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A REVIEW ON BIOMASS GASIFICATION FOR FUEL CELLS

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ABSTRACT

Biomass has been used as a supply of heat energy since man initially discovered fire. Biomass energy is obtained in many ways and numerous fuels are extracted from it. Traditional biomass conversion technologies like direct combustion, digestion, fermentation, and pyrolysis give low electrical efficiency compared to biomass gasification with fuel cells. The proper gasifier technologies selection supported the compatibility of the fuel cell. Fuel cell technology can be used as a standalone system or integrated with various technologies like Biomass gasification, ORC, GT, or MGT for electricity generation. The current paper included a review of different biomasses, gas cleaning methods, solid oxide fuel cells (SOFC), and finally the integration of biomass gasifiers with SOFC. Gas cleaning methods remove particulates, organic and inorganic impurities which reduces the performance of biomass-derived gases and fuel cells especially if we select gasification technology. Therefore, more researches are needed to produce a better gas cleaning system for SOFC to reduce the impurities, improve the efficiency and economical designing of the system. Therefore, the start towards the technical realization of the system is ready and presented in this paper.

Disciplinary: Renewable Energy & Clean Technology.

1. INTRODUCTION

The world population has experienced continuous growth and expected to reach 9 billion by 2050 for which the global demand for energy is increasing rapidly (Perea, *et al.* 2019). With the ample use of fossil fuels, increasing emissions from the combustion of fossil fuels and the rapid increase in the cost of fuels cause environmental pollutions and energy scarcity. With total energy demand increasing day by day the quantity of non-renewable energy is also depleting at an alarming rate (Jing, 2011). In response to such problems, considerable research work is performed in search of clean, renewable alternatives for sustainable development (Meng *et al.*, 2006). Biomass is one of the major renewable energy sources and available plenty on earth (Mao *et al.* 2018). Biomass

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Energy conversion can be done in two ways: (i) thermochemical and (ii) biochemical. In the thermochemical conversion process, biomass breaks down into its fundamental elements like biofuels, gases, and chemicals due to the applications of heat and pressure (Dincer, 2012). Different types of thermochemical processes are combustion, Pyrolysis, gasification, and liquefaction (Meng *et al.* 2006). Conventional biomass combustion-based technologies produced lowest electrical efficiency i.e. 20-25%, whereas Biomass Gasification (BG) combined with modern power generation systems like Gas Turbines and other IC Engines or Fuel Cells gives much higher efficiencies (Doherty, 2014).

BG is a means of imperfect combustion of biomass which in turn produces combustible gases like carbon monoxide (CO), hydrogen (H_2) and methane (CH_4). Both liquid and gaseous fuels are generated from biomass. But compared to gas the biomass to liquid alteration efficiency is low (Huang and Zhang, 2011). However, more investigations are occurring on fuel cells due to its higher efficiency than IC Engines, and SOFC receives significant attention because of its simplicity and viability (Stambouli, 2011). Fuel cells are considered as one of the major energy resources by many researchers and also the energy admittance of the 21st century (Bocci *et al.* 2016). Fuel cells can convert chemical energy of the biomass-derived gas to electrical energy with higher efficiency in a CO_2 neutral manner, leading to a much lesser environmental impact than the conventional power plants (Carlo, 2011, Larmininie, 2003 and Orecchine *et al.* 2005). Gas cleaning methods are used to remove the particulates, organic and inorganic impurities from the product gas. Hot gas technology could improve energy efficiency by reducing the loss of thermal energy and also lower operational costs by utilizing high-temperature biomass-derived gas. This work will give a brief review of BG-SOFC systems as the most inventive and well-grounded technology.

1.1 TECHNICAL OUTLINE

The technical outline of the BG-SOFC system is given in Figure 1.

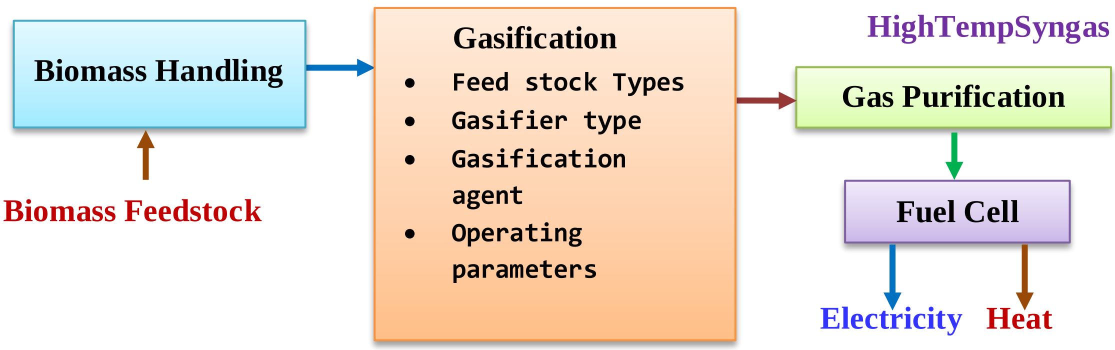

Figure 1: Technological Overview.

BG-SOFC system has four major components. Usually, in the biomass handling system, the biomass feedstock is crushed into pieces. Then the prepared feedstock through the process of gasification is transferred into combustible gases or product gases. The quality of product gases depends on many factors like types of feedstock, gasifier, factors affecting gasification, and operating parameters. Product gases mainly consist of hydrogen, carbon monoxide, carbon dioxide, methane, nitrogen, water vapor and impurities like organic compounds (tar), particulates, sulfur, and alkali compounds. In the next step, using various gas cleaning methods removal of the impurities from the product gas is taken place for the selected fuel cell type.

2. BIOMASS FEEDSTOCK OPTIONS AND CONVERSION PROCESSES

Biomass is a feasible resource and environmentally favorable due to its less carbon emission and other harmful emissions like nitrogen oxides and sulfur oxides. Biomass energy is the energy contained in plants and non-fossil organic matter. Varieties of biomasses are:

(i) Energy crops

(ii) Agricultural remains & unwanted biomass-derived products.

(iii) Forestry waste & residues

(iv) Industrial and Municipal residues (Meng Ni *et al.* 2006)

To convert biomass into useful products, several processes are used depending on characteristics, energy requirements, and its application (Sansaniwal*et al.*, 2017).

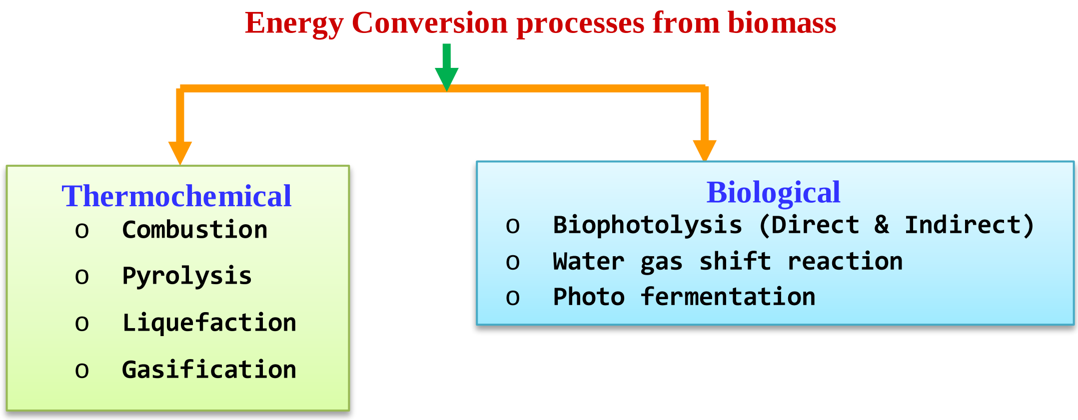

Figure 2: Biomass Conversion Processes

BG is a process of incomplete combustion of biomass which converts thermally solid/liquid organic compound into a combustible gas mixture. The produced gas mixture, called 'syngas', consists of hydrogen, carbon monoxide, carbon dioxide, methane along with nitrogen, water vapour and impurities. The calorific value of the syngas varies from 4-13 MJ/Nm^3, depends on biomass, gasification technology, and various operating parameters (Qian *et al.* 2013 and Wu *et al.* 2014). Gasification reactions are endothermic and the required energy is obtained through an allothermal and auto thermal process. The energy required for gasification is obtained through partial combustion during the auto-thermal process and during the allothermal process, the energy supplied externally from outside the gasifier through heated bed material or from the exhausted fuel and air streams of SOFC (Din and Zainal, 2016). Gasification stages are Oxidation Stage, Drying stage, Pyrolysis stage, and Reduction Stage.

3. GAS PURIFICATION SYSTEMS

The gas generated in gasifiers accommodate unwanted substances such as tar, solid particulates, ammonia, hydrochloric acid, sulfur compounds, and alkali metal species and must be removed to the acceptable levels and cleaned properly for the efficient operations of fuel cells and to meet pollution control regulations. Din and Zainal (2016) gives the six types of impurities in producer gas and its different phases are shown in.

The cleaning process is classified into many types. If the impurities are removed internally, known as "primary or in-situ" clean up whereas if cleaning of the impurities taken place downstream outside of the gasifier then it is known as “secondary cleanup process”.

3.1 PHYSICAL GAS CLEANING PROCESSES

Filtration or wet scrubbing methods used to remove the contaminant products by means of gas - solid or gas-liquid interactions. Wet scrubbing and filter hauling usually happen at low or ambient temperature conditions and at high temperature respectively using the materials such as ceramics, composites, sand & fiber glass etc. Characteristics of tar and other particles for various applications are presented Sansaniwal *et al*. (2017).

3.1.1 THERMAL TAR CRACKING

Thermal cracking is the decomposition of large atomic tar compounds into the lighter gases like methane, hydrogen and carbon dioxide at a higher temperature around 100°c for a certain period (Christopher, 2008). The tar quantity above 50-100 mg/Nm3 was considered critical for the end-user applications. Using any of the gas cleaning methods it can be reduced. Various studies on thermal cracking are presented in Han (2008), Anis *et al*. (2011), Andrea *et al*. (2012) and Teernai *et al*. (2013).

3.1.2 CATALYTIC TAR CONVERSION

The catalytic cracking method is used for very fewer tar concentrations of 50-100 mg/Nm^3, used in the secondary tar reformers or downstream applications outside the gasifiers. One of the major advantages of catalytic process over the physical and thermal cracking process is it can be used without further heating up or cooling down as same temperature as existing gas having. A comprehensive outline of tar cracking catalysts with their features given in Din and Zainal (2016).

3.1.3 COLD AND HOT-GAS FILTRATION

In the cold gas filtration cleaning system, cooling of the end product gas is required either before cleaning or after cleaning for downstream applications. Cold gas filtration is classified as dry gas cleaning (Raman *et al*. 2013 and Sharma *et al*. 2010) or wet gas cleaning (Shave *et al*. 2008). But according to VDI (2010), in hot gas filtration producer gas cleaning is carried out at 260°C. A comprehensive outlines of cold and hot gas filtration presented along with their merits and demerits in Din and Zainal (2016).

4. SOFC SYSTEM DESCRIPTION

Considering the environmental issues, the fuel cell has received considerable attention as ultra-clean, highly efficient energy conversion device. Fuel cells can continuously make electricity if they have a constant fuel supply. Low-temperature fuel cells such as PEMFC, AFC and PAFC require uses hydrogen as the only fuel whereas high-temperature fuel cells MCFC and SOFC use the only hydrocarbon as a fuel. One of the advantages of MCFC and SOFC is Light hydrocarbons are internally reformed to H_2 and CO due to their high operating temperature (Din and Zainal, 2016). Power generation using SOFC technology can reduce emissions, allow fuel flexibility and attain efficiency. The advantages of SOFC over MCFC are it has a solid construction with several stack configurations while MCFC cannot be aligned in individual directions. BG usually takes place around 900°C which is the typical operating temperature of SOFC i.e. 600-1000°C that makes the coupling of Biomass gasification-solid oxide fuel cell (BG-SOFC) simple & feasible. Presently more researches are carried out in SOFC on the identification and incorporation of ingenious materials for anode, cathode and electrolytes that can reduce its cost and enhance the long-lasting SOFC. In high temperature, the electrolyte of SOFC made up of Yttria Stabilized Zirconia (YSZ), a solid completely gas impermeable material contains high ionic conductivity and no electronic conductivity helped in conduction of oxygen ion. Oxygen in cathode gets reduced to the oxygen ions moved to the anode through the solid electrolyte. oxygen ions at anode combine with hydrogen produces water and carbon dioxide (Irshad *et al*. 2016). Nickel is used as an anode material because of its ability to withstand the operating conditions of SOFC: reducing conditions and acting as a good catalyst at 1000°C and intensify the fuel oxidation. Other possible materials are cobalt and noble metals. Another type of Ni/GDC (Gadolinium Doped Ceria) operates well with hydrocarbon fuel compared to YSZ (Jiang and Chan, 2004). It is observed that different fuel does not have a major impact on the performance of SOFC while the use of carbon-based fuel creates a problem.

5. SOME FEATURES ON GAS IMPURITIES FOR SOFC APPLICATIONS

Various types of anode and its characteristics play an important role in SOFC performance on producer gas. Fuel cell performance mainly depends on the characteristics of the impurities, concentration level and poisoning technique and this can be avoided by appropriate selection of biomass type, gasification technology and operating parameters (Sharma *et al*. 2016).

5.1 STUDIES ON PARTICULATE MATTER

For better performance of SOFC Particle size must be decreased to a size a few PPMW probably. An impurity characteristic in producer gas is given in Table 3 of Din and Zainal, (2016). Hofmann *et al*. (2008) reported its experiment on SOFC that increased exposure to the particulate matter could block the Ni/GDC anode, reduces the effective gas diffusion path and cause pull off of anode layer due to the reduce the catalytic area of anode through mechanically produced tension.

5.2 STUDIES ON TAR

Tar removal must be carried out before it condenses i.e.at 400°C-450°C before particulate evicted. The presence of tar in the dry state leads to carbon deposition on the anode, deactivate the catalysts (Ni), and degenerate the cell (Mermelstein *et al*. 2009 and Liu *et al*. 2011). A few researchers investigated tar to be a fuel that helps in electricity production by resolving and oxidizing. Mermelstein *et al*. (2010) observed that cell anode with benzene (2-15 gm/m^3) operated at a temperature of 765°C for 3h causes a significant reduction in carbon deposition with the increase of S/C ratio (>1). Paul *et al*. (2015) noted that syngas with contaminated toluene compared to uncontaminated syngas below 700°C decreases the amount of carbon and produces less graphite carbon. .However, at 700°C or above the number of carbon increases and produces more graphite carbon. Hofmann *et al*. (2008) observed that no carbon deposition occurs at a concentration of 1mg/m^3 of real tar on Ni/GDC anode whereas slight carbon deposition takes place when the concentration was 3000 mg/m^3 and the fuel utilization factor was high about 75% with a further higher concentration (10g/Nm^3). It is concluded from the currently published results that further research is required to study the impact of tars on SOFC anode different operating conditions for longer durations.

5.3 STUDIES ON H_2S, NH_3, HCL

The influence of H_2S on SOFC anode is reversible up to a few ppmv while causes irreversible damage at higher concentrations. Northim *et al.* (2007) tested a cell contain Ni/YSZ anode with a mixture of H_2/CO_2 and H_2S. They observed that up to 80ppm of Sulfur content a 2.5% drop in cell voltage occurs but no further decay took place with a concentration of 80-100ppm. Aravind and DeJong (2012) studied Ni/GDC anode is not affected by a few ppmv of H_2S for short-term operation. Arvind *et al.* (2013) reported Ni/GDC anode can tolerate 9ppmv HCl at 850°C, H_2 as fuel and cell performance did not decay in 90min. Xu et al. (2010) reported 1.6% performance loss in Ni/YSZ anode supported SOFC during the 300h test which is relatively very less than reported by Trembly *et al.* (2007) and Hagal *et al.* (2008). From the discussed literature, it concludes that cleaning of HCl to a few ppm in SOFC is required for better performance.

6. BIOMASS INTEGRATED GASIFICATION-SOFC SYSTEMS

BG-SOFC offers higher electrical efficiencies due to higher operating temperatures and fuel flexibility. In the past years, many theoretical, experimental, thermodynamic investigations, as well as simulation analysis, were taken place to determine required operating conditions of SOFC, the technical feasibility of the system, efficiency as well as the merits and demerits of a variety of SOFC system with biomass gasification system. Subotic *et al.* (2019) performed experimental and numerical analyses on SOFC single cells of industrial-size at an operating temperature of 750 °C fueled with producer gas from a downdraft gasifier, with hot gas cleaning taking the highest fuel utilization into account. Also, they did an additional 120h long-term test to find the local degradation of cells under stated operating conditions using the online-monitoring tool locally. Perna *et al.* (2018) studied the performance of an integrated micro gas turbine (MGT) and a solid oxide fuel cell (SOFC) fed by the syngas generated by a biomass downdraft gasifier. They observed that best performances were obtained at MGT pressure ratio equal to 4.5 and the S/C ratio to 0 which in term gives electric power is 262 kW (SOFC supplies 180kw), thermal power is 405 kW and the electric (AC) and cogeneration efficiencies are 35% and 88% respectively. Rasmus *et al.* (2017) conducted from five tests including polarization tests at various gas flows to study the performance of the two-stage Viking gasifier. The study compared experimentally the potential and feasibility of SOFC gasification system with a commercial gasifier and a SOFC stack provides biomass to electricity efficiency up to 43%. Qui *et al.* (2019) studied the performance of DC-SOFC using carbon-rich biochar derived from wheat straw, corncob, and biogases respectively as the fuels. Cells with bagasse char give the highest output performance of 260mw/cm^2whereas the cells with wheat straw char and corn cob char gives peak power densities of 187 and 204mW/cm^2 at 800°C and the test continued for 15h, 24h, and 22h respectively. They also found that the higher CO concentration represented the faster Boudourd reaction on the fuel. Dey *et al.* (2014) studied the performance of hybrid SOFC-gasifiers for different types of biomass input using the Aspen Plus model for gasifier reactions and 1D mathematical fuel cell. They conducted a test on a Coconut shell and sugar cane and found that SOFC with sugarcane biogases gives good performance i.e. power density of 0.58W/m^2 whereas coconut shell shows least power density i.e. 0.56W/m^2. Paengjuntuek *et al.* (2015) studied the energy performance of integrated biomass gasification fuel cell systems with rice straw feedstock for power generation. They found that at the optimal operating conditions with 205.35 kg rice straw/hr the total power generation from the steam turbine and SOFC is 1395.61 kW, electrical efficiency 39.55%, thermal efficiency 29.83% and total energy efficiency 69.38%. Skrzypkiewicz *et al.* (2016) conducted tests on a SOFC stack fueled by syngas using wood chips as the biomass input. They found that the gasifier converted 30 kW of fuel to syngas with an efficiency of 75%. They performed long term tests on SOFC stack fueled with the reference fuel, synthetic syngas, and the real syngas coming from gasification and concluded from the current-voltage characteristics and power curves that reference fuel gives the highest stack power of 1.1 kW. However, within the case of artificial syngas and also the syngas obtained from the gasification method process electrical power of the stack is less than for reference fuel about 250 W. It was observed that synthetic syngas operated similar to parameters for real syngas produced from the biomass gasification process, produces fewer impurities in the fuel to a good tolerance of SOFC cell.

Readily seen from literature, researchers have worked theoretically and experimentally for the development of BG-SOFC systems and it has to turn out as a promising technology.

7. CONCLUSION

Biomass is a renewable energy source in terms of both environmentally friendly and secured energy sources. The efficient utilization of biomass resources to produce heat and electricity is of utmost importance if it reduces the need for fossil fuels. The producer gas generated in the gasifier contains impurities particulates, tar, and alkali compounds and needs to be cleaned at various temperatures using available gas cleaning methods to meet SOFC performance. Various cleanup methods of biomass in gasification systems increase the complexity and capital costs of the system, but recently generated hot gas cleaning methods improve reliability, the efficiency of the system to a large extent. Still, the effect of impurities is an issue. The progress made in the last few decades is noticeable however no commercial systems are yet available and also the performance of the technology is challenged by few technical issues like anode materials, gasification processes, cleaning of impurities, etc. needs more attention. In the future, there are more researches needs to be carried out about more tolerant new anode materials towards impurities also elaborated investigations on the reaction mechanism find the cell degradation that reduces the cost of cleaning. Current literature does not provide sufficient information to enumerate characteristics of the contaminants with SOFC components. So that the limit for the different contaminants can be set. This study explores the feasibility of the BG-SOFC system with higher electrical efficiency and lower greenhouse gas emissions. Nevertheless, further work and researches are needed towards the improvement of system efficiency and reliability towards designing an economically feasible and environmentally sustainable fuel cell technology.

8. AVAILABILITY OF DATA AND MATERIAL

Information can be made available by contacting the corresponding author

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