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Barriers of commercial power generation using biomass gasification gas: A review

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ABSTRACT

Gasification is one of the promising technologies to convert biomass to gaseous fuels for distributed power generation. However, the commercial exploitation of biomass energy suffers from a number of logistics and technological challenges. In this review, the barriers in each of the steps from the collection of biomass to electricity generation are highlighted. The effects of parameters in supply chain management, pretreatment and conversion of biomass to gas, and cleaning and utilization of gas for power generation are discussed. Based on the studies, until recently, the gasification of biomass and gas cleaning are the most challenging part. For electricity generation, either using engine or gas turbine requires a stringent specification of gas composition and tar concentration in the product gas. Different types of updraft and downdraft gasifiers have been developed for gasification and a number of physical and catalytic tar separation methods have been investigated. However, the most efficient and popular one is yet to be developed for commercial purpose. In fact, the efficient gasification and gas cleaning methods can produce highly burnable gas with less tar content, so as to reduce the total consumption of biomass for a desired quantity of electricity generation. According to the recent report, an advanced gasification method with efficient tar cleaning can significantly reduce the biomass consumption, and thus the logistics and biomass pretreatment problems can be ultimately reduced.

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1. Introduction

Gasification is one of the promising technologies to exploit energy from renewable biomass, which is derived from all living matters, and thus is located everywhere on the earth. Forest residues such as dead trees and wood chips, agricultural residues, municipal organic wastes, and animal wastes are common examples of biomass. The advantages of utilizing these biomasses for energy could be accounted for as it is carbon neutral and homogeneously distributed all over the world. Therefore, the utilization of biomass energy can provide dual benefits: it can reduce carbon dioxide (CO_2) emission as well as increase fuel security as it is produced locally. Despite the many advantages of biomass energy it is not being used in commercial scale because of many challenges associated with supply chain management and conversion technologies.

Although biomass is available locally all over the world it is widely distributed across regions. For example, forest residues are distributed throughout the forest and so are agricultural residues in the rural area. In addition, biomass is excessively moist at the source which makes it difficult to transport, irregular in size, and thus difficult to feed into the conversion unit. Therefore, development of a biomass based power generation facility needs several factors to be considered such as supply chain management [1–3], pretreatment of biomass [4–6], conversion of biomass to fuel gas [7–8], and, cleaning and utilization of fuel gas for power generation [9–12].

In the supply chain management, harvesting, collection, refining and transportation of biomass are key issues to be facilitated by the supply chain operation management. Since raw biomass, especially agricultural biomass, is excessively wet (>50 wt%), it is not feasible to store it at the place of origin [13]. In other words, transportation of raw biomass is cost intensive [14]. Therefore, for sustainable supply of biomass to the biomass based power generation system needs optimum supply chain management, adopting available technologies. In addition, since the origin of biomass is often in the rural area, the entire supply chain system requires extensive involvement of the local community. Therefore, the success of biomass energy production also partly depends on the motivation and satisfaction of the grower who grows biomass at the root level [15].

Biomass conversion to fuel gas, which is termed as gasification, is the key technology for biomass based power generation. In order to produce optimum fuel gas composition for turbines or internal combustion engines, the optimization of multiple parameters including gasifier types (updraft, down draft), gasifying agent (air, steam), temperature, pressure and air-fuel ratio is essential [9]. The updraft gasifier can be further classified as fixed bed and fluidized bed. The fluidized bed gasifier is advantageous in terms of homogeneous heat distribution throughout the reactor and fast heat transfer rate to the particle, which facilitate the reaction rate. However, this process essentially requires tiny particles of biomass, the making of which is energy and cost intensive [16]. The fixed bed gasifier, which may be updraft or downdraft, is a simple construction and generally operates with high carbon conversion, long residence time, and low gas velocity. This method is suitable for small scale power generation. In addition, the selection of feedstock is equally important, because the composition of biomass significantly affects the product gas composition [17]. Moreover, some impurities such as tar, particulate matter, sulfur oxides, nitrogen oxides and ammonia always exist in the product gas. However, the internal combustion engine can only accept a very limited concentration of these contaminants [18]. It imposes the mandatory cleaning of the product gas by removing the contaminants to a certain minimum level. Among the contaminants, tar is the notorious one; it is a sticky material and deposits in the downstream equipment and blocks the narrow supply line [19].

Physical filtration of this sticky material creates two severe problems: (1) it blocks the pores of the filter and creates a pressure drop [19], and (2) tar consists of toxic chemicals (aromatic hydrocarbons), and thus handling and disposing of it is a health and environmental issue [20]. Catalytic hot gas cleaning is the most promising method, which provides multiple advantages such as (1) tar can be almost completely removed [21], (2) tar can be converted to product gas [22] and (3) other contaminants can also be trapped in the catalyst bed [22].

Table 1
Detail data related to collection, storage and delivery cost of biomass in different countries.

Biomass type	Origin of biomass, region/country	Physical nature of biomass	Mode of delivery	Costs related to collection, storage and delivery in US$ t^{-1}	Reference
Rice straw	China	Bulky	Satellite storage delivery	9.22	[27,34]
Mixed agricultural biomass	China	Bulky	Direct delivery	11.29	[35]
Switch grass	Great Plains, USA	Bulky	Direct delivery	75–83	[28]
Corn stover	Great Plains, USA	Bulky	Direct delivery	60–75	[28]
Agricultural/forest	Italy	Dense and high moisture	–	44/98	[29]
Agricultural/forest	Spain	Bulk/dense		30/66	[29]
Agricultural/forest	Portugal	Bulk/dense	–	28/36	[29]
Crops	India	Bulky	Multi-collection center	26-27	[30]
Wood	Japan	Dense	Supply region 9	166	[31]

Table 2
Different models for transportation of different biomasses.

Biomass type	Physical nature of biomass	Proposed model for transportation	Comments	Reference
Switch grass Corn stalk Wheat straw	Bulky	Multi-commodity Network Flow model	The model determined the locations of warehouses, the size of harvesting team, the types and amounts of biomass harvested/ purchased, stored, and processed in each month, the transportation of biomass in the system, and so on.	[38]
Switchgrass	Bulky	Mixed Integer Linear Programming model	This study showed that the operations of the logistic system were significantly different for harvesting and non-harvesting seasons and mass production with a steady and sufficient supply of biomass can increase the unit profit of bioenergy.	[39]
Cotton stock	Bulky	Algorithm-based management policies were simulated	A knapsack model, with travel times, was constructed and solved to obtain the lower bound for the transportation system.	[41]
Switchgrass	Bulky	Discrete event simulation procedure	This study simulated the transportation system of cotton gin using a discrete event simulation procedure, to determine the operating parameters under various management practices.	[41]
Woody biomass	Dense	Geographic Information System approach (GIS) and Total Transportation Cost model	GIS model identified the potential pulpwood-to-biofuel facility locations and the preferred location is selected using a total transportation cost model.	[43]
Cotton stock	Bulky	Linear Programming model	This study examines the feasibility and the problems that arise while trying to organize an integrated logistics network and optimize its transportation economy.	[45]
Agricultural residues, native perennial grasses, dedicated energy crops	Bulky	Mixed Integer Linear Programming model	A multi-region, multi-period, mixed integer mathematical programming model encompassing alternative feedstocks, feedstock production, delivery, and processing is developed. The model is used to identify key cost components and potential bottlenecks, and to reveal opportunities for reducing costs.	[46]
Orchard and vineyard trimmings from tribal and private farmers and slash from normal timber operation	Dense/ bulky	Supply curve model	The study showed that the ownership boundaries can restrict the available biomass supply and suggested that careful sitting and inclusion of all land owners is necessary for the most efficient use of resources.	[46]
Multiple biomass types	Dense/ bulky	Linear Mixed-Integer models	The biomass models are formulated consistently with current models for gas, electricity and heat infrastructures in the optimization model 'eTransport', which is designed for planning of energy systems with multiple energy carriers.	[13]

However, the catalyst deactivation due to carbon build up and poisonous gas adsorption on the catalyst surface is often considered a serious issue.

Biomass gasification gas can be used in different ways to produce electricity. For instance, it can be used in combination with a steam turbine and boiler, where fuel gas can be burned in the boiler to generate high temperature and high pressure steam which is then passed through the steam turbine to generate electricity [23]. The challenge of this system is related to the net electrical efficiency, which is extremely low (10–20%). The high capital cost and the limitation of boiler and steam turbines lead to avoiding this technology for power generation from biomass gasification gas.

The internal combustion gas turbine offers very good net electrical efficiency even in the small scale ranges; however, the direct combustion of the product gas mixed with impurities and expansion of the combustion gas into the turbomachinery of the turbine creates technical difficulties [24]. It can cause unpredictable failure and shortening of the life of the machineries. In fact, the cleaning of contaminants, especially tar and particulate matter from the product gas, can overcome the identified problems. Recent development in the customization of basic gas turbine is also expected to overcome the problems associated with internal gas turbines. The system is called externally-fired gas turbine [25]. The basic concept is that the gas is fired externally and the heat is exchanged to air through a gas–gas heat exchanger, which works as a working fluid to run the turbine. Two major advantages can be counted in this development: (1) the separation of the working fluid from the combustion fumes assures the safe rotation of the rotating parts, (2) the use of the exhaust clean hot air from the turbine outlet in the combustion chamber of fuel gas ensures the high thermal efficiency of the process.

The internal combustion engine is the last and widely investigated option for power generation from biomass gasification gas. This engine has already been optimized using gasification product gas, yielding high electrical efficiency [26]. For small scale and distributed power generation, it can be considered as an ideal tool for exploiting renewable energy from biomass. However, it has still somewhat stringent requirements in terms of the purity of the product gas and the technical aspects. In fact, the cleaning requirement of fuel gas is achievable using hot gas cleaning method, employing a cost effective catalyst such as char supported iron catalyst, and thus this method could be considered as the viable method.

When the distributed power generation from biomass is a concern at the site where the biomass is available, the access of the national grid from the site could create additional complexity. If the existing transmission facilities are not accessible for the site where the biomass power generation could be developed, new transmission lines with associated facilities must be constructed. The additional cost for constructing transmission facilities may determine the economic feasibility of the power generation project based on biomass.

This review is focused on identifying the problems associated with biomass gasification based power generation facilities in different aspects including biomass supply chain management, pretreatment and production of gas, cleaning and utilization of gasification gas for power generation by critically reviewing the studies that have been conducted very recently. Based on the collective knowledge from literature and personal view, some suggestions have also been proposed.

2. Biomass supply chain

2.1. Biomass collection

Although biomass in any form is abundantly available everywhere on the earth it is widely distributed across the region. Therefore, the collection and delivery of biomass to the energy conversion plant is cost intensive, and thus it has long been considered a big challenge negatively affecting the profitability and further development of biomass based energy. In addition, the unstable market of biomass due to lack of fully established biomass energy conversion technology is attributed to the difficulties of biomass collection system. The optimized collection, storage and transportation method along with suitable selection of the power plant location can significantly reduce the cost related to the biomass feedstock. Table 1 shows the collection, storage and delivery costs of different types of biomass in different countries. To estimate the available biomass and to establish a suitable collection method, a comprehensive research both in modeling and practical field has been conducted over the last few years based on regional biomass [27–33]. In China, especially for rich straw, multiple approaches have been proposed in terms of reducing collection and delivery cost [27,34]. The satellite storage and delivery can be considered as one of the cost effective ways to collect distributed agricultural biomass [35]. This study mathematically optimized the number of satellites for storage and the optimum distance of the power plant.

As in Table 1, the biomass cost (harvesting and collection) depends on the type of biomass as well as on the economic status of the country. Although the status of almost all of the EU countries is the same the cost of biomass varies across the EU countries [29]. In the Southern EU countries, the average biomass extraction costs have been roughly estimated to be \$27.6 t^{-1} for Spain for agricultural residues and \$59.6 t^{-1} for forest residues. The highest costs have been found to be for Italy (\$39.8 and \$88.8 t^{-1} for agricultural and forest residues, respectively) and the lowest ones to be for Portugal (\$25.7 and 32.9 t^{-1}). The cost is related to the difficulties of collection.

Comparing to EU countries, the biomass scenario in India is completely different. The GDP of India still depends on agricultural sectors, and thus a huge amount of biomass includes agriculture residues, wood processing residues, municipal solid waste (MSW) and livestock dung which are plentiful, especially in the rural area [36]. However, the people in India predominantly consume biomass, around 80% of wood and agricultural biomass, for their cooking purposes [37]. The surplus biomass is insufficient for large scale power generation using gasification technology. As can be seen in Table 1, the biomass price in India is almost close to EU countries. On the other hand, it is very expensive in Japan.

2.2. Biomass transportation

One of the most important challenges of biomass based power generation is the transportation of biomass from the origin where it is available to the power generation unit. Two major problems in effective transportation of biomass can be encountered: (1) excessive moisture content, and (2) low bulk density (except wood log). These two factors increase the biomass transportation cost, so as to increase the cost of bioenergy as a whole. The optimization of the transportation network and medium of transportation as a part of logistic support can ensure the consistent supply of biomass to the power plant, while it can reduce transportation cost as well.

A comprehensive research has been conducted in developing an optimized logistic system [38–44]. Different types of mathematical modeling have been proposed as summarized in Table 2. As can be seen in Table 2, for the transportation of cotton gin, a discrete event simulation procedure was used under various management practices [41]. A linear programming model was proposed for cotton stalk transportation from the field to warehouses [45]. This model was initially developed for designing a herbaceous biomass delivery system as well as for solving the day to day tactical planning problems [42]. A conceptual mixed integer linear programming (MILP) model for the transportation of lignocellulosic biomass-to-ethanol industry was developed with a case study in Oklahoma State in USA [46]. The model was used to identify the key cost component in biomass logistics, where transportation was one of the major components that contributed to elevate the biomass price. The MILP model for the switchgrass-to-bioenergy industry has also been developed by other researchers, which determines the suitable locations and capacities of new warehouses, the effective inventory policy, the year round harvesting schedule, and transportation of switchgrass [39]. A linear programming model is constructed for switchgrass transportation where the delivery cost is minimized by scheduling shipments from the various on-farm storage locations to meet the demand of feedstock supply [42].

A two-stage methodology has been proposed to identify the best location for biofuel production facility [43]. The first stage used a Geographic Information System approach to identify the best location of potential pulpwood as a feedstock and the second stage used a total transportation cost model to select an optimal biofuel facility location. A supply curves has been developed based on different feedstocks in five counties surrounding the Yakama Nation in central Washington using spatially explicit estimates of supply and transportation cost [44]. In this study the model that was developed for estimating the transportation cost of biomass was based on the methodology described in a Western Governors

Table 3
Methods of biomass drying and their efficiencies.

Types of dryers	Mode of feeding	Capacity of drying	Heat source	Capital cost	Comments	Reference
Perforated floor dryer	Batch	Low	Cylindrical air heater	Low	This drying method invariably produces a large vertical gradient in moisture content of the dried bed.	[59]
Rotary drier	Continuous	Large	Recycled heat from flue gas	High	This method can efficiently dry biomass for a large scale power plant; however, the high initial moisture content affects the drying rate.	[60]
Belt conveyer	Continuous	High	Recycled heat from flue gas	High	Although a higher flue gas temperature would reduce the capital costs, environmental issues may then become a problem, such as increased emissions.	[57]
Solar dryer	Batch	Low	Sun	High	Large scale operation is difficult.	[61]
Rotary dryer for filament type of biomass	Continuous	Low	Hot air	High	Complex drying system	[62]
Bubbling bed drum dryer	Batch	Low	Steam	Low	–	[63]
Thermal screw dryer	Continuous	High	Hot air	Medium	Solid to solid heat transfer is efficient.	[64]

Table 4
Comparison of physical properties of loose and densified biomass.

Type of densification	Name of biomass	Bulk density kg m^{-3}	Particle density kg m^{-3}	Reference
None	Saw dust	47.7	–	[70]
	Wood chip	209–273	320–373 (particle size1–3 mm)	[75,76]
	Straw biomass	46–60	–	[70]
Pellet	Saw dust	606	1234	[77]
	Straw biomass	360–500	600–850	[78]
Briquette	Saw dust	505	1000	[78]
	Rice husk	410	–	
	Palm fiber	250	–	

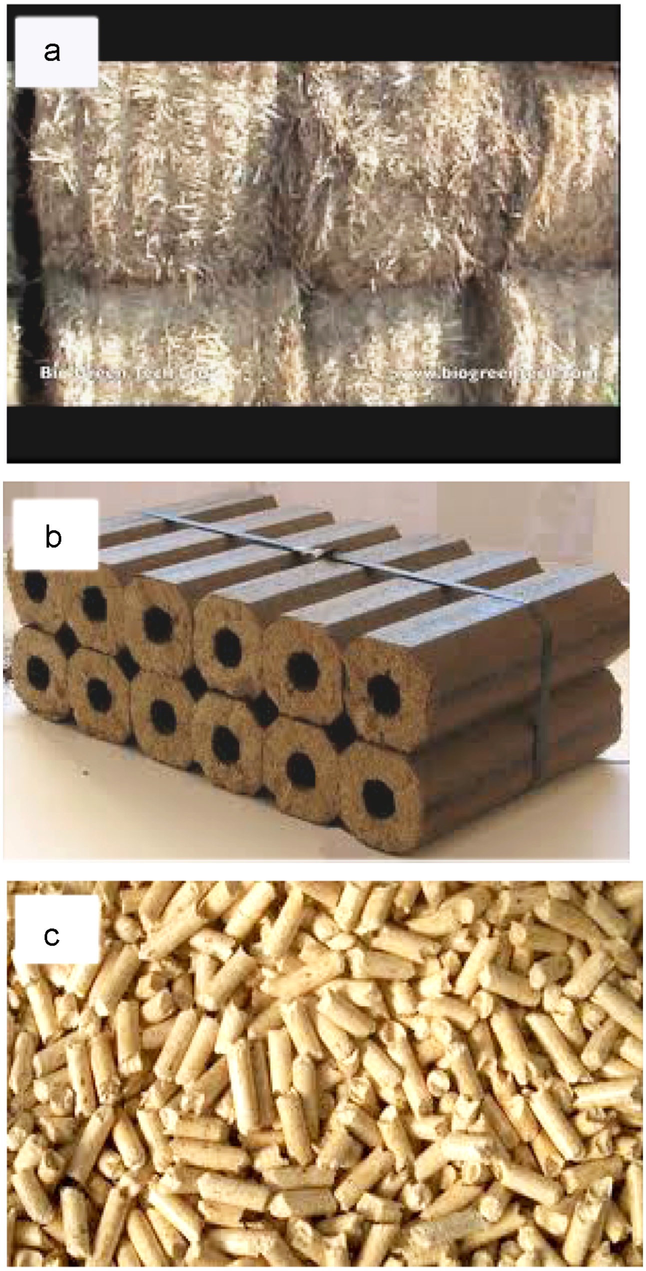

Fig. 1. Different forms of densified biomass: (a) bale, (b) briquette, and (c) pellet.

Association Report [47], where the time based and distance based transportation costs were estimated. The results suggested that the industrial cellulosic wastes produced as byproducts are cheaper than that of the harvested biomass as feedstocks for bioenergy. It is investigated that to make bio-energy sustainable, the multi-component feedstocks are more advantageous than the single component ones in terms of logistics and energy production [13]. To predict the advantages, a multi-commodity network flow model has been developed to design the logistics system for a multiple-feedstock biomass-to-bioenergy industry. The model was developed as a mixed integer linear programming, which determined the locations of warehouses, the size of the harvesting team, the types and amounts of biomass harvested/purchased, stored, and processed in each month, the transportation of biomass in the system, and so on. This work revealed that the mixture of multiple types of biomass is much more advantageous compared to the single feedstock (switchgrass).

3. Pretreatment of biomass

3.1. Biomass drying

In gasification, moisture content in biomass has a significant role in technological aspects. Under gasification temperature, steam generated from moisture works as a gasifying agent, reacting with volatiles and char to convert them to product gas as well as taking part in water–gas shift reaction in order to enhance the hydrogen content [48,49]. However, the excessive moisture content in biomass (more than 40 wt%) reduces the thermal efficiency of the gasification system [50]. This is because the heat absorbed by the unreacted steam in three steps, including heating of moisture from room temperature to 100 °C, latent heat of vaporization and heating of steam to gasification temperature is totally lost from the system, and thus increases the thermal cost [51]. On the other hand, the complete drying of biomass is cost intensive as well as during gasification it needs further addition of water to balance the hydrogen content in the product gas. Therefore, a limited amount of moisture in biomass usually around 40 wt% is beneficial for gasification [52,53].

The moisture content in raw biomass usually above 50 wt% such as palm empty fruit bunch (PEFB) is the abundantly available agricultural biomass in Malaysia and Indonesia [54]. The utilization of this kind of biomass for energy production is a real challenge. There are several crucial factors severely affecting the constant supply of this biomass and the most severe challenge is drying. There may be two options to reduce the moisture content to a desired range. It may be sun drying at the origin where the biomass is produced or it may be drying using heat at the plant where it would be converted to energy. Although the sun drying process is less costly it takes longer time to reach the equilibrium moisture content [6]. It also depends on the atmospheric humidity. The challenge in this slow drying process is that the biomass gets molds and biologically degrades. On the other hand, the drying at the processing plant is costly because of using costly drying equipment as well as supplying heat for drying.

Due to the emerging of biofuel technologies, a comprehensive research on biomass drying has been carried out in the last couple of decades [55–57]. In drying of biomass, several important issues have been investigated such as energy efficiency [58], emissions [56], heat integration [57] and dryer performance [58] as shown in Table 3. Drying to low moisture content (around 10 wt%) is time consuming and energy intensive. Therefore, for the implementation of biomass based power generation, the selection of drying option to achieve the optimum moisture content is of utmost importance. Different types of dryers and drying processes are utilized for biofuel drying as described in references [59–64] of Table 3. As a heat carrier, the hot fluid such as air, flue gas, or steam may be utilized directly (direct drying) or indirectly (indirect drying, heat transfer through hot surface) to biomass. The drying of biomass has a significant impact on the overall efficiency of biomass based power generation.

3.2. *Grinding and densification*

Although the utilization of mixed biomass for energy is advantageous in terms of logistics the variability in physical properties of individual biomass in the mixed stream often causes severe problems, especially for consistent feeding in the gasification unit [65]. Some biomasses such as palm kernel shell (PKS) and also wood chips are quite easy to feed in the gasification unit; however, the other agricultural biomasses such as empty fruit bunch (EFB) [66], grass [67], rice straw [68], wheat straw [69] etc. are bulky and fibrous, and thus difficult to feed into the gasifier [70]. The fibrous biomass often gets stuck in the feeding line. The heterogeneity and low bulk density of mixed biomass is attributed to the adverse effects in implementing the biomass gasification technology.

The problems related to biomass feeding can be overcome by densifying bulky biomass, which removes the internal and intra-void spaces of biomass and increases the bulk density [71] as shown in Table 4. Balling, briquetting and pelletizing are the common technologies for densifying biomass [72,73]. Although the order of equipment complexity, energy consumption and cost increase from balling to pelletization the balling is not really suitable for consistent feeding into biomass gasifier because of sizes as shown in Fig. 1 [74]. On the other hand, pellets provide advantages in terms of consistent feeding into the conversion unit because of their suitable size and shape as can be seen in Fig. 1 [74]. However, because of high density as shown in Table 4, they are too hard to break down in the gasifier in order to increase the heat transfer to the center of the particles [75–78]. In addition, production of pellets is energy intensive and costly. Considering, the complexity of machineries and cost effectiveness, briquette appears to be an attractive option for commercial utilization of biomass [78]. This is because it is moderately dense, easy to transport, store and feed into the conversion unit. However, in terms of thermodynamics and mass transfer in the conversion process, the particle size of biomass is of prime importance and severely affects the thermo-chemical conversion of biomass to the desired product [16,79].

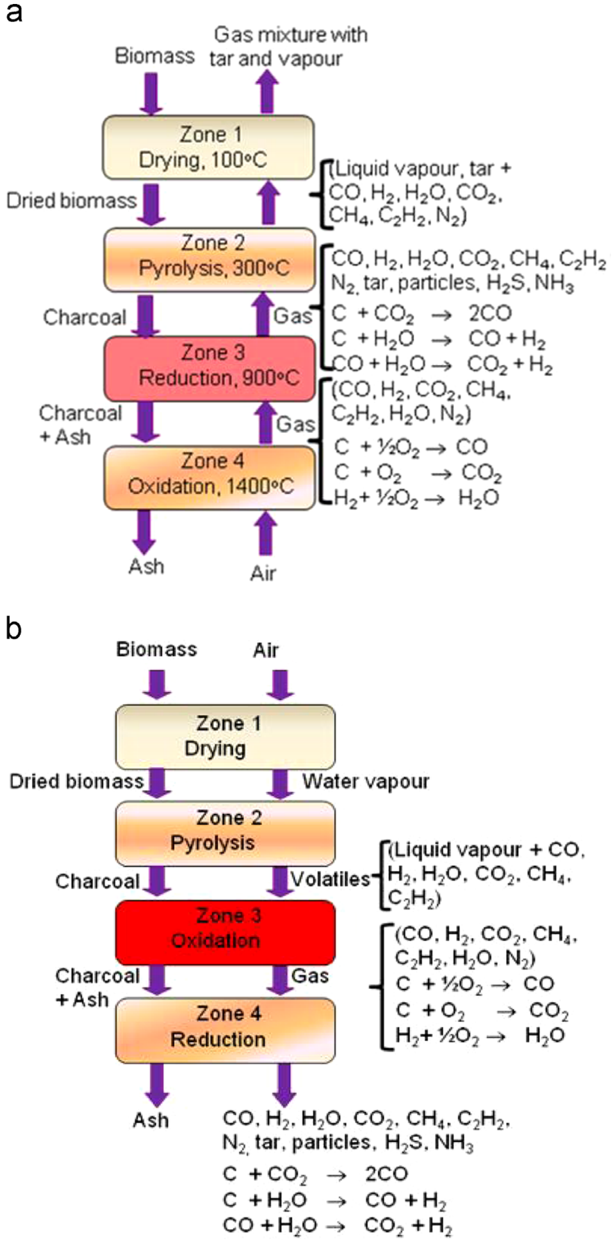

Fig. 2. Conceptual diagram of multiple steps in (a) updraft and (b) downdraft gasifier.

In biomass gasification, the heat and mass transfer is a kind of counter current flow, where heat transfers from the outer surface to the inner core of the particles, while the initial devolatilized product travels from the center to the surface. Faster transfer of both leads to faster conversion of intermediate products to the final gaseous products [80]. However, slower transfer is attributed to longer residence time for volatiles, which leads to repolymerization of volatiles to form unreactive solids. Complete conversion of the unreactive solids requires higher equivalence ratio of air, which is attributed to the lower heating value of the product gas. Reduction of particle size can enhance the heat and mass transfer, so as to reduce the unwanted repolymerization reaction of volatiles. However, all of those densified products have lower surface area per unit mass [77,78], which leads to a lower transferring rate of volatiles and heat. In comparison, as reported, the pulverization approach of biomass to produce powdered form could provide higher surface area ratio and uniformity of feeding into the gasification process [81].

4. Biomass gasification

Gasification is the key technology of biomass based power generation. However, there are a number of key technological challenges that retard the commercial application of biomass gasification for power generation. For power generation, the purpose of biomass gasification is to produce a combustible producer gas to run the engine, which rotates the generator shaft. However, the engines have some specific requirements for accepting fuel gas. For instance, the producer gas must have a certain percentage of burnable gas ($>$ 20% CO and $>$ 10% H_2), a minimum

Table 5
Gas composition and tar content in the product gas from different biomass gasification in up-draft gasifier under different conditions.

Biomass	**Gasification temperature (°C)**	**Equivalence ratio**	**Gas composition (vol%)**	**LHV (MJNm^{-3})**	**HHV MJ (Nm^{-3})**	**Power range (kW)**	**Reference**
Cedar wood	700–900	0–0.3	–	1–33.2	–		[82]
Cedar wood	650–950	0–0.3	H_2(30–50), CO (22–25), CO_2 (25–30), CH_4 (8-10), H_2S (35–39 ppmv), COS (< 2 ppmv), N_2 free	–	6.5–12.1		[83]
Mesquite wood		2.7	CO (13–21), H_2 (1.6–3), CH_4 (0.4–6), CO_2 (11–25), N_2 (60–64)	–	2.4–3.5	10	[84]
Juniper wood		2.7	CO (21–25), H_2 (2.5–3.5), CH_4 (1.5–1.8), CO_2 (9–12), N_2 (58–61)	–	3.5–3.9	10	[84]
Rice straw	700–850	0.07–0.25	CO (10–18), H_2 (6–10), CH_4 (4), CO_2 (14–19), N_2 (46–63), NH_3 (3100 ppmv), Cl_2 (260 ppmv)	0.47–1.92	3.62–5.14	45	[85]
–	725–925	–	CO (15–20), H_2 (55–60), CH_4 (8–10), CO_2 (15–18)	6.5–9.0	–	15	[86]
Agroland willow and one agriculture residue Dry Distiller's Grains	800–820	0.35–0.39	CO (20–25), H_2 (30–45), CH_4 (8–12), CO_2 (15–20), H2S (2300 ppmv), COS (200 ppmv)	2–12	–	60	[87]
Wood chip Coconut shell	700–900	0.3	CO (27–40), H_2 (22–27), CH_4 (7–9), CO_2 (39–42)	–	17	15	[88]

Table 6
Gas composition and tar content in the product gas from different biomass gasification in down-draft gasifier under different conditions.

Biomass	Gasification temperature (°C)	Equivalence ratio	Gas composition (vol%)	Tar content (g Nm^{-3})	HHV/LHV (MJ Nm^{-3})	Power range (kW)	Reference
Bagasse	1040	–	–	0.376–0.40	–	50	[89]
Hazelnut shells	1000	0.35	H_2(13), CO (23), CO_2 (11), CH_4 (4)	–	~5.0	45	[90]
Wood waste	900–1050	0.20–0-0.35	H_2(8–12), CO (15–22), CO_2 (5–8), CH_4 (1–3), N_2 (60–70)	–	4.5–6.25	15	[91]
Biomass	–	0.27	Total combustible 45%	0.045	6.5	10	[92]
Biomass	> 900	0.26	H_2 and CO reaches 63.27–72.56%,	–	11.11	–	[48]

amount of tar content (< 100 mg Nm^{-3}) and be completely free of dust and other poisonous gases (NH_3, SO_2 etc.). To satisfy the requirement of product gas, a comprehensive research has been done in the last couple of decades. Those researches mainly focused on the development of different types of reactors as discussed in the subsequent sections. The entire reactor systems can be classified into two categories: (1) updraft gasifier and (2) downdraft gasifier.

4.1. *Updraft gasification*

Updraft gasification is basically a counter current gasification system where the air and other gasifying agents are injected from the bottom, while the biomass enters from the top and moves downward under the force of gravity. The operating principle of this type of gasifier, as shown in Fig. 2a, is that the feedstock material is first introduced into the drying zone at the top, followed by the pyrolysis and reduction zone and finally the unconverted solid passes through the combustion zone. In the combustion zone, solid charcoal is combusted producing heat, which effectively transfers to the solid particles during counter current flow of the rising gas and descending solids. In this gasification system, the product gas exits from the low temperature pyrolysis and drying zone, and is thus assumed to be contaminated with substantial amount of tars (Table 5), which is the major problem of updraft gasifiers. If the gas is to be utilized for turbines or internal combustion engines for electricity generation or mechanical power, it must go through a series of filtering and cleaning devices in order to reduce the tar content to an acceptable range. The intensive cleaning process adds considerably higher investment cost and reduces the overall efficiency of the whole process. Therefore, the application of updraft gasification is not suitable for internal combustion engines.

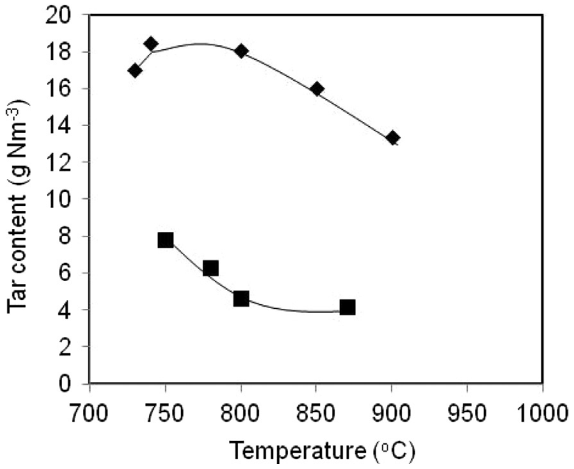

Fig. 3. Effect of temperature on tar yield in product gas.

As literature shows, a substantial amount of research on the updraft gasifier system has been carried out over the last few years [82–87]. Updraft gasifier can be classified as updraft fixed-bed gasifiers [82–84], fluidized bed gasifiers [85–87] and circulating fluidized bed gasifiers [88]. Fluidized and circulating fluidized bed gasifiers usually operate below 900 °C under atmospheric pressure in order to avoid ash melting. Most of the researches reported that the gas from any type of updraft gasifier contains a substantial amount of tar, and thus is not suitable for an internal combustion engine. In addition, the fluidized bed and circulating fluidized bed gasifiers require excessive air/gas flow to fluidize the bed materials, which is attributed to the poor burnable gas composition and low calorific value of the product gas as can be seen from Table 5.

4.2. Downdraft gasification

The downdraft gasifier features a co-current flow of air needed for gasification, where product gases and solids flow downwards. The operating principle of this gasifier, as shown in Fig. 2b, is such that the biomass and air are fed from the top, and are first introduced into the drying zone, followed by the pyrolysis, oxidation and reduction zones, and finally the product gas is drawn out from the bottom, through the reduction zone. Since the product gas travels through the high temperature oxidation zone and finally through the reduction zone, almost all of the organic vapors (tars) are consumed to form gas, and thus the gas is quite clean compared to the updraft gasifier. Two important requirements are needed to be maintained for this gasifier: (1) the temperature of the oxidation zone is to be kept at as high as possible (usually around 1000° C) and (2) the distribution of the gasifying agent must be homogeneous at the throat where the oxidation of solid and vapors generated from the pyrolysis zone takes place under atmospheric pressure. Since the gas is quite clean from the downdraft gasifier, it is suitable for internal combustion engines and turbines for electricity generation; however, because the gas leaves the gasifier at a relatively high temperature, it needs to be cooled down before downstream application.

Gasification of different types of biomasses under different conditions in downdraft gasifier has been conducted and some of the recent reports are summarized in Table 6. Agricultural waste such as bagasse was gasified in a downdraft gasifier where the effect of temperature on the tar content in the product gas was investigated [89]. The gas composition 23% CO, 13% H_2, 11% CO_2 and 4% CH_4 was achieved with HHV of 5 MJ Nm^{-3} for Hazelnut shells gasification [90]. The CO_2 concentration was reduced for wood shaving gasification, and thus the heating value slightly increased to 6.25 MJ Nm^{-3} [91]. Using an innovative two-stage downdraft gasifier, the higher heating value was achieved to 6.5 MJ Nm^{-3} with tar content of less than 0.045 g Nm^{-3} and total combustible gas of 45% [92]. Utilization of steam in the gasification significantly increased the hydrogen content, thereby increasing the lower heating value to 11.11 MJ Nm^{-3} [48].

5. Operating variables

5.1. Temperature

In the gasification of biomass, temperature is one of the most important parameters that can control the gas composition, tar concentration, reaction rate, ash build-up etc. Therefore, it needs to be highly controlled [93]. Low temperature gasification is attributed to high tar content (Fig. 3) and low CO and H_2 content in the product gas [94,95]. On the other hand, high temperature gasification leads to a desired high yield of CO and H_2, while reducing the tar content (Fig. 3). However, two major problems limit high temperature gasification above 1000 °C: (1) the ash melting, especially when high ash containing biomass is used such as rich and wheat straw (ash content around 20%) and (2) the requirement of stringent reactor specification. Therefore, numerous studies have been conducted to investigate the gas composition, tar concentration and other requirements within the temperature range of 750–900 °C. For instance, an attempt has been made to produce H_2 for charging a solid oxide fuel cell (SOFC) from sawdust in a downdraft gasifier at a temperature range of 750–1150 °C under atmospheric pressure [96]. An increase in CO and H_2 content and a decrease in CO_2 and CH_4 were observed when temperature was increased from 650 to 800 °C in a bubbling fluidized bed gasifier. The raising of temperature from 750 to 850 °C in a fluidized bed gasifier significantly reduced the tar content in the product gas, while increased the CO and H_2 concentration. However, the tar yield from the gasification below 1000 °C is significantly higher than the acceptable range [94–96], and thus it needs gas cleaning. The entrained flow gasifier usually provides very high quality producer gas due to very high operating temperatures (1200–1500 °C) under high oxygen pressure. The plasma gasifier can decompose all kinds of solids because it operates at even higher temperatures (1500–5000 °C).

5.2. Pressure

Depending on the downstream application of the product gas, gasification of biomass is often conducted under atmospheric and high pressures. Some downstream applications of product gas such as the conversion of gas to methanol or to synthetic diesel using Fischer–Tropsch synthesis method need high pressure of product gas, where gasification under pressurized condition is beneficial. In addition, an increase in the gasifier pressure reduces the tar yield in the product gas. However, some investigations conducted in the fluidized bed gasifier have shown that the concentration of tar, mainly naphthalene, increased with increasing gasifier pressure from 0.1 to 0.5 MPa, and thus the concentration of CO decreased, while CH_4 and CO_2 increased. A model gasification coupled to an SOFC and gas turbine was conducted to show that a moderate pressure, for instance up to 4 bar, does not have a major impact on the gasification process. Interestingly, it affected turbine efficiency and, thus the unit's overall efficiency increased from 23% to 35% [96].

5.3. Gasifying agent

As shown in Fig. 2a and b, the gasification process consists of four different physical and chemical processes. In the drying zone of the gasifier, the moisture in biomass evolved as steam, while in the pyrolysis zone, the volatile organic matter distills out from the fixed carbon. The volatiles and solid carbons then introduce into the oxidation and reduction zones successively or vice versa, depending on the gasifier types, while they react with gasifying agents to produce product gases. As gasifying agents, air, steam, carbon dioxide and pure oxygen are commonly being used the selection of gasifying agent entirely depends on the requirement of the product gas quality for different downstream applications. Utilization of air as a single gasifying agent produces gases with lower concentration of H_2 and CO, because air also contains nitrogen. In addition, some of the H_2 and CO take part in complete combustion, and thus it increases the CO_2 concentration. Addition of external steam with air increases the H_2 concentration, because of the water–gas shift reaction. It assists to balance CO and H_2 ratio for Fischer–Tropsch synthesis. However, addition of steam reduces the thermal efficiency of the gasification. Pure oxygen is suitable for producing gases with high concentration of CO and H_2 and low concentration of tar; however, pure oxygen itself is an expensive gasifying agent. Carbon dioxide also acts as a gasifying agent to react with carbon to produce carbon monoxide; however, the reaction is slow.

5.4. Air fuel ratio and equivalence ratio (ER)

The mass ratio of air to fuel in any combustion unit is defined as the air–fuel ratio (AFR). The minimum ratio of air to fuel that is exactly enough to burn the fuel completely is termed as stoichiometric ratio. Combustion of fuel requires a minimum stoichiometric ratio of air to fuel, while gasification requires an air–fuel ratio lower than stoichiometric ratio. The equivalence ratio can be defined as the ratio between the air–fuel ratio of the gasification process and the air–fuel ratio for complete combustion. The

Table 7
Effect of temperature on the gas composition and tar content in the product gas.

Catalyst type	Mode of Application of catalyst	Biomass type	Operating temperature (°C)	Tar removal	Reference
Dolomite	Primary bed	Sewage sludge	850	76	[103]
Olivine	Primary bed	Sewage sludge	850	50	[103]
Fe/Olivine	Primary bed	Wood	855–890	38	[104]
Ni/Al_2O_3	Primary bed	Wood	780	48.27	[105]
Rh/CeO_2	Primary bed	Cellulose/cedar wood	550	100	[106,107,108]
$Rh/CeO_2/SiO_2$	Primary bed	Cellulose	500	100	[109,110]
$Rh/CeO_2/SiO_2$	Primary/Secondary bed	Cedar wood, Jute stick, Bagasse, Rice straw	550–700	100	[111,112]
$Rh/CeO_2/SiO_2$, Ni/Al_2O_3, Dolomite, non-catalyst	Primary/Secondary bed	Cedar wood	550–700	139 g Nm^{-3} non-cat 20% reduction by dolomite 78% reduction by Ni cat	[113]
$Ni/Ca_{12}Al_{14}O_{33}$ or $12CaO \cdot 7Al_2O_3$	Primary/secondary bed	Toluene	500–800	100	[114]
$Ni+MnO_x/Al_2O_3$	Secondary bed	Cedar wood	550–650	100	[115]
Ni(x wt%)/CeZrO2	Secondary bed	Toluene, 1-methylnaphthalene	500–900	Toluene 100 1-methylnaphthalene, 90	[116]
Ilmenite	Secondary bed	Mallee wood	600–850	76	[117]
Fe/Char	Secondary bed	Mallee wood	500–850	95	[118,119,120]
Fe/Char	Secondary bed	Mallee wood, 4.4 kg h^{-1}	900	97	[121]

mathematical representations of air–fuel ratio and equivalence ratio are as follows:

$$\text{Air}-\text{fuel ratio} = \frac{\text{mol of air}}{\text{mol of fuel}} \tag{1}$$

$$\text{ER} = \frac{\text{actual air}-\text{fuel ratio}}{\text{air}-\text{fuel ratio for complete combustion}} \tag{2}$$

From Eq. (2), it seems that the higher ER creates more oxidation environment in the gasifier, and thus attributed to lower calorific product gas. On the other hand, lower ER results in higher calorific product gas; however, the tar yield is considerably higher. The higher concentration of burnable gas composition and lower tar concentration in the product gas is of prime importance for downstream application. Therefore, the process optimization is the focus of biomass gasification research.

The thermodynamic analysis to evaluate the effect of ER on energy efficiency in different biomass gasification was carried out and it was found that the efficiency decreased with increasing the ER [97]. In one study, it was found that the energy efficiency of the gasification system increased until the optimum ER (0.25), while it was decreased at higher ER [50].

6. Gas cleaning

The biomass gasification gas consists of a mixture of CO, H_2, CO_2, CH_4, N_2, water vapor, and some impurities such as tar (aromatic hydrocarbon species), particulate matter, sulfur compounds, hydrochloric acid, ammonia, and alkali metal species. The gas composition and impurities vary depending on the biomass feedstock, gasifier design, gasifying agents, and gasification conditions. However, in general, the impurities concentration, especially tar and particulate matter, often remains above the acceptable range for some specific downstream applications such as internal combustion engine, turbine, fuel cell, chemical conversion by Fischer–Tropsch synthesis etc. Based on many studies, the loading limit for particles in the producer gas is strictly imposed and it is varied based on the application. The internal combustion engine can satisfactorily accept the particle concentration $< 50\ \text{mg Nm}^{-3}$ with size of $< 10\ \mu\text{m}$, while it is $< 30\ \text{mg Nm}^{-3}$ for gas turbine [51–54]. Therefore, for most of the downstream applications, the product gas is required to be cleaned. There are multiple options to clean up the product gas, for example, physical processes, thermal process and catalytic process.

6.1. *Physical gas cleaning method*

The physical gas cleaning method is a simple filtration or wet scrubbing of the product gas in order to remove the tar and particulate matter from the gas stream through gas/solid or gas/liquid interactions. The filtration may be conducted either in high temperature or ambient temperature, while the scrubbing is usually conducted at ambient temperature. The high temperature filter must consist of temperature tolerable materials for example, ceramics, fiber glass, sand etc. On the other hand, the low temperature filter may consist of cotton fibers, charcoal, etc. In either condition of filtration, the fouling of particulate matter and sticky tar has been considered as a crucial problem. In the large scale operation, the clogging of the pores of the filter may cause a huge pressure drop. The water scrubbing of the product gas can scavenge particulate matter and tar; however, the handling of a huge amount of contaminated water is unhealthy and it contaminates the environment.

A high temperature granular bed filtration has been investigated and several field tests were conducted at about 550 °C [98]. As reported, this filter is comparatively better than that of the bag filtration method. In one research, tar has been termed as heavy tar and light tar and they were removed using vegetable oil and a char filter, respectively. The turbulence of oil increased the absorption of heavy tar [99]. However, the author did not mention post operative treatment of vegetable oil. In the CHRISGAS project, a ceramic filter has been developed for the cleaning of hot producer gas from steam–O_2 gasification of biomass at Delft University of Technology [100]. Ceramic candles were used in the temperature range between 600 and 800 °C for more than 50 h. Although the result was promising a filter cake was formed on the candle surface. Different types of fabric filters were investigated for cold gas filtration and it was observed that the pressure drop increased very quickly, due to the deposition of particles, which was difficult to remove.

6.2. *Thermal process*

A thermal process of gas cleaning is a process where the heavy aromatic tar species are cracked down to lighter and less problematic smaller molecules such as methane, carbon monoxide and hydrogen. In this process, the efficient tar cracking is usually achieved at temperatures higher than 1000 °C [96]. The most challenging aspects of high temperature tar cracking are (1) the cracking equipment must be constructed of high temperature tolerable expensive alloys, (2) it needs a highly controllable complex heating system, (3) the ash melts at this temperature, and (4) the product gas needs an intensive cooling system.

6.3. *Catalytic hot gas cleaning*

Downstream application of gasification product gas, especially for gas turbines or internal combustion engines, needs to meet some stringent requirements, such as the tar concentration must lie between 50 and 100 mg Nm^{-3} and the ammonia concentration must be less than 50 ppm [101,102]. The physical filtration and even high temperature thermal cracking is inefficient to meet these requirement. Utilization of effective catalysts often considered an attractive method to decrease the concentration of tar and ammonia in the product gas stream. In addition, the catalytic tar and ammonia decomposition often occurred at much lower temperatures (600–800 °C) compared to thermal cracking ($\approx$ 1200 °C). In the case of physical cleaning process, the product gas is needed to be cooled down to ambient temperature thus decreasing the thermal efficiency. The novelty of the catalytic process is that it operates at the same temperature of the exit product gas temperature, and thus it does not need to heat up or cool down. In addition, it converts tar to CO and H_2, so as to increase the burnable gas composition. The catalytic bed can also trap the particulate matter and ammonia, so as to provide almost completely clean gas for downstream application.

A comprehensive research on the catalytic hot gas cleaning has been done over the past few years. Various types of catalysts have been proven to be active for tar and ammonia decomposition as summarized in Table 7. For tar cracking, some attempts have been made utilizing the catalyst in the primary bed, where the catalyst was placed in the gasification reactor [103–105]. However, the catalyst was rapidly deactivated due to the fouling of ash and carbon on the catalyst surface [104,105]. Although the non-metallic catalysts showed longer activity the catalysts were eroded and elutriated from the bed [103]. The noble metal catalysts such as rhodium (Rh) showed superior catalytic activity in the primary and secondary bed, and converted almost all the tar and char at unusually low temperatures (500–700 °C) [106–113]. However, as the scanning electron images of spent catalyst (Rh/CeO_2), it sintered during reaction [106–108]. The sintering problem was overcome when CeO_2 and Rh was loaded on porous silica sequentially as $Rh/CeO_2/SiO_2$ [109–113]. However, these catalysts still need to be investigated for long run experiment.

Among the transition metal catalysts tested in the secondary reactor, nickel based and modified nickel based catalysts were widely investigated [114–116]. These catalysts are quite effective for tar destruction; however, the experiments were run in short reaction time. The recent development of some cheap catalyst based on iron and char for tar reforming has expedited the commercial exploitation of biomass gasification technology for power generation [117–121].

7. Suitability of various types of biomass for gasifying in various types of gasifiers

The chemical composition and physical properties of different biomasses vary widely depending on their origin. Biomass properties significantly affect the operation of the gasifier, product gas composition and overall efficiency of the biomass based power generation. In addition, depending on the biomass characteristics, the type and gasifier design also vary widely. For example, most wood species have ash contents below 2% [108] and are therefore suitable fuels for fixed bed gasifiers. However, because of the high volatile content of wood, an updraught gasifier produces high tar containing gas, which is unsuitable for engines but suitable for direct burning. After intensive cleaning, the gas can be used for engines; however, it is rather difficult to make the gas suitable for engines. A downdraught gasifier on the other hand can be designed to produce tar-free product gas when fueled by wood chips of low moisture content. Using a relatively simple cleanup train, the impurities can be removed and the gas can be used in internal combustion engines. However, in the case of sawdust, the downdraught gasifier also produces excess tars and in addition creates an inadmissible pressure drop in the gasifier.

Agricultural residues, especially in developing countries, are major sources of biomass available for gasification. Some agricultural residues like coconut shells [122] and maize cobs [123] are the best documented and unlikely to create serious problems in fixed bed gasifiers. Palm kernel shell (PKS), available in Malaysia and Indonesia, is also suitable for gasification. However, some fiberous biomasses like coconut husk and empty fruit bunch (EFB) [124] are reported to present bridging problems in the feeder section. These biomasses can be gasified after pretreatment. Most of the herbaceous biomasses have ash contents more than 10%, which often causes slugging problems in downdraught gasifiers [125]. The ash content in rice husks is even higher ($>$ 20%), and this is probably the most difficult biomass for gasification. The fixed bed updraft gasifier probably can gasify most of the agricultural biomasses. However, the cost and complexity of the fluidized bed, maintenance and labor costs, and the environmental consequences (disposal of tarry condensates) involved in cleaning the gas, reduce the cost effectiveness and prevent engine applications [126].

Among different gasifiers, downdraught equipment seems to be less complex and cheaper to install. It is easy to operate and it creates fewer environmental difficulties. However, the technology developed so far related to downdraft gasifiers is inadequate to handle agricultural residues (with a few exceptions) without installing expensive additional devices. Fluidized bed gasifiers on the other hand show great promise in gasifying a number of “difficult” agricultural wastes. However, only semi-commercial installations are currently available and operating experience is extremely limited. It seems that more studies are required for both types of gasifiers for individual biomass gasification.

8. Biomass gasification based power generation

Biomass gasification based a power generation system consists of pretreatment of biomass, gasification of biomass, gas cleaning and feeding of a combustible gas mixture in gas-turbine or gas-engine to generate electricity as shown in Fig. 4. The product gas can also be burned in a boiler to generate steam, which can run a steam turbine to produce electricity. As mentioned in the previous section, the raw gas mixture that exits the gasifier is often contaminated with tar, particulate matter, ammonia and others. The most difficult task is to clean up the gas to meet the stringent requirement of a gas turbine and engine operation in terms of tar concentration ($<$ 100 mg Nm^{-3}). For boiler operation, the product gas can directly be used without further treatment. However, the overall efficiency of electricity generation through a steam turbine is less than 20%, while it can achieve around 50% for gas turbine and engine. Among the electricity generation technologies, the gas engine is widely focused on, especially for distributed power generation due to its small system capacity, compact structure,

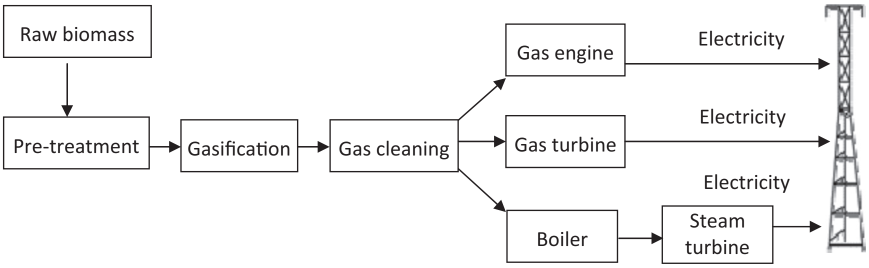

Fig. 4. Flow sheet diagram for power generation using biomass gasification gas.

low investment cost, simple operation and maintenance and low running cost [121].

In order to meet the gas quality requirement for engine operation, effective methods of gas cleaning are being investigated [127]. Because of the technical faults, especially regarding gas cleaning and ash problem many of the large scale gasification methods for electricity generation have been aborted [128]. Therefore, researchers have focused on technology development for gas cleaning in the laboratory bench scale and pilot scale. One recent development can be considered as one of the pioneering works to produce quality gas for gas engines [121].

9. Factors affecting engine power output using producer gas

A producer gas fueled engine generally leads to a reduced power output. The factors affecting the power output are as follows:

(a) heating value of the gas
(b) amount of combustible mixture supplied to the cylinder,
(c) the number of combustion strokes in a given time (number of revolutions per minute, rpm)

The heating value of producer gas varies depending on the concentration of combustible gases such as carbon monoxide, hydrogen and methane. In order to achieve complete combustion of producer gas, it has to be mixed with air in a suitable ratio, resulting in a dilute mixture having a lower heating value per unit volume than producer gas alone. The usual heating value of the producer gas and air mixture is around 2500 kJ m^{-3}, while the heating value of a stoichiometric mixture of petrol and air is about 3800 kJ m^{-3}. The difference of this heating value results in power loss of around 35% [129].

The amount of combustible gas mixture that enters into the cylinder of an engine depends on the cylinder volume and gas pressure. For an engine, the cylinder volume is constant; however, the inlet gas pressure may vary. The higher inlet pressure facilitates the increase of the volumetric efficiency of the engine, which is defined as the ratio between the actual pressure of the gas in the cylinder and normal pressure (1 atm). When the gasifier is directly connected to the engine, the inlet gas pressure at the air inlet manifold depends on the pressure drop over the total gasification system, reducing the entering gas pressure, in other words reducing the available combustible gases in the cylinder, obviously reduces the maximum power output of the engine.

The engine power output is also limited by the engine speed (revolution per minute, rpm). The producer gas and air mixture combustion speed is usually low as compared to the combustible mixtures of petrol and air, which reduce the efficiency of the engine.

The power loss of the engine run on producer gas can be recovered by increasing the compression ratio [129]. Normally, the compression ratio of a producer gas based commercial engine is 6.5–7.5. A higher hydrogen content in the producer gas can enhance the flame speed which can enhance the compression ratio as high as 10. However, a higher compression ratio creates some other problems such as starting difficulty, vibrational problems, wearing and tearing of piston and reducing the life of the system.

10. Gas cooling

The hot producer gas at the outlet of the gasifier needs to be cooled for downstream application. Different types of gas coolers are used to cool down the producer gas to ambient temperature such as natural convection coolers, forced convection coolers and water coolers. Natural convection coolers consist of a simple length of pipe to provide enough surfaces for heat to be transferred to the atmosphere. This kind of cooler is very simple to use and requires no additional energy input; however, it is very bulky. Forced convection coolers need a fan to circulate cooling air around the gas pipe. However, extra energy is needed to run a fan. Two types of water coolers are available: the scrubber and the heat exchanger. For the scrubber, the gas is brought in direct contact with water, which is sprayed onto the gas stream by means of a suitable nozzle device. The disadvantage of this system for gas cooling is that the impurities, especially tar, contaminate the circulating water. The contaminated water is difficult to maintain. In addition, the system requires some power for circulating water. The water cooled heat exchanger is considered to be the best option because the circulated water can be kept clean during operation and the power consumption of a suitable water pump can be justified.

11. Use of gas turbines or Stirling engines with producer gas

Producer gas can be used for gas turbines and Stirling engines [129]. A gas turbine can accept high inlet gas temperatures which aid to increase their thermal efficiency. However, the technology developed so far related to gasifiers and turbines is not suitable for power generation. The most severe problem is related to dust content in the producer gas, especially at high inlet temperatures. In addition, the tiny amount of alkaline vapors (Na, K and Ca) which are usually present in producer gas corrode the turbine blade. The possibility of using Stirling engines using producer gas has been studied [130]. A Stirling engine in small range is proven to be more advantageous because of low maintenance, high efficiency, low lubricant consumption etc. The gasifier producer gas can be used for Stirling engines more efficiently compared to the internal combustion engine. This is because, since the combustion products do not enter the Stirling engine, they require no cleanup.

12. Health and environmental hazards associated with the use of producer gas

Biomass gasification based power generation involves different types of hazards and environmental impacts [131].

Toxic hazards: The most toxic constituent of producer gas is carbon monoxide, as it has the tendency to combine with the hemoglobin of the blood and thus prevent oxygen absorption and distribution. Therefore, no leakage can be allowed and during starting up and shutting down, the vented gas must be discharged under controlled conditions. In addition, the other toxic gases such as SO_x and NO_x should be completely separated before being used as the producer gas. Tar is another contaminant, which is also toxic and environmentally hazardous.

Fire hazards: Gasification is normally a high temperature process, and thus the surface of the equipment is usually hot and the firing of the system because of sparking is likely to happen. Risks can be considerably decreased by properly insulating the hot surface.

Explosion hazards: The producer gas contains a significant portion of hydrogen gas and if a sufficient concentration of air is mixed with the gas mixture, an explosion may occur. Air leakage into the gas system combust the gas and generally does not give rise to explosions. The leakage at the lower part of the gasifier results in partial combustion of the gas leading to higher gas outlet temperatures and a lower gas quality. However, the pyrolytic gases in the feeder system can mix with air and can cause explosion.

Environmental hazards: Ashes and condensate are two main environmental hazards. The gasification of agricultural residues usually produces high ash. The ash does not contribute to environmental problems if it can be disposed of in proper way. However, the disposal of toxic tar-containing condensate from a large number of gasifiers can have undesirable environmental effects.

13. Economic evaluation

The cost of biomass gasification based power generation varies depending on the economic situation of the country. Therefore, the total initial investment and operational cost vary widely from country to country. An example from India “An assessment of a Biomass Gasification based Power Plant in the Sunderbans” is mentioned here [132]. The cost of diesel use per unit of power generation is USD 0.49 but the introduction of the gasifier has reduced it to USD 0.09 per unit. This is an indicator of benefit from the installation of gasifier power. On the basis of the following assumptions, the study has calculated the benefit cost ratio (BCR) and internal rate of return (IRR).

(A) The initial project cost of the gasifier plant: USD 272732.9.
(B) Lifetime of the plant: 15 years.
(C) Operation and maintenance cost is the actual cost needed for the transmission line maintenance, maintenance of the power plant, labor, and fuel cost (evaluated at the market price), etc.
    (1) Input raw material charges: USD 10161.72.
    (2) Labor charges: USD 4298.87.
    (3) Energy plantation: USD 5117.707.
    Total annual operation and maintenance cost is USD 19578.3.
(D) The benefits are effectively generated in terms of the savings in electricity bills and increase in business hours of the commercial units.
(E) The discount rate of 8% has been assumed for calculating BCR. In this case the IRR has been calculated as 19%. Thus considering all these criteria it can be concluded that the BGBPP is economically viable.

14. Conclusions

Biomass gasification can be considered as one of the competitive ways of converting distributed and low value lignocellulosic biomass to fuel gas for combined heat and power generation, fuel cell and synthetic diesel production. However, from the collection of biomass to the utilization of fuel gas for downstream application the process suffers numerous problems that slow down the commercial exploitation of biomass based energy technology. To overcome the logistic problems and to meet the power requirement at the remote areas, the distributed power generation at the location where biomass is abundant could be more economic. In order to reduce the technical problems, a small size (1–10 MW) of the plant could be suggested. The mixed gasifying agent, for instance, air and steam, could provide suitable gas composition for gas engines with higher thermal efficiency. The utilization of a catalyst, especially, a cheap and active catalyst for gas cleaning can provide the required gas quality for gas engines. However, more research is required to overcome the technical barriers of biomass gasification based power generation for commercialization.

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