Indian Journal of Science and Technology, *Vol 9(48), DOI: 10.17485/ijst/2016/v9i48/98100, December 2016*
ISSN (Print) : 0974-6846
ISSN (Online) : 0974-5645

Circulating Fluidized Bed Gasification: Status, Challenges and Prospects in Indian Perspective

Prabhansu[1], Prakash Chandra[1], Malay Kr Karmakar[2] and Pradip Kr Chatterjee[2*]

[1]Mechanical Engineering Department, National Institute of Technology, Patna-800005, Bihar, India; prabhansu.me13@nitp.ac.in, prakash@nitp.ac.in

[2]Thermal Engineering, CSIR-Central Mechanical Engineering Research Institute, Durgapur-713209, West Bengal, India; malaycmeri@gmail.com, pradipcmeri@gmail.com

Abstract

Objective: The present work relates the need for change and how Circulating Fluidized Bed (CFB) technology could prove a better alternative than the existing gasifiers in India. **Background/Analysis**: India is an energy deficit nation although it has rich coal reserves and biomass diversity. India ranks 3rd in world coal production, but it is low in grade comprising of high ash content. Biomass present in abundance includes bio-residue like bagasse, rice husk and saw dust beside other prominent crops that are found in India. Gasification technology is widely accepted way of harnessing these abundant energy resource. **Findings**: Presently conventional fixed bed gasifiers are installed in different regions of the country but this is gradually becoming obsolete. CFB gasification is at present an emerging technology for harnessing this vast resource of biomass and coal efficiently and environment friendly in India. It has evolved as an environment friendly technology for utilizing different of carbonaceous fuels like peat, lignite, biomass etc., for producing fuel gas with improved energy conversion ratio. A comprehensive survey has been conducted to study the CFB gasifiers and gasification processes in CFB so that it can be designed for scale-up and direct use in existing and upcoming related industries in India. This paper analyzes the feasibility of adopting the circulating fluidized bed technology for utilization of low grade coal and biomass available in India. **Novelty/Applications/Improvements**: Road map for adoption of CFB gasification technology for decentralized rural power production in India along with its future scope has been discussed.

Keywords: Circulating Fluidized Bed, Gasification, Indian Scenario, Low Grade Fuel, Road Map

Nomenclature

ER	Ratio of air used to stoichiometric air
S/B	Steam-to-biomass ratio
Ψ	CO2-to- biomass ratio
GR	steam+O2-to-biomass ratio

1. Introduction

1.1 Coal Reserves in India

As per Integrated Energy Policy Committee of Planning Commission, the primary source of energy in India will be coal till 2031-32 and possibly beyond. In India, 76% of the produced coal is consumed by power sector and different industries including fertilizers, cements, chemicals, papers and several other small and medium-scale industries that are dependent on coal for their process and energy requirements. As on 1.4.2013, 298.91 billion tonnes (including that in the state of Sikkim) of coal reserves up to the depth of 1,200 m have been established in India. The annual production of coal and lignite in the country was 556.40 million tonnes and 46.45 million tonnes respectively in 2012-13[1]. Indian non-coking coals are categorized into different grades ranging from A to G, in which grades from A to C represents the superior one, while D to G grades represents thermal coal. Over

*Author for correspondence

the years, quality of thermal coal has become worse and at large grades E, F and G containing high ash content (35-45%), high moisture level (4-20%), low sulfur content (0.2-0.7%), and low calorific values (10.5-20.9 MJ/kg) are available for use. Power plants in the country are mostly located at a distance of more than 1000 km away from the coalfields and are centered in the Eastern and Central part of India. Consequently, extra freight charges are borne in transporting bulky coal containing high ash beside other serious problems like ash disposal and handling and toxic emissions[2,3]. Use of gasification technology will be useful as the obtained fuel gas could be easily transported to the distant power plants without major problems occurring due to emissions and ash. Several projects are going on for in-situ gasification at the mining site itself, which will not only reduce the extra freight charges but also provide clean coal technology.

1.2 Bio-energy Scenario in India

According to a survey, the total potential of India is more than 23 GW from biomass to power[4]. 686 MT gross (crop residue) of biomass are produced and 34% from that are estimated to be surplus for bio-energy generation. The amount of bio-energy potential from 34% (234 MT) based on 39 crops residue is expected to be 4.15 EJ, which is capable of fulfilling 17% of India's total primary energy consumption[5]. To harness this huge amount of untapped energy in cleaner form, gasification industry has emerged as one of the prominent option[6]. In India, several gasifiers have been installed in various states like Bihar, Uttarakhand, Karnataka, Gujarat and Sunderban region. Table 1 shows the total commissioned power project where states like Uttar Pradesh, Tamil Nadu and Maharashtra tops the list with above 400 MW capacities.

2. Cost Economics and Government Subsidies

India is one of its kinds to have separate ministry specifically for the development of renewable technology in the name of Ministry of New and Renewable Energy, Government of India (M.N.R.E, G.O.I). Since mid nineties, M.N.R.E, G.O.I has been providing subsidies to biomass power projects. In all 130 biomasses and 158 bagasse co-generation projects have been installed in the country for feeding power to the grid which totals to 999.0 MW and 1666.0 MW respectively. Several new projects are under different stages of implementation. Table 2 shows tariffs fixed by commissions to different states in India for biomass cogeneration.

Table 1. List of commissioned biomass power / co-generation projects state wise (as on 31/03/2011)[7]

S. No	State	Total (in MW)
1	Andhra Pradesh	363.25
2	Bihar	9.50
3	Chattisgarh	231.90
4	Gujarat	0.50
5	Haryana	35.80
6	Karnataka	365.18
7	Madhya Pradesh	1.00
8	Maharashtra	403.00
9	Punjab	74.50
10	Rajasthan	73.30
11	Tamil Nadu	488.20
12	Uttarakhand	10.00
13	Uttar Pradesh	592.50
14	West Bengal	16.00
Total		2664.63

3. Need for Change

3.1 Status of Fixed Bed Gasifiers in India

The installed gasifiers are mainly conventional fixed bed type and are not stable and continuous in the long run[8]. Present gasifiers produce a lot of tar and generate fuel gas of very low calorific value. Tar produced starts to condense over the shaft of engine resulting in operational difficulty, cleanups and frequent shutdowns. Another problem in downdraft fixed gasifier is that the gases that leave the gasifier are at very high temperature and this amounts to significant heat loss which lowers its thermal efficiency considerably. It has also been found that the particulate content of the produced fuel gas is much higher than the acceptable limit[9]. Issue with rice husk gasification in these conventional gasifiers is that it generates high ash content (ash content 20% by weight). Residual disposal of tar is an environmental issue and is also a concern due to engine choking in existing fixed bed gasifiers[10]. So, there is a need for change with advanced and efficient one which can be achieved by using CFB gasifier. CFB gasification, an emerging technology, has the capability to reduce emissions considerably as compared to conventional fixed bed gasifiers[11]. It is

Table 2. Biomass cogeneration across different states in India[7]

State	Tariff fixed by commissions	RPO%
Andhra Pradesh	Rs.4.28/kWh (BM), Rs.3.48/kWh (Cogen)	3.75 (min)
Chattishgarh	Rs.3.93/Unit (BM)	5
Gujarat	Rs.4.40/unit (BM), Rs.4.55/unit (Cogen)	10
Haryana	Rs.4.00/unit (BM), Rs.3.74/unit (Cogen)	1
Karnataka	Rs.3.66/unit (BM), Rs.3.59/unit (Cogen)	10 (min)
Kerala	Rs.2.80/unit (BM)	3
Maharashtra	Rs.4.98 (BM), Rs.4.79/ unit (Cogen)	6
Madhya Pradesh	Rs.3.33 to 5.14/unit paise for 20 yrs.	0.8
Punjab	Rs.5.05/unit, (BM), Rs.4.57/unit (Cogen)	3 (min)
Rajasthan	Rs.4.72/unit-water cooled & Rs.5.17 air cooled (BM)	1.75
Tamil Nadu	Rs.4.50-4.74/unit (BM), Rs.4.37-4.49/ unit (Cogen)	13 (min)
Uttaranchal	Rs.3.06/unit (BM), Rs.3.12/unit (Cogen)	9
Uttar Pradesh	Rs.4.29/unit, for existing and 4.38 for new	4
West Bengal	Rs. 4.36/unit fixed for 10 years-BIOMASS	4
Bihar	Rs.4.17/unit BIOMASS, Rs.4.25/ unit (Cogen)	1.5
Orissa	Rs.4.09/unit	-

technologically advanced as it is suitable for faster rate of chemical reactions, low tar content due to high conversion rates and less unconverted carbon, superior environmental performance, more efficient, high mass transfer and the process behaves as an isothermal[12,13]. Therefore, a brief introduction of CFB gasifier is essential in order to understand its characteristics, behavior, operations and fuel gas cleaning technologies. The current paper focuses on aspects of gasification in circulating fluidized bed systems and its implementation in Indian scenario as it is currently undergoing rapid commercialization globally[14].

3.2 CFB Technology

The fluidized bed, in which smooth and steady recirculation of solids through the dipleg or other solid trapping device is done for continuous operations is known as circulating fluidized bed[15]. The invention of fast fluidized bed dates back in 1938 when Lewis and Gilliland found a new gas-solid contacting process at the Massachusetts Institute of Technology while working on fluid catalytic cracking[16]. CFB systems are usually consists of riser which is connected to a cyclone, down comer and loop seal[17]. Schematic diagram of CFB system is shown in Figure 1 and the flow regimes of its basic components are described in Table 3.

Several non-mechanical valves are used in CFB for leak tight operation among which L-valve[19–26], V-valve[27],

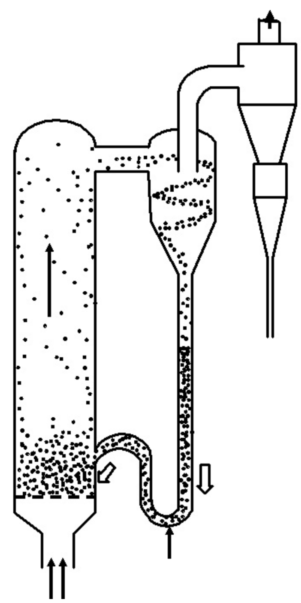

Figure 1. Schematic diagram of CFB system.

Table 3. Transport regimes in circulating fluidized bed components[18]

Location	Regime
Furnace (below secondary air level)	Turbulent or bubbling fluidized bed
Furnace (above secondary air level)	Fast fluidized bed
Cyclone	Swirl flow
Return leg (stand pipe)	Moving packed bed
Loop seal/external heat exchanger	Bubbling fluidized bed
Back-pass	Pneumatic transport

J-valve, seal pot and loop seal[28–30] are the important ones. Loop seal is gradually replacing other on-mechanical valves as it provides effective control of solids recirculation and establishes leak tight operation in the loop[31]. In addition to that, use of other configuration like internal circulation of fuel has also been reported by several researchers[32–34], where the fluidized bed is divided into inter-connected compartments. For continuous circulation of bed materials, differential superficial gas velocity is optimized between the fluidization chambers. The chambers can be of draft tube within an annulus[34,35], or separated by using baffles[36,37], vertical walls fitted with orifices[38] or combination of both[39].

3.3 Environmental Benefits of CFB

Inherent impurities like Sulphur compounds, tar, nitrogen compounds can be easily removed in the case of CFB systems. The carbon conversion efficiency in CFB systems is very high close to 99.5%. A typical CFB system captures 90% of the sulfur based compounds with only 1.5-2.5 times the sorbent, while a bubbling fluidized bed system may require 2.5-3 or more for 90 % capture. Low levels of nitrogen based compounds have been constantly observed in all plant scale CFB systems. A high carbon conversion rate per unit cross sectional area is one of the major advantages of CFB gasifiers[13].

If co-firing of biomass with low grade coal like peat and lignite is done, then the net carbon emission can be greatly reduced. Integrated gasification combined cycle (IGCC) is an energy efficient cycle which utilizes gasification in two step. In the first step, the fuel is converted to fuel gas and in the second step the fuel gas gets transformed to electricity in a combined cycle power block that consists of a gas and a steam turbine process including a heat recovery steam generator[40,41]. Ultra supercritical (USC), pressurized CFB systems and IGCC with pollutants and carbon capture technology can further increase the overall efficiency and make it more eco friendly[42].

3.4 CFB Technology Developers

In India, several biomass gasification plants (fixed bed type) are installed with capacity of 1kW to 1.5 MW. The prominent developers of these plants are CGPL, OVN, SYNERGY, ARUNA, BETEL, NETPRO, ENERGREEN and ARRYA[43]. Technology is improving day-by-day and it is an essential task to collaborate with global CFB developers to implement this technology in rural India. There are several CFB and dual bed technology developers across the globe. The important among them are Foster Wheeler and ECN. Details about different available developers and their technologies are summarized in Table 4.

CFB demonstration plant of 1-MW technology, a joint venture of Ruchi Soya Industries Limited (RSIL) and Thermax Limited (TL) is under development stage at Washim, Maharashtra. This project is jointly financed by the United Nations Development Programme–Global Environment Facility (UNDP/GEF) and the Ministry of New and Renewable Energy (MNRE) as research and development based demonstration Plant[4]. With its successful installation and operation, it might pave way for use of CFB gasification technology in India. With such collaborations and with indigenous improvements in the existing technology, effective cost of the overall plant can further be reduced.

4. Gasification Process in CFB System

Gasification is a thermo chemical conversion process, where a carbonaceous solid fuel is converted into a combustible gas. The operations involved in the gasification of CFB are divided into three categories i.e., upstream processing, gasification and downstream processing. Figure 2 shows the flow diagram of overall processes involved in the gasification process in a CFB system. Upstream processing comprises of size reduction, drying and pyrolysis whereas downstream processing involves removal of contaminants like particulate, alkali and tar. Gasification can be performed using different agents like air, oxygen and steam which decide the quality of obtained fuel gas.

4.1 Upstream Processing

There are three main processes involved in upstream processing i.e., size reduction, drying and torrefaction. Coal and biomass requires size reduction before they are fed into the CFB gasifier to obtain appropriate particle size. With the reduction in particle size, overall surface area and porosity of the particles improves and as a result heat and mass transfer rates are enhanced. This process often involves pellets formation of biomass so that density improves and material flow of the particle may take place in the feeder region. It also helps in easy removal of fuel gas obtained from the gasification process. The size of feedstock for CFB system should be less than 20 mm and moisture content should be between 5-60%[44,45].

Table 4. CFB technology developers in the global market[44]

Tech. type	Gasifier	Gasifier heating	Oxidant	H2	CO	H2 : CO ratio	CO2	H_2O	CH4	Hydro-carbon(C2+)	N2	HCN, NH3, NOx	Sulphur (COS, H2S, CS2)	Halide (HCl, Br, F)	Alkaline (Na, K)	Tars	Particulate (ash, soot)
CFB	ECN BIVKIN	Direct	Air	18%	16%	1.13	16%		5.5%	2.38%	42%	NH3 2200mg/Nm3	H2S 150mg/Nm3	HCl 150mg/Nm3		0.12%	
	Uhde	Direct	O2 / steam	30.1%	33.1%	0.91	30.6%		5.7%	770 ppm	0.4%	90 ppm NH3	H2S 0.03%	0ppm HCl			
	Fraunhofer	Direct	Air	18%	14%	1.29	16%	10%	3%		39%						
	CUTEC	Direct	O2 / steam	31.6%	22%	1.44	33.6%		7.9%	1.8%	3%					9.5g/Nm3	dust 12g/Nm3
	CHRISGAS	Direct	Air	11%	16%	0.69	10.5%	12%		6.5%	44%				<0.1ppm	<5g/Nm3	dust <2ppm
	Foster Wheeler	Direct	Air	16%	21.5%	0.74	10.5%				46.5%						
Dual	ECN MILENA	Indirect	Steam	18%	44%	0.41	11.0%	25%	15.0%	6%	4%	NH4 500-1000 ppmv	H2S 40-100 ppmv			40g/Nm3	
	Silva Gas & Taylor	Indirect	Steam	22%	44.4%	0.50	12.2%		15.6%	5.8%							
	REPOTEC	Indirect	Steam	38-45%	22-25%	1.6-1.8	20-23%		9-12%	2-4%	2-3%	1000-2000 ppm NH3	H2S 40-70ppm, other 30ppm			2.3g/Nm3	5-10g /Nm3

Woody biomass contains 30-31% moisture content on dry basis[46]. High moisture content results in incomplete gasification and reduction in gasification temperature. It is often recommended that the content of moisture prior to gasification should be below 10-15%[47]. Drying of biomass results in shrinkage of the cell wall. The long chain structure of the molecule moves closer and due to that binding strength greatly improves. Different materials were dried in CFB incinerator and it was found that the textile was the most difficult one to dry whereas coal was quite easily dried. The reason could be the density and fluidizing behavior of materials inside the CFB setup. Figure 3 shows the loss rate of moisture with the passage of time. It also shows the sequence of drying (easy to difficult) coal > paper > orange peel > PVC > textile[48].

Torrefaction/pyrolysis process involves thermal decomposition of biomass in the complete absence of oxygen and in the temperature range of 250 to 300 °C to drive off moisture, a hemi-cellulose completely and cellulose partially[49]. After torrefaction biomass has both reactive as well as unstable cellulose molecules as a result of broken hydrogen bonds. It remains with it 79-95% of total biomass energy and at the same time produces much more reactive feedstock than the original biomass with lower H/C and O/H content. Torrefied pellets have comparable properties with that of coal, so biomass could replace a bulk of dependence on coal[50]. With Pyrolysis, CO and H_2 production increases greatly in the gasification process[51,52].

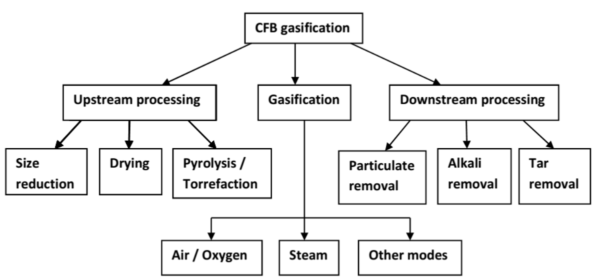

Figure 2. CFB gasification process and its classification.

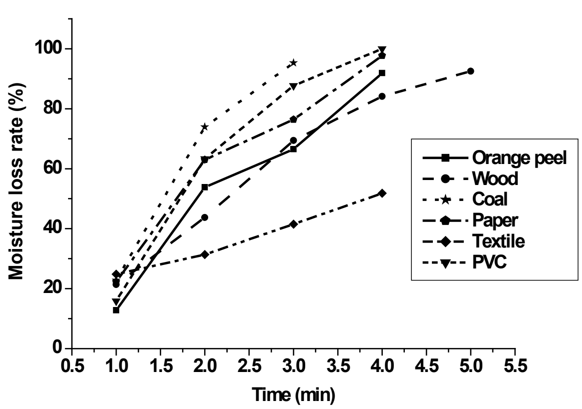

Figure 3. The effect of loss rate of moisture of different materials in CFB[48].

4.2 Gasification

Several researchers have studied CFB gasifier using different types of biomass and coal. In these studies, it was found that air ratio, suspension density, operating temperature, particle size and material species have been proved to play a very crucial role on gasification kinetics of woody biomass[53,54]. Table 5 describes various reactions involved in a typical gasification process.

Woody biomass mainly comprises of cellulose and hemi-cellulose (60-80%), lignin (10 to 25%) and some other extractives and minerals on dry basis[56,57]. The proportion of these species affects the gasification process greatly. It was reported[58] that efficiencies of carbon conversion for cellulose, hemi-cellulose and lignin are 97.7%,

Table 5. Typical gasification reaction[55]

Reaction type	Reaction
Carbon reactions	
C1, Boudouard	$C+O_2$ 2CO +172 kJ/mol
C2, Water gas or steam	C + H_2O CO +H_2 +131 kJ/mol
C3, Hydro-gasification	C+2H_2 CH_4-74.8 kJ/mol
C4	C + 0.5O_2 CO-111 kJ/mol
Oxidation reaction	
O1	C +O2 CO_2 -394 kJ/mol
O2	CO +0.5 O_2 CO_2-284 kJ/mol
O3	CH_4 + 2O_2 CO_2 +2H_2O-803kJ/mol
O4	H_2 + 0.5 O_2 H_2O -242 kJ/mol
Shift reaction	CO + H_2O CO_2 +H_2 -41.2 kJ/mol
Methanation reaction	
M10	2CO + 2H_2 CH_4 + CO_2 -247 kJ/mol
M11	CO +3H_2 CH_4 + H_2O -206 kJ/mol
M14	CO_2 +4H_2 CH_4 +2H_2O -165 kJ/mol
Steam reforming reactions	
M12	CH_4 +H_2O CO +3H_2 +206 kJ/mol
M13	CH_4 + 0.5O_2 CO + 2H_2 -36 kJ/mol

92.2% and 52.8% respectively. It was investigated that lignin contributed to high H_2 yield in the gasification process i.e., up to four times greater than that of cellulose[59]. The main benefit of using CFB system is its versatility in the choice of biomass. Any type of carbonaceous fuel may be used as feed stock in CFB gasifiers to produce combustible or fuel gas. Biomass reported in the literature includes very low grade fuels like orujillo[60], herbs residue[61] and even sewage sludge[62]. Most investigated biomass for CFB gasification is willow, as it has low ash content, due to which it is regarded as a very promising feedstock for fluidized bed applications[63,64]. In India, biomass available on mass scale mainly comprises of bagasse, rice husk and saw dust. The proportion of biomass in the feed stock greatly influences the fuel gas composition[65,66].

The agent that reacts with either heavier hydrocarbons or solid carbon or both, and convert them into gases like CO and H_2 of low-molecular weight, are termed as gasifying agents. The major gasifying agents are air, steam and oxygen which greatly influence the heating value of the fuel gas. The typical range of heating values in MJ/Nm[3] for air, steam and oxygen are 4-7, 10-18 and 12-28 respectively[67–69]. The most popular gasifying agent in CFB gasifier is oxygen, which is supplied in both pure form and through air. Its products comprise mainly of CO for low content of oxygen and CO_2 for high content of oxygen. The use of air on the other hand greatly reduces the heating value of the fuel gas due to presence of nitrogen in high content. It was shown[70] that the gas composition of CO_2 increases with increase in ER while other reducing species like H_2, CH_4 and CO decreases with increase in ER which is shown in Figure 4. In co-gasification study[71,72], it was found that with the increase in ER ratio, fuel gas yield increased.

Steam gasification is endothermic in nature and requires quite a large amount of energy[73]. Very little literature can be found on steam gasification in CFB. It was investigated that with the increase in S/B ratio for coir pith, there was increase in tar yield and decrease in gas heating value, gas yield & carbon conversion[74]. Figure 5 shows that for S/B ratio of 4.5, ER-0.2 and temperature of 1008 °C, hydrogen yield of 43% was obtained. Addition of air to steam gasification (air-steam gasification) is an alternative for supplying energy on the partial combustion of biomass with air, but it results in the lower quality of the product gas[75]. Peterson and Werther concluded that CO_2 gasification reactions often do not proceed to a good extent at relatively low temperatures thus preventing ash sintering[62].

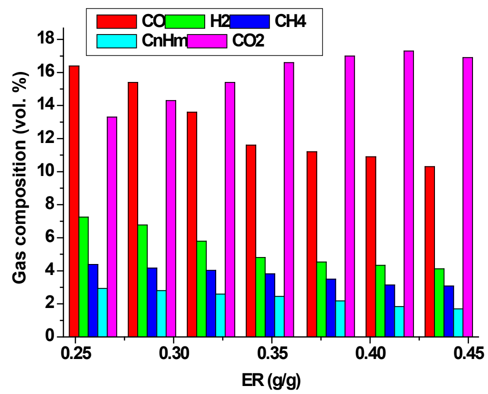

Figure 4. Effect of ER on gas composition[70].

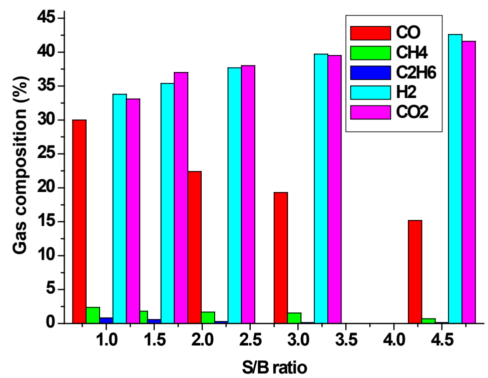

Figure 5. Effect of steam/biomass ratio on gas composition, ER-0.2 and gas outlet temperature ($1,008 \pm 11$°C)[74].

($1,008 \pm 11$°C)[74]

The temperature inside CFB is close to isothermal but it has immense effect on fuel gas composition and calorific value of the obtained gas. P. Garcia-Ibanez and his co-workers have performed air gasification for orujillo (olive oil waste) and found that Carbon conversion of 81.0–86.9% was obtained for leached orujillo at 800 °C and the gas yield increased with the increase in equivalence ratio[60]. In experiments conducted[76], the concentration of H_2 obtained from Agrol, willow and Dry Distiller's Grains with Solubles (DDGS) in the temperature range of 800 to 820 °C was around 24%, 28% and 20% respectively on a N_2 free basis. A series of tests were conducted[77,78] for willow & seed cake left over of sunflower and Jatropha using olivine, silica sand and pre-calcined olivine as bed materials. Hydrogen production, Carbon Conversion Efficiency (CCE) and Cold Gas Efficiency (CGE) as well as tar levels were found to be higher in the case of seed cake residues compared to willow. At 750 °C, tar level was found to be 18% more for willow wood compared to jatropha and sunflower was measured 44% higher than willow considering olivine as bed material[77].

In a series of test run conducted by E. Kurkela and his co-workers[79,80] for wood fuels, gasified at 0.2-0.25 MPa, using a mixture of steam and air as the gasifying agent, it was found that very high conversion of carbon in the range of 98.5 to 99% was obtained for all the three feedstock. Pressure up to 0.4 MPa was found stable for the operation of gasification in CFB. Also, all decomposition rate in the reformer for C_2-hydrocarbon gases resulted in over 98% conversion of tars and 92 to 99% of benzene, whereas the resultant conversion rates for methane and ammonia was much lower.

Catalysts greatly influence and enhance the gasification rates in CFB gasifier. In a study, it was found that negligible tar was formed using $Rh/CeO_2/SiO_2$ catalyst in low temperature gasification[81,82]. Pre-calcined olivine not only showed an increased activity for tar reduction in comparison to silica sand or untreated olivine, but also enhanced syngas quality and hydrogen production[78]. Increasing the steam-to-biomass ratio from approximately 0.7 to about 1.2 reduced tar and increased H_2 yield about 10% (dry basis) and by 20% (dry basis) for catalytic candles. By using catalytic filter candles, it was found the conversion of tar compounds increased by 2.8 times as compared non-catalytic filter elements[83]. Table 6 shows different CFB gasifiers being operated with varying process parameters. Gasifying mediums along with different carbonaceous fuels, operating pressure, bed material, outlet fuel gas composition and temperature range for gasification reaction are summarized in table as under.

Co-gasification and flexibility of fuel is the need of hour. One cannot rely only upon conventional fuels like coal. CFB gasifiers are pioneer in fuel flexibility as well as co-gasification of biomass with coal. No major modification in the setup is required while working with co-firing of biomass and coal. Successful experiments on co-gasification of lignite (up to 55% by weight) and wood in a CFB gasifier was reported[87]. Beech wood chips and lignite were used as fuel and steam as gasifying agent in the temperature range of 800-900 °C. CO and H_2 were major components in the product gas. It was found that with the increase in lignite content, tar content reduces. Similar experiments were performed in internal circulating fluidized bed gasifier[88]. Pine wood, German brown coal and wood wood/coal pettets were used as fuel. Steam was used as gasifying agent and gasification was done in the temperature range of 691-952 °C. Major gases obtained as product are H_2 and CO_2.

4.3 Downstream Processing

In order to obtain clean fuel gas, it is quite essential to perform downstream processing which involves removal of particulate matter, alkali, chlorine, heavy metals, nitrogen, sulphur and tar to produce clean fuel gas for further applications. Important and critical ones include particulate, alkali and tar removal technologies which are briefly discussed in the subsequent sub headings.

4.3.1 Particulate Matter Removal

Fuel gas obtained as end product also comprises of some particulate impurities like char and ash particles and its amount generated is dependent on the variety of used gasifier[47]. It may range from less than 1 μm to more than 100 μm[89]. High temperature removal of particulate matter includes barrier filtration, electrostatic separation and inertial separation. The important device mostly used in circulating fluidized bed is cyclone since a long time beside dust agglomerators and impact separator[90,91]. Rigid filters made of metallic or ceramic material have shown to remove particulates matter upto 99.9% when operating at 400 °C and particle size less than 100 μm[92]. For removal at near ambient condition, different types of scrubbers are used which includes impactor scrubber, cyclonic spray scrubber and electrostatic scrubber[93]. Impactor wet scrubber has the capability to remove more than 98% of particulate matter with larger particle size[93].

4.3.2 Alkali Removal

Alkali and alkaline metals like Na, Ca, K, Mg etc., are present in the feed stock and forms oxide at 700 °C during gasification. At 650 °C and below, it condenses and gets deposited on the downstream section of the gasifiers causing corrosion. These deactivate the catalysts which are used for tar removal[94–96]. In order to remove alkali metals effectively, less than 600 °C is essential in order to bypass particulate removal equipment[97,98]. Bauxite has proved to have better removal capabilities with as high as 99% efficiency which is reached in less than 0.2s[91]. Simultaneous removals of alkali and chlorine have been achieved by the use of alumino-silicates and sodium carbonate into the gas stream[99]. At ambient temperature, it is found that alkali compounds are water soluble, so they can be removed by leaching or water washing process and efficiency of more than 95% has been obtained by its use[100].

Table 6. Summary of gasification process in CFB systems

Dimension of gasifier (m)	flow rate	Fuel used	Gasifying agent	Bed material	Temp.range (°C)	Ope. pres. (bar)	Fuel gas composition
D-0.156, H-5	0.14-4 m/s	Juliflora wood chip	Air	Silica sand	700-900	1	CO-21-26%, CH_4-1.7-3.5%, CO_2-7-20%, H_2-7-10%[86]
D-0.07-0.06, H-5.4	5.4-18.7 m^3/hr	Coal	Air-steam	Silica sand	897-936	1-5	CO-10.17-13.6%, CH_4-1.96-2.74%, H_2-13.68-15.86% [85]
-----------	-------	Japan cedar	Air-steam	-------	650-700	1	CO-19%, CH_4-0.5%, CO_2-19.5%, H_2-61%[84]
D-0.078, H-6.0	11.1 kg/hr	50% cardoon + 50% giant reed	Air	Olivine	700-800	1	CO-29.3-34.6%, CH_4-9.3-9.9%, CO_2-34.1-38.5%, H_2-22.1-22.3%[45]
D-0.083, H-5.5	O2-4kg/h Steam-12 kg/h	Cardoon	O2/ steam	Magnesite	700-750	1	CO-6.78-8.5%, CH_4-4.1-4.54%, CO_2-34.1-38.5%, H_2-34.6-36.6%[45]
----------	300-450 m^3/hr	Herb residue	Air	-----------	675-854	1	CO-11.55-16.32%, CO_2-13.23-16.55%, H_2-4.87-7.28%[61]
D-0.1, H-15	4-20 m/s	Sewage sludge	CO_2 (ψ=0.2))	Silica sand	750-850	1	CO-4.8%, H_2-6.1%, CO_2-16.6%, CH_4-3.6% [62]
D-0.078, H-6.2	7.8 m^3/hr	Willow wood	Air	Calc. olivine	750	1	CO-30.4%, CH_4-8.7%, CO_2-36.6%, H_2-23.7%[78]
D-0.078, H-6.2	7.8 m^3/hr	Sunflower	Air	Calc. olivine	750	1	CO-29.8%, CH_4-6.2%, CO_2-35.9%, H_2-28.2%[78]
D-0.078, H-6	11.22 m^3/h	Willow wood	air	Olivine and quartz sand	750-800	1	CO-29.5-35.1%, CH_4-7.8-9.4%, CO_2-30.3-37.7%, H_2-21.8-25.5%[76]
D-0.078, H-6	11.4 m^3/h	Jatropha	Air	Olivine and quartz sand	750-800	1	CO-25.2-36.9%, CH_4-6.8-8.4%, CO_2-28.7-32.1%, H_2-22.6-26.5%[77]
D-0.078, H-6	7.8 m^3/h	Sunflower	Air	Olivine and quartz sand	750-800	1	CO-29.3-36%, CH_4-8.2-9.4%, CO_2-29.8-35.1%, H_2-27.1-28.4%[77]
D-0.20, H-6.5	2-6 m/s	Orujillo	Air	Silica sand	< 900	1	CO-6.9-8.6%, CH_4-1.8-3.0%, CO_2-19.0-21.7%, H_2-5.4-9.3%[60]

4.3.3 Tar Removal

It is found that with the increase in temperature, tar content decreased considerably. In a study, 2.2 and 6.8 g/Nm^3 were obtained as lowest and the highest amount of tar content for willow wood investigated with olivine as recirculation material at a temperature of 800 °C and with common sand as inventory at 750 °C, respectively[77]. Tar can be removed by thermal & catalytic cracking, physical separation processes and non-thermal plasmas. Higher temperatures of more than 1100 °C are required for removal of tar through thermal cracking process[101,102]. Calcined dolomites as catalysts have shown removal efficiency of tar by 95%[103]. Similarly olivine (Mg,Fe)SiO4) is found to have increased conversion of carbon in the gasification of recycled polyethylene pellets[104]. In non-thermal plasmas, pulsed corona plasma is quite attractive and is shown to reduce tar at 400 °C[105,106]. Wet scrubbers similar to particulate removal have also shown good capability in tar removal. OLGA technique (a Dutch acronym for oil based gas washer) operates in the range of 60-450 °C removes and reuses tar components[107].

5. Challenges and Hindrances in the Road Map

CFB gasification technology finds tough challenges for its successful exploration and utilization in the country. Prominent among them are: Firstly, CFB systems are generally of very large capacity i.e., 10 to several hundreds of MW capacity and involve a lot of initial capital investment. Secondly, this technology is relatively new to the manufacturers so it will be difficult on their part to manufacture it on mass scale. Thirdly, agricultural lands in the country are of defragmented nature which restricts the use of high mechanization, resulting in reduced efficiency and increased procurement cost of biomass/coal feeds. Fourthly, biomass price is on constant rise after commissioning of new power projects by MNRE, GOI and Government subsidies are not being regulated regularly. Lastly, it is common human mentality that waste is equivalent to ash so they are least bothered about its utilization.

6. Future Scope and Suggestions

With proper planning and step-by-step approach, the task will certainly be accomplished[108]. The actions plan that is recommended to enhance the efficient commercialization of this new technology are: (1) There is always possibility of manufacturing pilot plants for successful demonstration and minor feeds and where requirement is higher one can opt for larger capacities. (2) India has successfully installed downdraft gasifier of different sizes according to the biomass available and its requirement, so the acquired experience in fixed bed gasification should be implemented in the advancement of CFB gasification technology. (3) A common collection point should be made in different local communities to collect the crop waste and biomass. (4) A robust model must be prepared in order to motivate and attract local farmers and entrepreneurs should come forward to supply biomass/crop waste to the processing centers. (5) The places that are far off from CFB gasification plants should be made to supply biomass in the form of pellets which are denser and can be easily transported. (6) There could also be a possibility of growing energy crops in case of crop failure or in marginal and degraded land which includes fast growing grasses like bamboo and napier.

7. Conclusion

In India, the CFB gasification systems can play an important role in effectively harnessing huge potential of available biomass resources to produce useful clean combustible fuel. Off grid use of biomass energy through CFB technology has a wide scope that can contribute towards electrification in the rural areas and in decentralized energy production. In view of this, biomass gasification has already gained greater attention for the generation of fuel gas in recent years due to its reduced emission, near isothermal reactions and better transport rates. The conversion process of biomass has been improved to get tar free fuel gas by using different types of catalysts. For CFB, pre-calcined olivine has shown to have an increased activity for tar reduction in case of air gasification. For steam-oxygen process, pressurized CFB gasification up to 0.4 MPa is found to be stable. Catalytic candles have been shown to reduce tar and increase H2 yield up to two times as compared to non-catalytic filter elements. In near future CFB technology can be adopted to meet the demand of energy with the utilization of low grade fuel resources. Government of India is providing various subsidies to biomass powered plants. Low grade Indian coal can be mixed with biomass materials to reduce net carbon emission to the environment. Use of CFB systems in dual fluidized bed and IGCC can further increase the overall efficiency of plant. Hurdles in the road to mass scale installation of CFB gasifiers includes new gasifier to Indian manufacturers, rise in price of biomass, non-regularity in existing government subsidies and awareness in marginal farmers. These may be overcome by manufacturing mass scale CFB gasifiers in sizes as per requirement, use of experience in down draft gasifiers etc.

8. Acknowledgement

The authors thankfully acknowledge the Director NIT Patna and the Director CSIR-CMERI Durgapur for their continuous support and enthusiasm.

9. References

1. Indian minerals yearbook 2013 (Part- III: Mineral reviews), 52nd Edition, Coal & Lignite, Government of India, Ministry of Mines, Indian Bureau of Mines [Internet]. 2015 Jan. [cited 2016 Apr 03]. Available from: www.ibm.nic.in/writereaddata/files/05262015171116IMYB2013%20IMINE%2001.pdf.
2. Mathur R, Chand S, Tezuka T. Optimal use of coal for power generation in India. Energy Policy. 2003; 31:319–31.
3. Chakravarty S, Mohanty A, Banerjee A, Tripathy R, Mandal GK, Basariya MR, Sharma M. Composition, mineral matter characteristics and ash fusion behavior of some Indian coals. Fuel. 2015; 150:96–101.
4. Biopower India - A quarterly magazine on biomass energy. MNRE-UNDP-GEF biomass power project, Ministry of New and Renewable Energy, Government of India; 2014 Jan-Mar; 1(1).
5. Hiloidhari M, Das D, Baruah DC. Bioenergy potential from crop residue biomass in India. Renewable and Sustainable Energy Reviews. 2014; 32:504–12.
6. Prabhansu MKK, Chandra P, Chatterjee PK. A review on the fuel gas cleaning technologies in gasification process. Journal of Environmental Chemical Engineering. 2015; 3:689–702.
7. Available from: mnre.gov.in/schemes/grid-connected/biomass-powercogen/.
8. UNDP. Study of available business models of biomass gasification power projects under the project. Removal of Barriers to Biomass Power Generation in India, New Delhi: United Nations Development Programme; 2013. 46.
9. Buragohain B, Mahanta P, Moholkar VS. Biomass gasification for decentralized power generation: The Indian perspective. Renewable and Sustainable Energy Reviews. 2010; 14:73–92.
10. Biopower India - A quarterly magazine on biomass energy. MNRE-UNDP-GEF biomass power project. Ministry of New and Renewable Energy, Government of India.2015 Oct–Dec; 1(6).
11. Hadley TD, Doblin C, Orellana J, Lim KS. Experimental quantification of the solids flux in an internally circulating fluidized bed. The 13th International Conference on Fluidization - New Paradigm in Fluidization Engineering, Australia; 2010.
12. Kunii D, Levenspiel O. Fluidization Engineering. Second edition, Butterworth, Heinemann, Reed Publishing: USA; 1991.
13. Basu P, Fraser SA. Circulating fluidized bed boilers, design and operations. Butterworth-Heinemann, Reed Publishing: USA; 1991.
14. Gomez-Barea A, Leckner B. Modeling of biomass gasification in fluidized bed. Progress in Energy and Combustion Science. 2010; 36:444–509.
15. Babu SP. Thermal gasification of biomass. Proc Workshop No. 1: Perspectives on Biomass Gasification, IEA Bioenergy Agreement, Task 33, International Energy Agency, Paris, France; 2006.
16. Prabhansu, Karmakar M, Chandra P, Chatterjee PK. Technological advancement in circulating fluidized bed gasification: Case study. 67th Annual Session of Indian Institute of Chemical Engineers, CHEMCON 2014, Chandigarh, 2014 Dec 27–30; 2014.
17. Liszka M, Malik T, Budnik M, Ziebik A. Comparison of IGCC (integrated gasification combined cycle) and CFB (circulating fluidized bed) cogeneration plants equipped with CO_2 removal. Energy. 2013; 58:86–96.
18. Basu P. Combustion and gasification in fluidized beds. Taylor & Francis Group, LLC; 2006. p. 43.
19. Knowlton TM, Hirsan I. L-valves characterized for solids flow. Hydrocarbon Process. 1978; 3:149–56.
20. Geldart D, Jones P. The behaviour of L-valves with granular powder. Powder Technology. 1991; 67:163–74.
21. Huang W, Xu G, Li H, Kang Z. A mathematical model for the L-valve and its application in matter transfer control. Journal of Huazhong University of Science and Technology. 1995; 23(4):100–4.
22. Wang AB. An experimental study on the characters of solid–gas mixture flow in the L-valve. MS Thesis. Tsinghua University; 1987.
23. Ozawa M, Tobita S, Mii T, Tomoyasu Y, Takebayashi T, Suzuki K. Flow pattern and flow behavior of solid particles in L-valve. In: Basu P, Horic M, Hasatani M, editors. Circulating Fluidized Bed Technology, Vol III, Pergamon, Oxford; 1991. p. 615–20.
24. Zheng Q, Ma Z, Wang AB. Experimental study of the flow pattern and flow behaviour of gas–solid two phase flow in L-valve. In: Avidan AA, editor, Circulating Fluidized Bed Technology, Vol IV, Hidden Valley, USA; 1993. p. 246–52.
25. Rhodes M, Cheng H. Operation of an L-valve in a circulating fluidized bed of fine solids. In: Avidan AA, editor, Circulating Fluidized Bed Technology, Vol IV, Hidden Valley, USA; 1993. p. 240–5.

26. Tong H, Li H, Lu X, Zheng Q. Hydrodynamic modeling of the L-valve. Powder Technology. 2003; 129:8–14.
27. Chong YO, O'Dea DP, Leung LS, Nicklin DJ. Design of standpipe and non-mechanical V valve for a circulating fluidized bed. Circulating Fluidized Bed Technology II. Basu P, Large JF, editors, Pergamon Press. Oxford; 1988. p. 493–500.
28. Basu P, Cheng L. An analysis of loop seal operations in a Circulating fluidized bed. Chemical Engineering Research and Design. 2000 Oct; 78(7):991–8.
29. Basu P, Luo ZY, Boyd M, Cheng LM, Cen KF. An experimental investigation into a loop seal in a circulating fluidized bed. 6th International Conference on Circulating Fluidized Beds, Wurzburg, Germany; 1999 Aug 22–27. p. 805–10.
30. Kim SW, Kim SD, Lee DH. Pressure balance model for circulating fluidized beds with a loop-seal. Industrial & Engineering Chemistry Research. 2002; 41:4949–56.
31. Bareschino P, Solimene R, Chirone R, Salatino P. Gas and solid flow patterns in the loop seal of a circulating fluidized bed. Powder Technology. 2014.
32. Abe T, Gokon N, Izawa T, Kodama T. Internally-circulating fluidized bed reactor using thermal storage material for solar coal coke gasification. International Conference on Concentrating Solar Power and Chemical Energy Systems, Solar PACES 2014. Energy Procedia. 2015; 69:1722–30.
33. Barisano D, Canneto G, Nanna F, Alvino E, Pinto G, Villone A, Carnevale M, Valerio V, Battafarano A, Braccio G. Steam/oxygen biomass gasification at pilot scale in an internally circulating bubbling fluidized bed reactor. Fuel Processing Technology. 2015.
34. Jeon JH, Kim SD, Kim SJ, Kang Y. Solid circulation and gas bypassing characteristics in a square internally circulating fluidized bed with draft tube. Chemical Engineering and Processing, Process Intensification. 2008; 47(12):2351–60.
35. Song BH, Kim YT, Kim SD. Circulation of solids and gas bypassing in an internally circulating fluidized bed with a draft tube. Chemical Engineering Journal. 1997; 682(3):115–22.
36. Ohshita T, Higo T, Kosugi S, Inumaru N, Kawaguchi H. Internal Circulating Fluidized Bed Type Boiler and Method of Controlling the Same. Patent 5138982; 1992.
37. Ohshita T, Nagato S, Miyoshi N, Toyoda S. Pressurized internal circulating fluidized-bed boiler. Patent 5313913; 1994.
38. Fang M, Yu C, Shi Z, Wang Q, Luo Z, Cen K. Experimental research on solid circulation in a twin fluidized bed system. Chemical Engineering Journal. 2003; 943:171–8.
39. Snieders FF, Hoffmann AC, Cheesman D, Yates JG, Stein M, Seville JPK. The dynamics of large particles in a four-compartment interconnected fluidized bed. Powder Technology. 1999; 101(3):229–39.
40. Skone T, James R. Life cycle analysis: Integrated Gasification Combined Cycle (IGCC) power plant, DOE/NETL-4 03/110209. 2010 Sep 30.
41. Rai H, Bharti A, Singh R, Prasad NK. Energy efficient coal gasification for IGCC power plant. International Journal of Innovative Technology and Exploring Engineering. 2013 May; 2(6).
42. Franco A, Diaz AR. The future challenges for "clean coal technologies": Joining efficiency increase and pollutant emission control. Energy. 2009; 34:348–54.
43. Available from: http://www.eai.in/ref/ae/bio/csbg/list_of_installation.html.
44. NNFCC project 09/008. Review of technologies for gasification of biomass and wastes, final report. A project funded by DECC, project managed by NNFCC and conducted by E4Tech; 2009 Jun.
45. Christodoulou C, Tsekos C, Tsalidis G, Fantini M, Panopoulos KD, de Jong W, Kakaras E. Attempts on cardoon gasification in two different circulating fluidized beds. Case Studies in Thermal Engineering. 2014; 4:42–52.
46. Simpson W, Tenwolde A. Physical properties and moisture relations of wood. Wood Handbook, Forest Products Society: Madison, Wis, USA; 1999.
47. McKendry P. Energy production from biomass (part 3): Gasification technologies. Bioresource Technology. 2002; 83(1):55–63.
48. Hai LQ, Guo ZY, Qian CM, Hong MA, He CC. Study on drying and combustion process in grate-CFB incinerator. Science in China Series E: Technological Sciences. 2009 May; 52(5):1153–60.
49. Prins MJ, Ptasinski KJ, Janssen FJJG. More efficient biomass gasification via torrefaction. Energy. 2006; 31(15):3458–70.
50. Kleinschmidt CP. Overview of international developments in torrefaction. Bio-energy Trade, Torrefaction workshop [Internet]. [cited 2016 Apr 06]. Available from: http://www.bioenergytrade.org/downloads/ grazkleinschmidtpaper2011.pdf. 2011.
51. Couhert C, Salvador S, Commandre JM. Impact of torrefaction on syngas production from wood. Fuel. 2009; 88(11):2286–90.
52. Acharya B, Sule I, Dutta A. A review on advances of torrefaction technologies for biomass processing. Biomass Conversion and Biorefinery. 2012; 2:349–69. DOI 10.1007/s13399-012-0058-y.
53. Rapagna SJ, Kiennemann AN, Foscolo PU. Steam-gasification of biomass in a fluidized bed of olivine particles. Biomass Bioenergy. 2000; 19:187–97.
54. Li XT, Gracea JR, Lim CJ. Biomass gasification in a circulating fluidized bed. Biomass Bioenergy. 2004; 26:171–93.
55. Basu P, Biomass gasification and pyrolysis, practical design and theory. Academic Press: Elsevier; 2010.

56. Gates BC, Huber GW, Marshall CL, Ross PN, Siirola J, Wang Y. Catalysts for emerging energy applications. MRS Bulletin. 2008; 33(4):429–35.
57. Pang S, Mujumdar AS. Drying of woody biomass for bioenergy: Drying technologies and optimization for an integrated bioenergy plant. Drying Technology. 2010; 28(5):690–701. DOI: 10.1080/07373931003799236
58. Hanaoka T, Inoue S, Uno S, Ogi T, Minowa T. Effect of woody biomass components on air-steam gasification. Biomass and Bioenergy. 2005; 28(1):69–76.
59. Yang H, Yan R, Chen H, Lee DH, Zheng C. Characteristics of hemicellulose, cellulose and lignin pyrolysis. Fuel. 2007; 86(12–13):1781–88.
60. Garcia-Ibanez P, Cabanillas A, Sanchez JM. Gasification of leached orujillo (olive oil waste) in a pilot plant circulating fluidized bed reactor. Preliminary results. Bio & Bioenergy. 2004; 27:183–94.
61. Guo F, Dong Y. Herb residues gasification in a circulating fluidized bed. Advanced Materials Research. 2012; 549:508–12.
62. Petersen I, Werther J. Experimental investigation and modeling of gasification of sewage sludge in the circulating fluidized bed. Chemical Engineering and Processing. 2005; 44:717–36.
63. Christodoulou C, Grimekis D, Panopoulos KD, Pachatouridou EP, Iliopoulou EF, Kakaras E. Comparing calcined and un-treated olivine as bed materials for tar reduction in fluidized bed gasification. Fuel Processing Technology. 2014; 124:275.
64. Christodoulou C, Grimekis D, Panopoulos KD, Vamvuka D, Karellas S, Kakaras E. Circulating fluidized bed gasification tests of seed cakes residues after oil extraction and comparison with wood. Fuel. 2014; 132:71.
65. Kumabe K, Hanaoka T, Fujimoto S, Minowa T, Sakanishi K. Cogasification of woody biomass and coal with air and steam. Fuel. 2007; 86(5–6):684–9.
66. V´elez JF, Chejne F, Vald´es CF, Emery EJ, Londo˜no CA. Cogasification of Colombian coal and biomass in fluidized bed: An experimental study. Fuel. 2009; 88(3):424–30.
67. Puig-Arnavat M, Burno J, Coronas A. Review and analysis of biomass gasification models. Renewable & Sustainable Energy Reviews. 2010; 14:2841–51.
68. Saxena R, Seal D, Kumar S, Goyal H. Thermo-chemical routes for hydrogen rich gas from biomass: A review. Renewable & Sustainable Energy Reviews. 2008; 12:1909–27.
69. Doherty W, Reynolds A, Kenedy D. The effect of air preheating in a biomass CFB gasifier using ASPEN Plus simulation. Biomass Bioenergy. 2009; 33:1158–67.
70. Guo F, Dong Y, Dong L, Jing Y. An innovative example of herb residues recycling by gasification in a fluidized bed. Waste Management. 2013; 33:825–32.
71. Ponzio A, Kalisz S, Blasiak W. Effect of operating conditions on tar and gas composition in High Temperature Air/steam Gasification (HTAG) of plastic containing waste. Fuel Processing Technology. 2006; 87(3):223–33.
72. Gil J, Corella J, Aznar MP, Caballero MA. Biomass gasification in atmospheric and bubbling fluidized bed: Effect of the type of gasifying agent on the product distribution. Biomass and Bioenergy. 1999; 17(5):389–403.
73. Umeki K, Yamamoto K, Namioka T, Yoshikawa K. High temperature steam-only gasification of woody biomass. Applied Energy. 2010; 87:791–8.
74. Sheeba KN, Babu JSC, Jaisankar S. Steam gasification characteristics of coir pith in a circulating fluidized bed gasifier. Energy Sources, Part A, Taylor & Francis Group. 2013; 35:110–21.
75. Lv P, Xiong Z, Chang J, Wu C, Chen Y, Zhu J. An experimental study on biomass air-steam gasification in a fluidized bed. Bioresource Technology. 2004; 95:95–101.
76. Meng X, Jong W, Fu N, Verkooijen AHM. Biomass gasification in a 100 kWth steam-oxygen blown circulating fluidized bed gasifier. Effects of operational conditions on product gas distribution and tar formation. Biomass and Bioenergy. 2011; 35:2910–24.
77. Christodoulou C, Grimekis D, Panopoulos KD, Vamvuka D, Karellas S, Kakaras E. Circulating fluidized bed gasification tests of seed cakes residues after oil extraction and comparison with wood. Fuel. 2014; 132:71–81.
78. Christodoulou C, Grimekis D, Panopoulos KD, Pachatouridou EP, Iliopoulou EF, Kakaras E. Comparing calcined and un-treated olivine as bed materials for tar reduction in fluidized bed gasification. Fuel Processing Technology. 2014; 124:275–85.
79. Kurkela E, Kurkela M, Hiltunen I. Steam–oxygen gasification of forest residues and bark followed by hot gas filtration and catalytic reforming of tars: Results of an extended time test. Fuel Processing Technology. 2016; 141:148–58.
80. Kurkela E, Kurkela M, Hiltunen I. The effects of wood particle size and different process variables on the performance of steam-oxygen blown circulating fluidized-bed gasifier. Tcbiomass 2013 Conference, 2013 Sep 3–6, Chicago, Illinois, Environmental Progress & Sustainable Energy. 2014 Oct; 33(3):681–7.
81. Asadullah M, Ito SI, Kunimori K, Tomishige K. Role of catalyst and its fluidization in the catalytic gasification of biomass to syngas at low temperature. Industrial and Engineering Chemistry Research. 2002; 41(18):4567–75.
82. Asadullah M, Miyazawa T, Ito S, Kunimori K, Koyama S, Tomishige K. A comparison of Rh/CeO2/SiO2 catalysts with steam reforming catalysts, dolomite and inert materials as bed materials in low throughput fluidized bed gasification systems. Biomass and Bioenergy. 2004; 26(3):269–79.

83. Fantini M, Nacken M, Heidenreich S, Siedlecki M, Fornasari G, Benito P, Leite MAH, de Jong W. Bagasse gasification in a 100 kWth steam-oxygen blown circulating fluidized bed gasifier with catalytic and non-catalytic upgrading of the syngas using ceramic filters. Energy Prod and Man in the 21st Cent, Vol. 2. WIT Transactions on Ecology and the Environment. 2014; 190:1079–90.
84. Chutichai B, Patcharavorachot Y, Assabumrungrat S, Arpornwichanop A. Parametric analysis of a circulating fluidized bed biomass gasifier for hydrogen production. Energy. 2015:1–8.
85. Feng D, Sheng JB, Ji HY, Bin L, Yu S, Yiming W, Yao ZM. Research on the main factors for changes in pressure based on turbulent circulating fluidized bed coal gasification technology. Korean Journal of Chemical Engineering. 2010; 27(6):1707–14.
86. Nagaraja M, Sundaresan R. Gasification of Juliflora chips in a circulating fluidized bed gasifier. International Journal of Engineering and Science. 2013 Apr; 3(2).
87. Vreugdenhil BJ, van der Drift A, van der Meijden CM. Co-gasification of biomass and lignite in the indirect gasifier milena. Pittsburgh Coal Conference. Pittsburgh. USA; 2009 Sep. p. 20–3.
88. Miccio F, Ruoppolo G, Kalisz S, Andersen L, Morgan T J, Baxter D. Combined gasification of coal and biomass in internal circulating fluidized bed. Fuel Processing Technology. 2012; 95:45–54.
89. Hoffmann AC, Stein LE. Gas cyclones and swirl tubes: principles, design, and operation. 2nd ed., vol. xxvi. Berlin, New York: Springer; 2008. p. 422.
90. Atimtay AT. Cleaner energy production with integrated gasification combined cycle systems and use of metal oxide sorbents for H_2S cleanup from coal gas. Clean Technologies and Environmental Policy. 2001; 2(4):197–208.
91. Cummer KR, Brown RC. Ancillary equipment for biomass gasification. Biomass & Bioenergy. 2002; 23(2):113–28.
92. Sharma SD, Dolan M, Park D, Morpeth L, Ilyushechkin A, McLennan K. A critical review of syngas cleaning technologies-fundamental limitations and practical problems. Powder Technology. 2008; 180(1–2):115–21.
93. Schifftner KC, Hesketh HE. Wet scrubbers. 2nd ed., vol. xv. Lancaster, Pa: Technomic. 1996, 206.
94. Smeenk J, Brown RC, Eckels D. Determination of vapor phase alkali content during biomass gasification fourth biomass conference of the Americas: Oakland CA. 2009 29 Aug– 2 Sep.
95. Dayton DC, French RJ, Milne TA. Direct observation of alkali vapor release during biomass combustion and gasification.1. Application of molecular beam/mass spectrometry to switchgrass combustion. Energy Fuel. 1995; 9(5):855–65.
96. Turn SQ, Kinoshita CM, Ishimura DM, Zhou J. The fate of inorganic constituents of biomass in fluidized bed gasification. Fuel. 1998; 77(3):135–44.
97. Trembly JP, Gemmen RS, Bayless DJ. The effect of IGFC warm gas cleanup system conditions on the gas-solid partitioning and form of trace species in coal syngas and their interactions with SOFC anodes. Journal of Power Sources. 2007; 163(2):986–96.
98. Higman C, Burgt MVD. Gasification. 2nd ed., vol. xvi. Amsterdam, Boston: Gulf Professional Pub./Elsevier Science; 2008. p. 435.
99. Sharma SD, Dolan M, Ilyushechkin AY, McLennan KG, Nguyen T, Chase D. Recent developments in dry hot syngas cleaning processes. Fuel. 2010; 89(4):817–26.
100. Baxter LL, Miles TR, Jenkins BM, Milne T, Dayton D, Bryers RW. The behavior of inorganic material in biomass-fired power boilers: field and laboratory experiences. Fuel Processing Technology. 1998; 54(1–3):47–78.
101. Han J, Kim H. The reduction and control technology of tar during biomass gasification/pyrolysis: An overview. Renewable & Sustainable Energy Reviews. 2008; 12(2):397–416.
102. Tregrossi A, Ciajolo A, Barbella R. The combustion of benzene in rich premixed flames at atmospheric pressure. Combust Flame. 1999; 117(3):553–61.
103. Abu El-Rub Z, Bramer EA, Brem G. Review of catalysts for tar elimination in biomass gasification processes. Industrial & Engineering Chemistry Research. 2004; 43(22):6911–19.
104. Mastellone ML, Arena U. Olivine as a tar removal catalyst during fluidized bed gasification of plastic waste. AIChE Journal. 2008; 54(6):1656–67.
105. Nair SA, Yan K, Safitri A, Pemen AJM, van Heesch EJM, Ptasinski KJ. Streamer corona plasma for fuel gas cleaning: comparison of energization techniques. Journal of Electrostatics. 2005; 63(12):1105–14.
106. Nair SA, Pemen AJM, Yan K, van Gompel FM, van Leuken HEM, van Heesch EJM. Tar removal from biomass-derived fuel gas by pulsed corona discharges. Fuel Processing Technology. 2003; 84(1–3):161–73.
107. Zwart RWR, Drift AVd, Bos A, Visser HJM, Cieplik MK, Ko¨nemann HWJ. Oil-based gas washinge flexible tar removal for high-efficient production of clean heat and power as well as sustainable fuels and chemicals. Environmental Progress & Sustainable Energy. 2009; 28(3):324–35.
108. Borisovna SO, Fedorovna ML, Ivanovna KT. Management in the Knowledge Society: Tendencies and Prospects. Indian Journal of Science and Technology. 2016 Mar; 9(12). DOI: 10.17485/ijst/2016/v9i12/89536.