleaning and distributing system. Throughout this chapter, the design specification of the downdraft gasifier is presented. This system can be used to convert solid agricultural waste to a syngas that is a burnable gas used to provide energy requirements for small communities, as shown in **Figure 2**.

The energy (household) requirements: for 50 families.

The gas demand per day is: 500 m<sup>3</sup>/day.

The syngas gas will be produced on two batches: Morning and afternoon (each one will last for 250 m<sup>3</sup>/batch).

The first batch will take place from 7 to 10 am.

The second batch will take place from 2 to 5 pm.

The storage unit will hold around 200 m<sup>3</sup> gas and accordingly will provide heating requirements during the period of nonoperation.

The system consists of the following units: biomass shredding, grinding unit, gasification unit, air controlling system, air heating and gas precooling unit, cyclone (acts like cyclone to remove dust), gas cooler, water filter (scrubbing unit), gas distribution system, control system, cork filter, and storage tank.

No.	Object	Cost, Egyptian pounds
1	Gasifier with control system	30,000
2	Gas cleaner	10,000
3	Belt conveyor	15,000
4	Milling and pelletization of biomass	50,000
5	Gas holder	15,000
6	Gas distribution system 100 × 500	60,000
7	Gas stoves 100 × 350	35,000
8	Gas meters 100 × 400	40,000
9	Erection	10,000
10	Contingency (10%)	26,000
	Total	2,90, 000

\$ = 8.5 Egyptian pounds.

Assume that:

Cost of material = 300 L.E/ton

Cost of preparation = 100 L.E/ton

Cost of raw materials = 0.25 × 400 × 360 = 36 000 L.E/year

Labors required = 2 × 1500 = 3000 L.E/month = 3000 × 12 = 36000 L.E/year

Income gas production = 500 m<sup>3</sup>/day

≈ 60 kg L.P.G/day

= 60 × 360 = 21,600 Kg/year

= 21,600 × 7 = 151,200 L.E/year

Profit = income – raw material – depreciation

Profit = 151,200 – 36,000 – 36,000 – 29,000 = 49,400

Return on Investment = profit/initial cost

Return on Investment = (49,400/290,000) × 100 = 17%

Therefore, the payback period is about 6 years based on the international prices of L.P.G.

**Cost of equipment for gasification system.**

The cost of land required for erection of the plant is not included in this calculation of the feasibility study.

**7. Conclusions**

Gasification represents a viable solution to overcome the energy shortage by developing commercial gasification units in rural and off-grid areas. An integrated system comprising a

gasification-electrical generation method represents an ideal solution from the technical and economical points of view.

However, due to the wide varieties of available biomass feedstock, it is recommended to manipulate different systems in each location depending on the feedstock, produced syngas, and energy demands. Downdraft gasifier is recommended for small-scale applications in rural areas. The co-current nature of air and biomass flow reduces the tar content and increases CO and H<sub>2</sub> in the produced syngas. The syngas produced from downdraft gasifier can be used after a simple purification process in thermal applications. From a cost study, the payback period of a gasification system is around 5 years.

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