Biomass. Incineration, Pyrolysis, Combustion and Gasification

Abdelmalik M. Shakorfow

Department of Chemical and Petroleum Engineering, Engineering Faculty, Elmergib University, Khmos, Libya

Abstract: In this paper, biomass and its important properties most relevant to biomass gasification are discussed. To generate heat and/or electricity while save the environment, incineration, pyrolysis, combustion and gasification processes have all been tested mainly exploiting biomass. It is aimed in this paper, to discuss these processes with more attention on gasification process being the most efficient and economical process for hydrogen generation. It was found that biomass is a good candidate for gasification process although it has not been utilized enough. Gasification process in comparison to incineration, pyrolysis, combustion processes is the most practical while economical process if hydrogen production and protection of the environment are the main targets.

Keywords: Biomass; incineration; pyrolysis; combustion; and gasification

1. Introduction

Nowadays, although biomass and other wastes, which when employed to generate electricity have given satisfactory results in terms of efficiency of electricity generation and effect on the environment, are ubiquitously available, emphasis on traditional, limited and environmental-harmful fossil fuels to generate electricity still seems a maximal. If not dealt with by some method, biomass and other wastes can be a burden to the environment. Available methods to process such wastes are: incineration, pyrolysis, combustion and gasification. With such methods not only energy can be generated from biomass or other wastes but also the environment becomes cleaner. Equally important, fossil fuels may become among several resources to generate electricity and that not the only available option as currently the case in most regions of the world. According to several studies, biomass has seen several gasification applications. To this end in this paper; therefore, biomass and its important properties most relevant to biomass gasification are discussed. This is; then, followed by the main characteristics of incineration, pyrolysis, combustion and gasification processes. Through the paper, gasification process, in particular, has been given more focus for being widely used for the purpose of heat and/or power generation while little focus was paid to incineration process.

Centuries ago, fossil fuels, which include: coal, oil and natural gas, have been the only available source of energy worldwide. Initially were life standards were simpler, they had met people's demand, perhaps, due to their reserves availability and little consumption. Currently; however, they are not only considered un-sustainable but also, when consumed through combustion, pollutants of a great concern to the environment. In terms of sustainability, fossil fuels reserves may be susceptible to depletion in three generations, if the existing consumption rate of fossil fuels has not been retarded (Boyle , 2004; Kaygusu, K., 2012). In nearly two decades, early 1980s to early 2000s, in Asia/Oceania region, generation of electricity based on fossil fuels was increased four-fold while it doubled worldwide (Takeharu, 2010). In another aspect, in terms of environment pollution, if improperly contained, a huge amount of greenhouse gas emissions annually ejected to the environment is mainly linked to fossil fuels consumption through combustion (Le, et al., 2009; Davis and Caldeira, 2010; Street and Yu, 2011). According to Cassedy, this amount of emissions is estimated at more than 20 billion metric tons per annum (Cassedy, 2000). Increase of fossil fuels prices whether due to geographical, economical, operational or political issues is also an issue. Studies, that highlight the severe dependency of people's daily life on consumption of fossil fuels (Luis, 2007; Jorge, et al., 2008; Ajay, et al., 2009; Andrés, et al., 2009; Abrar, et al., 2010; Hengfu, et al., 2010; Takeharu, 2010; Chawdhury, and Mahkamov, 2011; Ihsan, 2012; Jorge, et al., 2012; Niclas and Claus, 2012; Brandon, 2013; Sharmina, et al., 2013; Thanasit, et al., 2013; Xu, Q., 2013; Chad, 2014; Onursal, et al., 2015, etc.) and emphasize depletion of reserves of such fuels (Venkata, et al., 2008; Jorge, et al., 2012; Sharmina, et al., 2013; Park, et al., 2014; Onursal, et al., 2015, etc.) as well as warn of its environmental burdens (Luis, 2007; Abrar, et al., 2010; Ihsan, 2012; Niclas and Claus, 2012; Sheng and Ying, 2012; Nicholas, 2013; Wu, H., 2013; Chunfei, et al., 2014; Reem, et al., 2014; Zhengfeng, et al., 2014, etc.) are enormous. Taking this into account, looking for sustainable while environmentally-clean energy source(s) becomes an inevitable option.

If sufficiently available, renewable energy supplies have been widely proposed as an alternative to fossil fuels to tackle issues of sustainability and environmental pollution, associated with fossil fuels, or at least mitigate them. Among renewable energy supplies, in addition to biomass, are: tides, wind, solar, hydro, geothermal. Biomass accounts for more than two thirds of the world's renewable energy sources. Biomass is the fourth largest energy resource after the three fossil fuels mentioned previously (Onursal, et al., 2015). In Europe, 56% of energy renewable resources are biomass (Niclas and Claus, 2012). In the United States alone, more than 500 million tones of manure, that's biomass, are produced annually. In addition to this, there is also a huge amount of sewage sludge produced through municipal wastewater treatment units (Gerba and Smith, 2005; US Environmental Protection Agency, 2007). Both biomass and municipal solid waste are continuously and increasingly generated.

Volume 5 Issue 7, July 2016

www.ijsr.net

Licensed Under Creative Commons Attribution CC BY

Paper ID: NOV164715 10.21275/v5i7.NOV164715

13
2. Biomass

Biomass is a broad term; hence, to avoid confusion it might be useful to represent its definition with examples of biomass and some of its properties. Further, main analyses relevant to gasification process usually conducted on biomass along its annual demand and availability are discussed next. 'Any organic substances that are directly or indirectly derived from those plants that are able to conduct photosynthesis process are defined as biomass' (Boyle, 2004). The term biomass covers a broad range of materials that offer themselves as fuels or raw materials and that what they have in common is that they are all derived from recently living organisms. Whereas traditional fossil fuels which also have been driven from plant (coal) or animal (oil and gas) life, but it has taken millions of years to convert to their current forms (fossil fuels) (Higamn and Burgt, 2003). According to Prade (2011), there are two main biomass types: residues and energy carrier production. Residues biomass are those residual materials originate from agriculture and industrial processes. Energy carrier production, as the name implies, are biomasses merely cultivated for energy applications. Biomass is a renewable sustainable energy resource. Its renewability is facilitated by the ability of a plant to store and release carbon dioxide during photosynthesis process and during biomass-to-energy conversion process, respectively. Details of biomass photosynthesis process is available in (Carpentieri, et al., 2005; Demirbas, A, 2009). Depending on biomass type, its composition may differ notably. Typically, a biomass may comprise of the following constituents: cellulose, hemicelluloses, lignin, extractives, lipids, proteins, simple sugars, starches, water, in-organics (ashes) and other compounds. The main constituents of biomass are briefly described elsewhere (Hanaoka, et al., 2005; Gates, et al., 2008; Barneto, 2009). According to biomass origin, composition, production conditions and collection sites, different biomass classes can be identified, refer to Table (1) (Santoanni, et al., 2008; Marcin, et al., 2011; Wu, H., 2013).

3. Properties of Biomass Relevant to Gasification

Owing to its wide range, properties of biomass are different from a biomass to another (Higamn and Burgt, 2003). Accordingly, performance of a certain biomass as a fuel in a gasification process could vary from that performance of another different biomass. In biomass gasification, important biomass properties are: i-moisture content; that is the quantity of the contained water molecules that physico-chemically bond to solid fuel material (biomass) (Xu, Q., 2013). It ranges from 10% up to 50-70% for cereal grain straws and forest residues, respectively (Alok D. and Gupt .V.K., 2014). Maximum allowed moisture content of a biomass differs with respect to the gasifier type used for gasification. For instance, although a downdraft gasifier can give a satisfactory result when the moisture content of the biomass gasified is no higher than 30-40% on a dry basis, an updraft gasifier can cope with quite higher moisture contents (Dogru, et al., 2002; Venkata , et al., 2008). Entrained-bed gasifiers are sensitive to moisture content in a biomass as moisture may inhibit the overall gasification reactions (Robert, et al., 1992). High moisture content of a biomass can be a problematic property and may disqualify it from been economically gasifiable. With excessive biomass moisture content, energy required for drying and that energy of the produced syn gas may be comparable rendering gasification process is not economically feasible (Maker, T. M., 2004; Onursal, et al., 2015). High moisture content in a biomass (more than 40 wt%) reduces the thermal efficiency of gasification system (Hosseini, et al., 2012). Loss of heat is as a result of using available gasification heat to heat up the moisture down from ambient temperature up to the required temperature for drying (around 100 °C), to heat up the steam generated following drying up to the high temperatures required for gasification. Latent heat of vaporization can also be lost from the drying up to the high temperatures required for gasification system (Singh RN., 2004). A make up heat to the gasification system is; then, required, of-course at an additional cost. It should not be understood; however, that complete drying, in order to avoid heat loss(es) during gasification, is desirable. In fact, a minimum amount of no more than 40 wt% of moisture content in biomass is beneficial to the gasification system as will be briefly explained next and also to avoid or at least minimize costs associated with drying (Xu, et al. 2008; Dong, et al., 2010). Cost of drying includes cost of drying equipment as well as cost of energy (heat) used for drying (Asadullah, M., 2014). Remaining moisture within biomass following its drying can be converted into steam by the aid of heat generated while gasification. This steam can act as a gasification agent which can react with volatiles generated during gasification as well as with char to produce syn gas and also it can enhance the production of hydrogen that produced through water-gas shift reaction (Lv, et al., 2007; Yan, et al., 2010), ii-an important property of biomass in gasification processes is the ash content. This ash is the solid residue produced in a gasification process by combustion. This ash; however, is undesirable and its formation through gasification should be avoided. Formation of ash reduces the energy content of biomass, the fuel to gasification. Exposing to high temperatures near its melting point followed by cooling, ash can react forming slag. Downdraft gasifiers, in particular, are sensitive to slag formation as slag can obstruct the flow of

Table 1: Main Classes of Biomass*:

| No. | Class                  | Such as:                                      |
|-----|------------------------|-----------------------------------------------|
| 1-  | Forest products        | Wood, logging residues, trees, shrubs and wood residues, sawdust and bark, etc. |
| 2-  | Bio-renewable residues | Agricultural wastes, crop residues, mill wood wastes, urban wood wastes and urban organic wastes |
| 3-  | Energy crops           | Short rotation woody crops, herbaceous woody crops, grasses, starch crops, sugar crops, forage crops and oil seed crops |
| 4-  | Aquatic plants         | Algae, water weed, water hyacinth, reed and rushes |
| 5-  | Food crops             | Grains and oil crops |
| 6-  | Sugar crops            | Sugar cane, sugar beets, molasses and sorghum |
| 7-  | Landfill               | Waste materials |
| 8-  | Industrial/organic wastes | Chemical solvents, paper products, sandpaper, paints and industrial by-products |
| 9-  | Algae, kelps, lichens and mosses | Algae, kelps, lichens and mosses |

*Adapted from: Marcin, et al., 2011.
In accordance to the recent statistics, shown in Table (2), made by Sims and others in 2007 on the energy demand and availability of main renewable resources on an annual basis in the year 2005; implementation of renewable energy resources for energy production applications seems limited in spite of their wealth availability (Sims, et al., 2007). On the contrary; however, their traditional cooking and heating applications are otherwise. This applies not only on hydro, wind, geothermal and solar but also on biomass, part of the focus of this paper. Current total demand of these renewables in 2005 was not more than 6.5 % of the estimated total available. Estimated biomass availability was 250 EJ while the rate of use for energy production purposes was surprisingly only 9 EJ while rate of use of biomass for traditional cooking and heating applications was nearly fourfold, at 37 EJ. In another more recent separate study, it was reported that energy production in the Czech Republic was 4 % based on renewables. Biomass alone was the most renewable resource used (Marek, et al., 2012).

4. Incineration, Pyrolysis, Combustion and Gasification

Traditionally, these wastes (biomass and other wastes) have been mainly dealt with through landfilling. With landfilling; however, a number of environmental problems have been reported. In a study by Wu , H. (2013), these environmental problems were: pollution of surface water with phosphate compounds, nitrogen and phosphorus originally contained in the animal waste, pollution of the surroundings through generated odours, greenhouse emissions and some metals such as copper, zinc and arsenic (Otero et al., 2010). Further, excessive landfilling results in soil, water and air quality degradation (Larney and Hao, 2007). In one line, to save the environment and in another line due to depletion of fossil fuels, alternative strategies for power generation were; therefore, a necessity. Among these strategies were processes including: thermo-chemical, bio-chemical, and physicochemical pathways (Brunner et al., 2004; Porteous, 2005; Psomopoulos et al., 2009, Huang et al., 2011, Marek and Tomasz, 2012; Xu, Q., 2013). Apart from the thermo-chemical processes, no other process is further considered throughout this paper.

| Renewable resource | Estimated availability, EJ | Rate of use (2005), EJ |
|--------------------|--------------------------|-----------------------|
| Hydro              | 62                       | 25.8                  |
| Wind               | 600                      | 0.95                  |
| Biomass            | 250                      | 46                    |
| Geothermal         | 5000                     | 2                     |
| Solar (PV)         | 1600                     | 0.2                   |
| Total              | 7512                     | 75                    |
| Current demand     | 490                      |                       |

* = including 37 EJ of traditional biomass use (heating and cooking)

In general, thermo-chemical processes employ higher temperatures than those employed in bio-chemical or physicochemical processes. Also, thermo-chemical processes can efficiently handle different types of solid wastes as well as mixed waste.
biomasses with a sound higher conversion rates than that may be obtained via another conversion process. A list of most important advantages of thermo-chemical processes is included within this review. Thermo-chemical processes include: incineration, combustion (full oxidation) (Overview of DOE’s Gasification Program, U.S. Department of Energy, 2009), pyrolysis (partial gasification) (Basu, P., 2006), and gasification (Xu, Q., 2013) (partial oxidation) (Overview of DOE’s Gasification Program, U.S. Department of Energy, 2009). Incineration which perhaps due to lower thermal efficiencies and higher greenhouse gas emissions than combustion has not found a worldwide application. Of these greenhouse gas emissions that may generate from an incinerator are: SO₂, NOₓ, HCl, HF, polyaromatic hydrocarbons (PAH), polychlorinated biphenyls (PCB), dioxins and furans with a wide range of heavy metals (Jaeger and Mayer, 2000; Jorge, et al., 2008) which are carcinogenic and toxic chemicals. In fact, in some developed countries like United States incineration has been banned. Although with newer incinerators, emissions may be lower; however, gas cleaning system is too costly (Jorge, et al., 2008). In response to this and to the public concern over incineration process due to its risky emissions, incineration process has been limited in use and scarce information in the literature is available on it; thus, will not be considered further through this article. In a thermo-chemical process, one or more process of these three processes, excluding incineration, is used as the case with gasification process in which combustion, pyrolysis, and gasification are all used, although the process is totally termed gasification. In combustion process, in the presence of an excess air more than what's chemically required, chemical energy is converted into heat along with CO₂ and H₂O as by-products while reducing the volume of the original waste (Otero et al., 2010). In combustion, excess air is required to boost the fuel efficiency and to avoid the formation of very toxic carbon monoxide and soot (Alok D. and Gupta V.K., 2014). In a pyrolysis process, a biomass is decomposed thermally but in no oxygen environment. Gasification process sits in the middle between these two processes as it involves using a limited rather controlled amount of an oxidant of many available oxidants such as: air, oxygen, steam or a combination of air with steam or a combination of air with oxygen, at different air compositions (Mansaray and Ghaly, 1999; Thiruchitrambalam, 2004; Ro et al.; 2009; Wang et al.; 2011; Sharmina, et al., 2014). Gasification technology goes back to nearly 200 years ago (Wu, H., 2013). It has been in use since the World War II (WWII) where millions of vehicles in Europe, in particular, were equipped with gasifiers as a source of fuel by means of a synthetic gas (Egloff, 1943; Marcin, et al., 2011; Wu, H., 2013). Further historic details on gasification process can be found in a study by Gert Hendrik Coetzee (Gert Hendrik Coetzee, 2011). This; however, as a result of fossil fuel prices decrease at a time, did not last where fossil fuels took over from gasification. Later, due to various reasons some of which were geographical, economical, operational and not surprisingly political, prices of fossil fuels increased again. Further, due to concerns over depletion of fossil fuels as well as concerns over their associated greenhouse gases emissions, gasification process is currently turned out to be prevalent yet again. Gasification utilizes the chemical energy held in a biomass waste converting it into chemical product(s) and sensible energy of its produced gas. In terms of carbon content, a pyrolysis process produces much more carbon than gasification process (Kezhen, et al., 2013). Deciding a suitable process among pyrolysis, combustion, or gasification for a certain biomass is mainly determined by the components of the biomass (McKendry, P., 2002).

Main advantages of thermo-chemical processes together (pyrolysis, combustion and gasification) are: i- great reductions of waste, preserving a landfill space. Reductions of 70-80% in mass and 80-90% in volume of waste have been reported (Consonni et al., 2005), ii- huge savings in land use compared to landfilling. A piece of land required to construct a thermo-chemical plant to process a certain quantity of waste is drastically smaller than that required for landfiling of similar quantity of waste. It has been estimated that to process 1 Mt/y of waste for a 30 years period of time, in a waste-to-energy plant, less than 100000 m² of land is required. Landfilling of 30 Mt of the same waste; however, requires 3000000 m³ (Psomopoulos et al., 2009), iii- instead of releasing organic pollutants, e.g. halogenated hydrocarbons into the atmosphere or into the earth as the case with landfiling, in gasification; nevertheless, they are destructed and disposed of (McKay, 2002). Alternatively, they can be safely used through concentration and immobilization (ISWA, 2008; Samaras et al., 2010), iv- recyclable materials such as ferrous and non-ferrous metals that may come out of a thermo-chemical process can be utilized (ISWA, 2006; CEWEP, 2011), v- in terms of greenhouse gas emissions, a thermo-chemical process releases less emissions than landfiling. In a study by Psomopoulos and others, it was estimated that landfiling of a waste produces 1 ton of CO₂ emissions more than if the same amount of waste has been combusted (Psomopoulos et al., 2009), vi- in general, due to severe emissions regulations imposed, thermo-chemical processes, gasification in particular, are characterized with better environmental performances resulting in less environmental impact compared to other energy processes (US-EPA, 2003; Rechberger and Scholler, 2006) and vii-particularly if a combined heat and power plant has been used, it is possible to environmentally exploit the renewable energy contained within the waste (Rechberger and Scholler, 2006). What discussed next is a comparison between the various thermo-chemical processes: pyrolysis, combustion and gasification. This is; then, followed by a deeper focus on gasification process, the topic of this review.

4.1 Pyrolysis, Combustion and Gasification

Main characteristics of pyrolysis, combustion and gasification processes are contained in Table (3) (Arena and Mastellone, 2009; Marcin et al., 2011). Gasification process is further considered next. As included in the Table (3), in pyrolysis, solid waste (biomass) is thermally decomposed to gases (CO, CO₂ and CH₄) and condensable volatile liquid tars (bio-oil) (Nor et al., 2007; Wang et al., 2008; Isack, 2012; Alok D. and Gupta V.K., 2014). This oil can limit the use of pyrolysis process due to some difficulties that may encounter in its downstream processing and its little use (Wang et al., 2008; Xu, Q., 2013). Products of a pyrolysis process depend on pyrolysis operation environment of temperature, pressure, heating rate and residence time (Nor et al., 2007; Xu, Q.,
Pyrolysis employs temperatures between 500 and 800 °C; combustion between 850-1200 °C while gasification, depending on feed stock and gasifying agent, employs temperatures between 550-900 °C with air-gasification, 1000-1600 °C with other gasification agents (Abrar, et al., 2010; Marcin, et al., 2011; Sharmina, et al., 2013; Reem, et al., 2014; Sharmina, et al., 2014). Regarding char production, pyrolysis process produces more char than what gasification process does. In the latter process, only nearly 10% from the total products is char (Kezhen, et al., 2013). They all employ atmospheric pressure, although pyrolysis may employ higher pressure. In a study by Marcin and his co-workers (Marcin, et al., 2011) higher pressures were suggested for better gasification results. Initially, with pressurized gasification conditions volumetric gas flow rate can be reduced for which a smaller gasifier as well as compact cleaning equipment can be used (Higman and Burgt, 2003). Also, better reaction rates and higher methane yield while lower tar yield can be achieved at pressurized conditions. Having said this; however, it should also be mentioned that design and operation of a gasifier at pressurized conditions require some additional precautions (Marcin, et al., 2011). In terms of chemicals synthesis and energy generation, liquid products produced by pyrolysis process can be up-graded to a liquid fuel while gaseous products can be used as a fuel gas (Xu, Q., 2013). Heat generated out of a combustion process can be used to provide heat or generate electricity or both (co-generation of heat and electricity). Fuel gas generated from a gasification process can be used as a fuel gas or can be used to generate heat and/or electricity or to synthesize chemicals, provided that it has been adequately cooled and cleaned. It should be noted that pyrolysis, combustion and gasification all generate pollutants of particulates and compounds of chloride, nitrogen and sulfur. In addition to these pollutants tars are also generated by both pyrolysis and gasification processes; combustion products are; however, free from tars. As a result of these pollutants out of pyrolysis, combustion and gasification processes cleaning is usually required.

Table 3: Main Characteristics of the Three Thermo-chemical Fuel Conversion Processes, Modified from (Arena and Mastellone, 2009) and (Marcin et al., 2011)

| Process       | Pyrolysis | Combustion | Gasification |
|---------------|-----------|------------|--------------|
| Main products | oil, tar (liquid/vapour), CO₂, H₂O, combustible gas(es) as: CO₂, H₂, CH₄ and char. | heat, flue gas and gases as: CO₂, H₂O, N₂, | gases as: CO₂, H₂O and N₂ (in case air was the gasifying agent), heat, tar and combustible gas(es) as: CO₂, H₂ and CH₄. |
| Heat supply   | allo-thermal. | exothermal. | allo/auto-thermal. |
| Carbon conversion, % | ~75. | 99. | 80-95. |
| Oxygen stoichiometry | Nil. | >1, typically 1.3 for solid fuels. | 0-1, typically 0.2-0.4. |
| Chemical reactivity of main product | reactive, combustible. | non-reactive. | stable, combustible. |
| Physical existence | solid, liquid and gas. | gas. | gas. |
| High heating value (HHV), MJ/kg | 16-19. | Nil. | 5-20. |
| Oxidant      | none. | air. | air, pure oxygen, steam or their combinations. |
| Operating temperature, °C | 500-800. | 850-1200. | 550-900 with air gasification. 1000-1600 with other gasifying agents. |
| Operating pressure | higher than or atmospheric. | atmospheric. | atmospheric. |
| Pollutants   | particulates, tars and compounds of chloride, nitrogen and sulfur. | particulates and compounds of chloride, nitrogen and sulfur. | particulates, tars and compounds of chloride, nitrogen and sulfur. |
Simultaneously considering gasification and combustion processes, several features could be identified. Initially, in a gasification process it is aimed to produce a gas, syn gas, which can be considered to be an intermediate outcome of the process. Provided that it has been adequately treated, this syn gas can; then, be passed to a heat or power generation appliance or a combined one (cogeneration of heat and power) in which it is combusted, a unit for poly-generation of a range of chemical(s) such as: steam, sulfur, methanol, ammonia, etc. (Edward, et al., 2007) or to a unit of fuel production, e.g. hydrogen (the primary emphasis in biomass gasification (Barban, G. and T. Vald'es-Sols, 2007, Wu, H., 2013;)) or gasoline, etc. through Fischer-Tropsch reactions) (Huang, et al., 2012; Nguyen, et al., 2012; Yin, et al., 2012). In a classical combustion process; however, the merely aim is to have the concerning feedstock of solid waste (e.g. biomass) combusted although it is also possible to generate heat and steam by which heat and/or electricity can be generated via a steam turbine or via a gas turbine, respectively (Marcin et al., 2011). It is; then, obvious that gas of gasification, being a gaseous material in nature, can be transported, stored and controlled much simpler than a solid waste of any nature (Devi et al., 2003; Erich, E, 2007; Ajay, et al., 2009; Ajay, et al., 2010). It is also for this reason a small gasifier with an economical feasibility can be built but not a small combustion unit (Consongni and Vigano, 2010). In case gasification process is carried out with air as a gasifying agent, required temperature for gasification reactions may be lower than that employed in a combustion process, refer to Table (3). In fact, this might inhibit gasifier's bed agglomeration, fouling and slagging and also volatilization of alkali compounds which can be promoted by a higher temperature (Paula, et. al., 2012). Also, heat loss in gasification is lower while energy production rates are better compared to those encountered and obtained from combustion, respectively (Lisy, et al., 2009). A comparison of the solid fuel combustion and gasification processes in terms of overall conversion efficiency and heat loss was made by Marcin, and his colleagues, for whom the reader is directed (Marcin, et al., 2011). Although both gasification and combustion processes do generate pollutants, amount and nature of these pollutants may be lower while simpler in the former process than in the latter one (Consongni and Vigano, 2010), perhaps due to the predominant reducing atmosphere imposed in gasification process (Consongni and Vigano, 2010). In combustion; however, synergic action of high temperatures and excess air required for combustion reactions results in an increased amount of emissions (Ajay, et al., 2009 ;). For further distinctive features of both gasification and combustion processes including main reactions, the reader is directed to a study made by Ronald, W. (Ronald, W., 2010).

4.2 Gasification

Gasification is a thermo-chemical process in which a solid waste is converted into a fuel generally known as producer or synthetic (syn) gas. The conversion process is aid by indirect combustion (thermo), in which oxidation is partial, as well as by a series of chemical reactions (chemical). The oxidant/oxidation medium, which is synonymously termed gasification agent, is allowed to the gasification system in an amount less than that obliged by the stoichiometry of combustion reactions. Required heat can be self-supplied internally or can be provided from an external source. Internal heat (auto-thermal) required for gasification process can be facilitated through the heat generated by partly combusting the waste (fuel) undergoing gasification. An example of auto-thermal gasification is air gasification. In a gasification system operated in an auto-thermal approach, heat required for tars thermal cracking and for devolatilized solid char gasification is internally supplied as a result of those exothermic partial oxidation reactions. With this approach it is also possible to maintain isothermal operation of the gasifier. When heat is granted via an external source, gasification is known as allo-thermal, e.g. plasma torch gasification. Heat can also be supplied by using a hot-bed material or by combusting a quantity of the chars or gases separately. In either scenario, produced syn gas is different than the hot flue gas, that has no residual heating value (Higman and Burgt, 2003), usually obtained via usual direct combustion. It is a hot fuel gas rich with products that have been partly oxidized and thus far possess a calorific value. This calorific value is what, partly, grants a value to the produced syn gas to be mainly exploited for heat/power generation. Products of syn gas originate from the organic matter of the gasified waste and mainly may include carbon monoxide, hydrogen and some methane. Carbon monoxide and hydrogen in a syn gas also grant a value to syn gas as being row materials for the production of some chemicals and fuels (Heermann et al., 2001; E4tech, 2009; Stantec, 2010; Young, 2010). In fact, syn gas obtained through gasification, compared to conventional combustion, can be used for multiple applications. Of these are: combustion in a burner for heating purposes, power generation through a steam turbine or also power generation through a gas engine, a gas turbine or a steam turbine (Hanaoka, et al., 2010). Advantages and disadvantages of each appliance of these appliances along the level of syn gas cleaning required for each appliance were discussed by Arena and Mastellone (2009) and also by Arena and others (2011) (Arena and Mastellone, 2009; Arena et al., 2011). This wide spectrum of applications of syn gas obtained via gasification may return to the diversity of its composition as a result of wide range of operating conditions of temperature, equivalence ratio (ER) and/or steam to biomass ratio (SBR), in case steam has been used as a gasifying agent, etc., possible to manipulate in a gasification process. The wide range of available reactors for gasification process can also contribute towards alteration(s) of syn gas composition. Different reactors produce a syn gas of different compositions owing to their configurations, internal details and capacities, etc. In addition to carbon monoxide, hydrogen and some methane, a syn gas may also carry some contaminants such as alkali, nitrogen and sulfur compounds, tar, particulates/dust and trace of chlorine (Heermann et al., 2001; Knoef, H., 2005).

The main emphasis in biomass gasification is the production of hydrogen. Considering current energy resources and those ones under scrutiny, hydrogen can be a successful candidate as an energy carrier for a cleaner future. Hydrogen can be generated by a number of processes such as: pyrolysis (Abrar, et al., 2010), electrolysis thermolysis, combustion and gasification (Sandi, et al., 2001), based on several feed stocks

Volume 5 Issue 7, July 2016

www.ijsr.net

Licensed Under Creative Commons Attribution CC BY
such as: water, fossil fuels and various types of biomass, etc. (Sandi, et al., 2001). A common feature of these feed stocks is that they all contain a hydrogen source. This is required since hydrogen is not a naturally generated species; hence, it has to be generated from a hydrogen-containing stock (Luis, 2007). Among these processes and feed stocks, gasification has been reported to be the most efficient and economical choice for hydrogen generation (Abrar, et al., 2010; Wu, H., 2013) and biomass as the most beneficial fuel for hydrogen generation (Shanmughom, et al., 2014), respectively. Upon combustion, energy released by hydrogen exceeds the energy that may be released by any other fuel (Marban, G. and T. Valdés-Solís, 2007). Since the main emphasis in biomass gasification is the production of hydrogen, those factors may affect gasification can be related to the yield and quality of hydrogen from a gasification process, e.g. feed stock composition, biomass moisture content, type of gasifier used and gasification agent and its amount, etc. If hydrogen is sufficiently available, its utilization as an energy carrier, either as a fuel for transportation, fuel for power generation or for industrial applications, does not create those problems usually caused by combustion of fossil fuels related to global warming and its emissions (Woodrow and Clark, 2006; Shanmughom, et al., 2014).

Due to advantages of gasification technology over other thermo-chemical and non-thermo-chemical processes, gasification technology has seen increased applications in terms of waste management for the purpose of heat or power production. Variety of feed stocks available for gasification technology is tremendous. Dairy manure (Wu, H., 2013), densified sludge and wastewater (George, et al., 1995), oil palm fronds (Samson, et al., 2014), spent poultry litter, municipal solid wastes (MSWs), green waste, wood waste and coffee beans husks (Sharmina, et al., 2013), solid waste (Sharmina, et al., 2014), corn stover and distillers grains (Ajay, et al., 2010), wood (FAO forestry paper, 1986), combined biomass and coal (Xu, Q., 2013), coal (Ihsan, 2012), sewage sludge (Dogrul, et al., 2002; Calvo, et al., 2013), crop straw (grains, oil-bearing crops, cotton, hemp and sugar crops)(Zhengfeng, et al., 2014), sugarcane bagasse (Anthony, et al., 2014), agricultural residues, forestry residues, wood, animal manures, switch grass, sorghum and red cedar (Kezhen, et al., 2013), bamboo (Thanasit, et al., 2013), algae (Muhammad, et al., 2014), cashew nut shell char (Venkata, et al., 2008) and equally important refinery sludge (Reem, et al., 2014), etc. One can observe that such feed stocks are all waste of low-value but massive in amount. Furthermore, if improperly dealt with it can create a burden to the environment. In fact, via gasification such feed stocks can be turned into useful product such as heat, electricity or both heat and electricity as well as into a transportation fuel. It is not out of the ordinary such various biomasses hold different physical, chemical and/or morphological properties. To this end, different biomasses may demand different gasification processes and arrangements. By way of example, not exhaustive enumeration, several gasification investigations of several different feed stocks have been carried out. Young and Pian (2003), examined the possibility of incorporating an advanced gasifier to enhance the operation of a dairy farm for the purpose of power production based on biomass conversion (Young and Pian, 2003). Priyadarsan and his co-workers studied the gasification of feedlot manure and poultry litter biomass in a fixed bed gasifier (Priyadarsan et al., 2004). Adiabatic fixed bed gasification of dairy biomass waste using steam and air as a gasification agent was also carried out by Gordillo and Annamalai (2010) (Gordillo and Annamalai, 2010). Wu, H. (2013) has studied the gasification of dairy manure and feedlot manure biomasses. It should be emphasized that properties of each feed stock of these may vary which in turn may lead to the production of different products including chars subsequent to a gasification process (Kezhen, et al., 2013). Advantages of gasification technology include: i- adaptability of most gasifiers to most wastes in terms of size, shape and physical characteristics. Corn stover, municipal solid waste, sawdust, soybeans and wood, etc. are all common feed stocks for biomass gasification of which their particles sizes as well as their other physical characteristics are not necessarily uniform. ii-shorter conversion time of the processed feedstock into a fuel than anaerobic digestion, iii-energy efficiency obtained via gasification process is much higher than those obtained via pyrolysis or combustion processes (Faaij et al., 1997; Stiegel and Maxwell, 2001; Ajay, et al., 2009; Rentizelas et al., 2009; Xu, Q., 2013). A reason of high efficiency in gasification process is that combustion step is performed through several stages not in one single stage as the case with combustion process (Ihsan, 2012). Also, use of such advanced technologies such as fuel cells and turbines to process the syn gas obtained from a gasification process can also increase the energy efficiency (Sipilä, K., 1993), iv-in addition to the great variety of feed stocks available for gasification, syn gas of gasification can also be employed for a number of important practical applications including: heat and/or power generation or both (combined heat and power, CHP) and synthesis of some chemicals. Synthesis of chemicals based on gasification's syn gas is based on the content of syn gas of gases such as CO and H2 (C1 chemistry). Such chemicals include: ammonia, urea, resins, methanol, acetic acid, formaldehyde, oxo-alcohols, etc. (Higman and Burgt, 2003), v- furthermore, according to end-line application(s), composition of gasification syn gas can also be controlled through changing operating condition(s), gasification agent, etc. (Xu, Q., 2013), vi-destruction of pathogens and pharmaceutically active compounds due to high temperatures employed and vii-low to zero fugitive gas emissions, that's environmentally friendly (Rajvanshi, 1986; Cantrell et al., 2007; Whitty and Zhang, 2008; Ajay, et al., 2009; Wang, 2013; Wu, H., 2013). One reason of low emissions in gasification process is that combustion step is performed through several stages not in one single stage as the case with combustion process (Ihsan, 2012). Although, out of gasification process there is an amount of CO2 emissions may be emitted to the atmosphere, theoretically; however, this amount is equal to the amount of CO2 that was required for biomass growth prior to the gasification process. To this end, throughout carbon cycle on the earth, it can be inferred that there will be no additional CO2 emissions to the atmosphere (Jingjing, et al., 2001, Panigrahi et al., 2003, L. et al., 2007, Ajay, et al., 2010; Sharmina, et al., 2013). Also, emissions of NOx and SOx out of a gasification (a reduced-oxygen environment) process are much lower than those released from burning of a fossil fuel...
through a combustion process (Boyel, 2004; Jorge, et al., 2008). Once a biomass, that's a solid phase, has undergone a gasification process, it is; virtually has been converted and; of-course, so its constituents (nitrogen and sulfur containing compounds, etc.) into the gas phase in full with the exception of some solid residues, perhaps. Such a phase conversion renders separation of whatever undesired constituent(s), that's in the gaseous phase, an easier task (Rezaian and Cheremisinoff, 2005). Consequently, formation of their corresponding NOx and SOx during the combustion step through gasification can be avoided or at least minimized; hence, reducing the amount of those dangerous emissions in the environment (Ajay, et al., 2010).

5. Conclusions

Dependence on traditional, limited and environmental-harmful fossil fuels to generate electricity should be diminished. Biomass could be an alternative to such fossil fuels to generate electricity, although via different routes, e.g. incineration, pyrolysis, combustion. In terms of hydrogen production, biomass is a good candidate for gasification process in comparison to incineration, pyrolysis, combustion processes. Biomass exploitation for the purpose of power generation; nevertheless, has not been enough as it should. Gasification-based syn gas can be used for several applications such as: combustion in a burner for heating purposes, power generation through a steam turbine or also power generation through a gas engine, a gas engine or a steam turbine. Versatility of products obtained via gasification process is also another advantage of gasification process over combustion process.

References

[1] Abrar Inayat, Murni M. Ahmad, Suzana Yusup and Mohamed Ibrahim Abdul Mutalib. Biomass Steam Gasification with In-Situ CO2 Capture for Enriched Hydrogen Gas Production: A Reaction Kinetics Modelling Approach. Energies 2010, 3, 1472-1484; doi:10.3390/en3081472.

[2] Ajay Kumar, David D. Jones and Milford A. Hanna. Thermochemical Biomass Gasification: A Review of the Current Status of the Technology. Energies 2009, 2, 556-581; doi:10.3390/en20300556.

[3] Ajay Kumar, David D. Jones and Milford A. Hanna. Thermochemical Biomass Gasification: A Review of the Current Status of the Technology. Energies 2009, 2, 556-581; doi:10.3390/en20300556.

[4] Ajay Kumar, Yasar Demirel, David D. Jones and Milford Hanna. Optimization and economic evaluation of industrial gas production and combined heat and power generation from gasification of corn stover and distillers grains. 2010. Published in Bioresource Technology 101:10 (May 2010), pp. 3696–3701; doi:10.1016/j.biortech.2009.12.103.

[5] Alok Dhaundiyal and Dr.V.K. Gupta (2014). The Analysis of Pine Needles as a Substrate for Gasification, HYDRO NEPAL ISSUE NO. 15 JULY, 2014.

[6] Andrès Melgara, Juan Pérezb, Alfonso Horrilloc (2009). Biomass gasification process in a downdraft fixed bed gasifier: a real time diagnosis model based on gas composition analysis. Antioquia N.º 49. pp. 9-18.

[7] Anthony Anukam, Sampson Mamphweli, EdsonMeyer, and Omobola Okoh (2014). Computer Simulation of the Mass and Energy Balance during Gasification of Sugarcane Bagasse. Journal of Energy. Volume 2014, Article ID 713054, 9 pages.

[8] Arena U. and Mastellone M.L. (2009). Fluidized bed gasification of RDF and PDF. AMRA Scientific Report. ISBN 978-88-89972-10-6 (in Italian, with an executive summary in English), available at: www.amracenter.com, Accessed on: 12.May.2016.

[9] Arena, U., Di Gregorio, F., Amorese, C., Mastellone, M.L., 2011. A techno-economic comparison of fluidized bed gasification of two mixed plastic wastes. Waste Management 31, 1494–1504.

[10] Asadullah Mohammad. Barriers of commercial power generation using biomass gasification gas: A review (2014). Renewable and Sustainable Energy Reviews, vol. 29, pp: 201–215.

[11] Barneto, A.G.; Carmona, J.A.; Gálvez, A.; Conesa, J. Effects of the composting and the heating rate on biomass gasification. Energy Fuels 2009, 23, 951–957.

[12] Basu, P., 2006. Combustion and Gasification in Fluidized Beds, Taylor & Francis Group, CRC Press, London.

[13] Boyel, G. (2004). Renewable energy. Oxford; New York: Oxford University Press in association with the Open University.

[14] Brandon Jay Hathaway. Solar Gasification of Biomass: Design and Characterization of a Molten Salt Gasification Reactor (2013). Ph D thesis, University of MINNESOTA.

[15] Brunner, P.H., Morf, L., Rechberger, H. (2004). Thermal waste treatment – a necessary element for sustainable waste management. In: Twardowska, Allen, Kettrup, Lacy (Eds.), Solid Waste: Assessment, Monitoring, Remediation. Elsevier B.Y, Amsterdam, The Netherlands.

[16] Calvo, L. F., A. I. García, and M. Otero (2013). An Experimental Investigation of Sewage Sludge Gasification in a Fluidized Bed Reactor. The Scientific World Journal. Volume 2013, Article ID 713054, 9 pages. http://dx.doi.org/10.1155/2013/713054. Hindawi Publishing Corporation.

[17] Cantrell, K., Ro, K., Mahajan, D., Anjom, M., & Hunt, P. G. (2007). Role of thermochemical conversion in livestock waste-to-energy treatments: Obstacles and opportunities. Industrial and Engineering Chemistry Research, 46(26), 8918-8927.

[18] Carpentieri, M.; Corti, A.; Lombardi, L. Life cycle assessment (LCA) of an integrated biomass gasification combined cycle (IBGCC) with CO2 removal. Energy Convers. Manage. 2005, 46, 1790–1808.

[19] Cassedy, E. S. (2000). Prospects for Sustainable Energy: A Critical Assessment. Cambridge; UK: University Press
fluidized bed air gasification of sawdust. *Bioresour. Technol.* 2012, 110, 670–675.

[52] Huang, Y. F., Kuan, W. H., Chiueh, P. T. & Lo, S. L. (2011). A sequential method to analyze the kinetics of biomass pyrolysis. *Bioresource Technology* 102(19): 9241–9246.

[53] Ihsan Mert Sarigul. MODEL-BASED ESTIMATION OF ADIABATIC FLAME TEMPERATURE DURING COAL GASIFICATION (2012). Ph D thesis, University of Utah.

[54] Isack Amos Legonda. BIOMASS GASIFICATION USING A HORIZONTAL ENTRAINED-FLOW GASIFIER AND CATALYTIC PROCESSING OF THE PRODUCT GAS (2012). Ph D thesis, Cardiff University.

[55] ISWA 2006. Management of Bottom Ash from WTE Plants, ISWA-WG Thermal Treatment Subgroup Bottom Ash from WTE-Plants, available at: [www.iswa.org](http://www.iswa.org). Accessed on: 28.March, 2016.

[56] ISWA 2008. Management of APC residues from WTE Plants, ISWA-WG Thermal Treatment of Waste, 2 ed., available at: [www.iswa.org](http://www.iswa.org). Accessed on: 30.March,2016.

[57] Jaeger, M. and M. Mayer, —The Noell conversion process—a gasification process for the pollutant-free disposal of sewage sludge and the recovery of energy and materials,” *Water Science and Technology*, vol. 41, no. 8, pp. 37–44, 2000.

[58] Jingjing, L.; Xing, Z.; DeLaquil, P.; Larson, E.D (2001). Biomass energy in China and its potential. *Energy Sustain. Dev*, 5, 66–80.

[59] Jorge E. Preciado, John J. Ortiz-Martinez, Juan C. Gonzalez-Rivera, Rocío Sierra-Ramírez and Gerardo Gordillo (2012). Simulation of Gas Production from Steam Oxygen Gasification of Colombian Coal Using Aspen Plus®. *Energies* 2012, 5, 4924-4940; doi:10.3390/en5124924.

[60] Jorge L. Hau, Ruby Ray, Rex B. Thorpe and Adisa Azapagic (2008). A Thermodynamic Model of the Outputs of Gasification of Solid Waste. *INTERNATIONAL JOURNAL OF CHEMICAL REACTOR ENGINEERING*, Volume 6 2008 Article A35.

[61] Kaupp, A. and J.R. Goss (198 1). "State of the Art for Small Scale (to 50 kW) Gas Producer - Engine Systems," Final Report, U.S. Department of Agriculture, Forest Service Contract No. 53-319R-0-141.

[62] Kaygusuz, K. Energy for sustainable development: A case of developing countries. *Renew. Sustain. Energy Rev.* 2012, 16, 1116–1126.

[63] Kezhen Qian, Ajay Kumar, Krishna Patil, Danielle Bellmer, Donghai Wang, Wenciao Yuan and Raymond L. Huhnke (2013). Effects of Biomass Feedstocks and Gasification Conditions on the Physiochemical Properties of Char. *Energies*, 6, 3972-3986.

[64] Knoef, H., 2005. Practical aspects of biomass gasification, chapter 3 in Handbook Biomass Gasification edited by H. Knoef, H. BTG-Biomass Technology Group (BTG), ISBN: 90–8100681–9. Enschede, The Netherlands.

[65] L. Wei, S. Xu, L. Zhang, C. Liu, H. Zhu, and S. Liu, –Steam gasification of biomass for hydrogen-rich gas in a free-fall reactor,” *International Journal of Hydrogen Energy,* vol. 32, no. 1, pp. 24–31, 2007.

[66] Larney, F. J., & Hao, X. (2007). A review of composting as a management alternative for beef cattle feedlot manure in southern Alberta Canada. *Bioresource Technology*, 98(17), 3221-3227.

[67] Le Quere, C.; Raupach, M.R.; Canadell, J.G.; Marland, G. Trends in the sources and sinks of carbon dioxide. *Nat. Geosci*. 2009, 2, 831–836.

[68] LISY M., BALAS M., MOSKALIK J., POPISIL J. Research in to biomass and waste gasification in atmospheric fluidized bed, 2009, Proceedings of the 3rd WSEAS International Conference on Renewable Energy Sources, RES 99, ISBN 978-960-474-093-2.

[69] Luis Gilberto Velazquez Vargas. DEVELOPMENT OF CHEMICAL LOOPING GASIFICATION PROCESSES FOR THE PRODUCTION OF HYDROGEN FROM COAL (2007). Ph D thesis, Ohio State University.

[70] Lv P, Yuan Z , MaL, Wu C, Chen Y, Zhu J. Hydrogen-rich gas production from biomass air and oxygen/steam gasification in a downdraft gasifier. *Renewable Energy* 2007;32:2173–85.

[71] Maker, T. M. (2004). *Wood-chip Heating Systems.* Retrieved from http://www. biomasscenter.org/pdfs/Wood-Chip Heating Guide. Pdf.

[72] Mansaray, K. G. & Ghaly, A. E. (1999). Determination of kinetic parameters of rice.

[73] Marban, G. and T. Valdes-Solis, Towards the hydrogen economy?” *International Journal of Hydrogen Energy*, vol. 32, no. 12, pp. 1625–1637, 2007.

[74] Marcin Siedlecki, Wiebren de Jong and Adrian H.M. Verkooijen (2011). Fluidized Bed Gasification as a Mature And Reliable Technology for the Production of Bio-Syngas and Applied in the Production of Liquid Transportation Fuels—A Review. *Energies* 2011, 4, 389-434; doi:10.3390/en4030389.

[75] Marek Balas, Martin Lisy, Jirímoskalík (2012). Temperature and pressure effect on gasification process. Advances in Fluid Mechanics and Heat & Mass Transfer. ISBN: 978-1-61804-114-2, pp: 198-202.

[76] Marek Sciazko and Tomasz Chmielniak (2012). Cost Estimates of Coal Gasification for Chemicals and Motor Fuels. , chapter 10. http://dx.doi.org/10.5772/48556.

[77] McKay, 2002. Dioxin characterization, formation and minimization during municipal solid waste (MSW) incineration: a review. *Chemical Engineering Journal* 86, 343–368.

[78] McKendry, P. Energy production from biomass (part 3): Gasification technologies. *Bioresour. Technol. 2002, 83*, 55–63.

[79] Muhammad Aziz, Takuya Oda and Takao Kashiwagi. Advanced Energy Harvesting from Macroalgae—Innovative Integration of Drying, Gasification and Combined Cycle (2014). *Energies* 2014, 7, 8217-8235; doi:10.3390/en7128217.

[80] Nguyen, T.D.B.; Ngo, S.I.; Lim, Y.-I.; Lee, J.W.; Lee, U.-D.; Song, B.-H. Three-stage.
[81] Nicholas S. Siefert. Experimental and Thermo-Economic Analysis of Catalytic Gasification and Fuel Cell Power Systems (2013). Ph D thesis, Carnegie Mellon University.

[82] Niclas Scott Bentzen and Claus Felby (2012). Biomass for energy in the European Union – a review of bioenergy resource assessments. http://www.biotechnologyforbiofuels.com/content/5/1/25.

[83] Nor Fazdilah Othman, Mohd Hariffin Bosrooh, Kamsani Abdul Majid (2007). PARTIAL GASIFICATION OF DIFFERENT TYPES OF COALS IN A FLUIDISED BED GASIFIER. Journal Mekanikal, No. 23, 40 – 49.

[84] Onursal Yakaboyl, John Harinck, K. G. Smit and Niclas Scott Bentsen and Claus Felby (2012). Thermodynamic Analysis of Refinery Sludge Gasification in Adiabatic Updraft Gasifier. The Scientific World Journal, Volume 2014, Article ID 758137, 8 pages http://dx.doi.org/10.1155/2014/758137. Hindawi Publishing Corporation.

[85] Rentizelas, A., Karellas, S., Kakaras, E., Tatsiopoulos, I., 2009. Comparative techno-economic analysis of ORC and gasification for bioenergy applications. Biomass and Bioenergy 50, 674–681.

[86] Reem Ahmed, Chandra M. Sinnatham, Usama Eldnerdash and Duvvuri Subbarao (2014). Thermodynamic Analysis of Refinery Sludge Gasification in Adiabatic Updraft Gasifier. The Scientific World Journal, Volume 2014, Article ID 758137, 8 pages http://dx.doi.org/10.1155/2014/758137. Hindawi Publishing Corporation.

[87] Robert Sheng, Rene Laurens, Christopher F. Blazek and Gary W. Schanche (1992). Coal Gasification Processes for Retrofitting Military Central Heating Plants: Overview. US Army Corps of Engineers. Construction Engineering Research Laboratory. Coal Use Technologies.

[88] Ronald, W. Breault (2010). Gasification Processes Old and New: A Basic Review of the Major Technologies. Energies 2010, 3, 216-240; doi:10.3390/en3020216.

[89] Samaras P., Karagiannis D., Kalogirou E., Themelis N., Kontogianni St. 2010. An inventory of characteristics and treatment processes for fly ash from waste-to-energy facilities for municipal solid wastes, 3rd Int. Symposium on Energy from Biomass and Waste, Venice, Italy, 8–11 November, 2010. CISA Publisher, Italy- ISBN 978-88-6265-008.

[90] Samson Mekbib Attaw, Moo, Chuan Kueh, and Shaharin Anwar Sulaiman (2014). Study on Tar Generated from Downdraft.}

[91] Rajvanshi, A. K. 1986. Biomass Gasification. In Alternative Energy in Agriculture, 83-102. D. Y. Goswami, ed. Boca Raton, FL: CRC Press.

[92] Qihui Yan, Hong Zhang, Bingjie Sun,and Liejin Guo. Effect of Heating Method on Hydrogen Production by Biomass Gasification in Supercritical Water. Advances in Condensed Matter Physics, Volume 2014, Article ID 519389, 5 pages http://dx.doi.org/10.1155/2014/519389. Hindawi Publishing Corporation.

[93] Rajvanshi, A. K. 1986. Biomass Gasification. In Alternative Energy in Agriculture, 83-102. D. Y. Goswami, ed. Boca Raton, FL: CRC Press.

[94] Rechberger H. and Sch. Iler G. 2006. Comparison of Relevant Air Emissions from Selected Combustion Technologies. Project CAST. CEWEP – Congress, Waste-to- Energy in European Policy, 18 May 2006.

[95] Reed, T. B. (1988). Handbook of Downdraft Gasifier Engine Systems. Retrieved from http://taylor.ifas.ufl.edu/documents/Handbook_of_Biomass_Downdraft_Gasifier_Engine_Systems.pdf.

[96] Reem Ahmed, Chandra M. Sinnatham, Usama Eldnerdash and Duvvuri Subbarao (2014). Thermodynamics Analysis of Refinery Sludge Gasification in Adiabatic Updraft Gasifier. The Scientific World Journal, Volume 2014, Article ID 758137, 8 pages http://dx.doi.org/10.1155/2014/758137. Hindawi Publishing Corporation.

[97] Rentizelas, A., Karellas, S., Kakaras, E., Tatsiopoulos, I., 2009. Comparative techno-economic analysis of ORC and gasification for bioenergy applications. Biomass and Bioenergy 50, 674–681.

[98] Rezaiyan, J. and Cheremisnoff, N.P. (2005). Gasification Technologies – A Primer for Engineers and Scientists, Taylor & Francis, London, pp336.

[99] Ro, K. S., Cantrell, K. B., Hunt, P. G., Ducey, T. F., Vanotti, M. B. & Szogi, A. A. (2009). Thermochemical conversion of livestock wastes: Carbonization of swine solids. Bioresources Technology 100(22): 5466-5471.

[100] Robert Sheng, Rene Laurens, Christopher F. Blazek and Gary W. Schanche (1992). Coal Gasification Processes for Retrofitting Military Central Heating Plants: Overview. US Army Corps of Engineers. Construction Engineering Research Laboratory. Coal Use Technologies.

[101] Ronald, W. Breault (2010). Gasification Processes Old and New: A Basic Review of the Major Technologies. Energies 2010, 3, 216-240; doi:10.3390/en3020216.

[102] Samaras P., Karagiannis D., Kalogirou E., Themelis N., Kontogianni St. 2010. An inventory of characteristics and treatment processes for fly ash from waste-to-energy facilities for municipal solid wastes, 3rd Int. Symposium on Energy from Biomass and Waste, Venice, Italy, 8–11 November, 2010. CISA Publisher, Italy- ISBN 978-88-6265-008.

[103] Samson Mekbib Attaw, Moo, Chuan Kueh, and Shaharin Anwar Sulaiman (2014). Study on Tar Generated from Downdraft.

[104] Sandi Schwartz, Tina Mascianguoli, and Boonchai Boonyaratanaoknornk. BIOINSPIRED CHEMISTRY FOR ENERGY. A WORKSHOP SUMMARY TO THE CHEMICAL SCIENCES ROUNDTABLE. THE NATIONAL ACADEMIES PRESS 500 Fifth Street, N.W. Washington, DC 20001.

[105] Santioanni, D.A., Bingham, M.F., Woodard, D .M., & Kinnell, J.C. (2008). Power from animal waste- streaming. Acta Universitatis Agriculturae Sueciae, 2011(95), 93. Retrieved from http://pub.epsilon.slu.se/8415/llprade_t_l11102.pdf.

[106] Se-Won Park, Yong-Chil Seo, Jang-Soo Lee, Heung-Min Yoo, Won-Seok Yang, Jun-Kyung Park. A Study on Optimum Condition and Gaseous Pollutant Characteristics for Gasification of High-Calorific Waste (2014), Department of Environmental Engineering, Yonsei University, Japan Society of Material Cycles and Waste Management, FC-1.
[107] Shamughom Rupesh, Chandrasekharan Muraleedharan, and Palatel Arun (2014). Analysis of Hydrogen Generation through Thermochemical Gasification of Coconut Shell Using Thermodynamic Equilibrium Model Considering

[108] Char and Tar. International Scholarly Research Notices. Volume 2014, Article ID 654946, 9 pages. http://dx.doi.org/10.1155/2014/654946. Hindawi Publishing Corporation.

[109] Sharmina Begum, Mohammad G. Rasul, Delwar Akbar and Naveed Ramzan. Energies (2013). Performance Analysis of an Integrated Fixed Bed Gasifier Model for Different Biomass Feedstocks (2013), 6, 6508-6524; doi:10.3390/en6126508.

[110] Sharmina Begum, Mohammad G. Rasul, Delwar Akbar and David Cork. An Experimental and Numerical Investigation of Fluidized Bed Gasification of Solid Waste. Energies 2014, 7, 43-61; doi:10.3390/en7010043.

[111] Sheng LIU and Ying-Li HAO (2012). PARTICLE DEPOSITION CHARACTERISTICS IN ENTRAINED FLOW COAL GASIFIER. THERMAL SCIENCE, Year 2012, Vol. 16, No. 5, pp. 1544-1548.

[112] Sims, R.E.H.; Schock, R.N.; Adegbululgb, A.; Fenham, K.; Konstantinaviciute, I.; Moomaw, W.; Nimir, H.B.; Schlamadinger, B.; Torres-Martínez, J.; Turner, C.; Uchiyama, Y.; Vuori, S.J.V.; Wamukonya, N.; Zhang, X. Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change; Metz, B., Davidson, O.R., Bosch, P.R., Dave, R., Meyer, L.A., Eds.; Cambridge University Press: Cambridge, UK; New York, NY, USA, 2007.

[113] Singh RN. Equilibrium moisture content of biomass briquettes. Biomass and Bioenergy 2004;26:251–3.

[114] Sipilä, K. New power production technologies: various options for biomass and cogeneration. Bioresour. Technol. 1993, 46, 5–12.

[115] Stantec 2010. Waste to Energy. A technical review of municipal solid waste thermal treatment practices. Final Report for Environmental Quality Branch Environmental Protection Division. Project No.: 1231-10166, available at: www.env.gov.bc.ca/epd/mun-waste/reports/pdf/bcmoe-wte-emmisions-rev-mar2011.pdf. Accessed on: 25.April.2016.

[116] steady-state model for biomass gasification in a dual circulating fluidized-bed. Energy Convers. Manag. 2012, 54, 100–112.

[117] Stiegel, G.J., Maxwell, R.C., 2001. Gasification technologies: the path to clean, affordable energy in the 21st century. Fuel Processing Technology 71, 79–97.

[118] Street, J.; Yu, F. Production of high-value products including gasoline hydrocarbons from thermochemical conversion of syngas. Biofuels 2011, 2, 677–691.

[119] Takeharu Hasegawa (2010). Gas Turbine Combustion and Ammonia Removal Technology of Gasified Fuels. Energies 2010, 3, 335–449; doi:10.3390/en3030335.

[120] Takeharu Hasegawa. Gas Turbine Combustion and Ammonia Removal Technology of Gasified Fuels (2010). Energies 2010, 3, 335–449; doi:10.3390/en3030335.

[121] Technical Documentation: Integrated Gasification Combined Cycle Systems (IGCC) with Carbon Capture and Storage (CCS). Work Performed Under Contract No.: DE-AC21-92MC29094. Reporting Period Start, October 2003. Reporting Period End, May 2007. Report Submitted, May 2007 Carnegie Mellon University. Center for Energy and Environmental Studies. Department of Engineering and Public Policy. Pittsburgh, PA 15213-3890.

[122] Thanasit Wongsiriamnuay, Nattakarn Kannang and Nakorn Tippayawat. Effect of Operating Conditions on Catalytic Gasification of Bamboo in a Fluidized Bed (2013), International Journal of Chemical Engineering, Volume 2013, Article ID 297941, 9 pages http://dx.doi.org/10.1155/2013/297941, Hindawi Publishing Corporation.

[123] Thermochemical Gasification of Coconut Shell Using Thermodynamic Equilibrium Model Considering Char and Tar. International Scholarly Research Notices Volume 2014, Article ID 654946, 9 pages http://dx.doi.org/10.1155/2014/654946, Hindawi Publishing Corporation.

[124] Thiruchitrambalam Valliyappan. Hydrogen or Syn Gas Production from Glycerol Using Pyrolysis and Steam Gasification Processes (2004). M. Sc. Thesis, University of Saskatchewan.

[125] US Environmental Protection Agency (eds.). (2007). Compliance and enforcement national priority: clean water act, wet weather, concentrated animal feeding operations (CAFOs). Available at: http://epa.gov/oeccaerth/resources/publications/data/planning/priorities/fy2008priorit ycwa.pdf (accessed on: 09.,March,2016).

[126] US-EPA Environmental Protection Agency 2003. Letter to President of Integrated Waste Service Association, available at: www.wte.org/docs/epaletter.pdf. Accessed on: 14.April.2016.

[127] van Krevelen, D. Coal: Typology, Chemistry, Physics, Constitution, 3rd ed.; Elsevier: Amsterdam, The Netherlands, 1993.

[128] Venkata Ramanan, M., E. Lakshmanan, R. Sethumadhavan and S. Renganarayanan (2008). PERFORMANCE PREDICTION AND VALIDATION OF EQUILIBRIUM MODELING FOR GASIFICATION OF CASHEW NUT SHELL CHAR. Brazilian Journal of Chemical Engineering, Vol. 25, No. 03, pp. 585 – 601.

[129] Wang, L., Shahbazi, A. & Hanna, M. A. (2011). Characterization of corn stover, distiller grains and cattle manure for thermochemical conversion. Biomass and Bioenergy 35(1): 171-178.

[130] Wang, L.; Weller, C.L.; Jones, D.D.; Hanna, M.A. Contemporary issues in thermal gasification of biomass and its application to electricity and fuel production. Biomass Bioenergy 2008, 32, 573–581.
[131] Wang, W. A Thermal Conversion Efficiency Study on Biomass Gasification of Arundo Donax and Woodchips (2013). M. Sc. Thesis, Eastern Illinois University.

[132] Whitty, K.J.; Zhang, H.R.; Eddings, E.G. Emission from syngas combustion. *Combust. Sci. Technol.* **2008**, *180*, 1117–1136.

[133] Woodrow W. Clark II, J. R, —A green hydrogen economy”, Energy Policy 34, 2630–2639, 2006.

[134] Wu, H. Biomass Gasification: An alternative solution to animal waste management (2013). Ph D thesis, University of Nebraska-Lincoln.

[135] Xu G, Murakami T, Suda T, Tani H, Mito Y. Efficient gasification of wet biomass residue to produce middle calorific gas. *Particuology* **2008**, 6, 376–82.

[136] Xu, Q. Investigation of Co-Gasification Characteristics of Biomass and Coal in Fluidized Bed Gasifiers (2013). Ph D thesis, University of Canterbury.

[137] Yan F, Luo S- Y, Hu Z-Q , Xiao B, Cheng G. Hydrogen-rich gas production by steam gasification of char from biomass fast pyrolysis in a fixed-bed reactor: influence of temperature and steam on hydrogen yield and syngas composition. *Bioresource Technology* **2010**, 101: 5633–7.

[138] Yin, R.; Liu, R.; Wu, J.; Wu, X.; Sun, C.; Wu, C. Influence of particle size on performance of a pilot-scale fixed-bed gasification system. *Bioresour. Technol.* **2012**, *119*, 15–21.

[139] Young, G., 2010. Municipal solid waste to energy conversion processes: economic, Technical and renewable comparisons, J. Wiley & Sons, Inc.

[140] Young, L. & Pian, C. C. P. 2003. High-temperature, air-blown gasification of dairy-farm wastes for energy production. *Energy* **28**(7): 655-672.

[141] Zhengfeng Zhang, Wei Zhao and Wenwu Zhao (2014). Commercialization Development of Crop Straw Gasification technologies in China. *Sustainability* **2014**, 6, 9159-9178;doi:10.3390/su6129159.