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An overview of biomass-fuelled proton exchange membrane fuel cell (PEMFC) systems

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Abstract

PEMFC fuelled by biomass-derived hydrogen is an efficient and sustainable energy system for small-scale residential applications. Gasification and anaerobic digestion combined with steam reforming are seen as the most suitable conversion processes for hydrogen production. Since the biomass-derived hydrogen contains many kinds of contaminants including CO, CO_2, H_2S, NH_3 and N_2, extensive work has been done on the mechanism and mitigation methods for their poisoning the PEMFC. Although the biomass-fuelled PEMFC systems have been tested in several experiments and checked through simulation work for different perspectives, further research and demonstration work are required to improve the system efficiency and reliability.

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Keywords: Biomass; PEMFC; Anearobic digestion; Steam reforming; Gasification

1. Introduction

1.1. Background

Fuel cell is a device that converts chemical energy into electricity through electrochemical reactions. There are different fuel cell types, which are usually distinguished by the electrolyte that is used. For PEMFC, the electrolyte is a solid polymer, which makes this type of fuel cell inherently very simple. The overall reaction of the PEMFC is the conversion of the hydrogen and oxygen into water and electricity at 30-100 ºC [1].

PEMFCs are considered a promising technology for clean and efficient power generation [2]. Because of its low operating temperature, the PEMFC responses faster than other fuel cell types to load changing

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and thus can generate power dynamically. These distinguishing characteristics make it preferred for residential applications.

Hydrogen is the most common fuel for fuel cells, but it is not a readily available fuel and it needs to be produced from other sources. Presently, most hydrogen is produced from natural gas due to its abundant availability and advantageous price [3]. Nevertheless, the current technologies for producing hydrogen from fossil fuels are too costly, inefficient in energy use and environmentally unfriendly [4-5]. Therefore, using clean and green sources such as biomass for the production of hydrogen is receiving more interest and biomass-derived hydrogen is likely to give the fuel cell a more sustainable future [6].

Biomass is a potentially renewable energy source for hydrogen production. It can be divided into two main groups: one is liquid biomass, e.g. manure from farms and sludge from municipal wastes; the other is solid biomass, e.g. forest residues from forest industries. In order to be used by PEMFC, these different types of biomass need to be processed to hydrogen by different conversion chains. Anaerobic digestion combined with steam reforming and gasification are seen as the most suitable conversion processes for liquid and solid biomass, since their product gas (syngas and biogas respectively) easily can be directly exploited in fuel cells. This paper will focus on PEMFC systems combined with these two conversion processes [7].

1.2. Anaerobic digestion

Anaerobic digestion is a biological process that occurs naturally when organic material (biomass) decomposes in a humid atmosphere in the absence of air but in the presence of a group of natural microorganisms which are metabolically active, i.e. methane bacteria [8]. The product of the anaerobic digestion is biogas, which mainly consists of methane (45-75 % by vol.) and carbon dioxide (25-55 % by vol.)[8]. The biogas can be reformed to a hydrogen-rich gas, by using steam reforming, for fuelling the PEMFC.

1.3. Biogas steam reforming and gasification

Among several hydrogen production processes, the steam reforming process, using natural gas as feedstock, is widely used in chemical industries, and it is responsible for 50% of the hydrogen produced in the world [9]. Biogas, on the other hand, is a renewable resource for hydrogen production through steam reforming, which can make the fuel cell system more sustainable. There are two main reactions taking place in the steam reformer:

$$CH_4 + H_2O \leftrightarrow CO + 3H_2 \qquad CH_4 + 2H_2O \leftrightarrow CO_2 + 4H_2$$

Gasification is a thermochemical process that converts carbonaceous material into gas by using a gasifying agent, which comprises several overlapping process steps: drying, pyrolysis, combustion and gasification [10]. In principal, all different types of biomass can be converted by gasification into syngas mainly consisting of hydrogen, carbon monoxide, carbon dioxide and methane.

1.4. The aim

This paper gives an overview of the biomass-fuelled PEMFC system, focusing on the anaerobic digestion and gasification for biomass-derived hydrogen production. Anaerobic digestion is combined with steam reforming. These conversion systems are analyzed from various perspectives including the impact of the contaminants in the product gas generated from the steam reformer and gasification on the performance of the PEM fuel cells, the experiments and simulation for the biomass-fuelled PEMFC systems.

2. Biomass-fuelled PEMFC systems

2.1. *The impact of the contaminants in the product gas on the performance of the PEMFC*

Research on the impact of contaminants e.g. CO and H_2S on the performance of PEM fuel cells is extensive in literature and the following briefly reviews the highlights. As is widely known, the tolerance of a PEMFC to CO in the fuel is very low, even less than 10 ppm [1, 11]. CO will poison the catalyst of the fuel cell and decrease its performance significantly in a short time through covering the surface area of the catalyst [12-14]. The effective methods for CO removal are preferential oxidation, which oxidizes the CO with a highly selective catalyst during the fuel processing and water-gas shift which converts CO to CO_2 in the presence of steam [12,22].

H_2S poisoning is much more severe than CO poisoning. A trace amount of H_2S in the reformate gas, e.g. 1 ppm is enough to decease the performance of the fuel cell significantly [12]. For H_2S poisoning, the mitigation is not as well defined as for CO. For the stack, mitigation methods are to use the H_2S-tolerence catalysts, cyclic voltammetry or air-bleeding [12, 15-16]. For the reformate gas, the H_2S normally is removed by the purification processes before the steam reformer or after the gasifier using activated carbon or metal oxides such as FeO or ZnO [17-18].

CO_2 is one main component in the product gas, the concentration of which usually around 20%. CO_2 poisons the fuel cell via encouraging the formation of CO through the reverse water-gas shift reaction (RWGS) [12, 19]. However, the experiment results showed that the decease of the fuel cell performance due to CO_2 poisoning is small regarding the electric efficiency of the stack and can even be neglected during short-time operation.

For air-steam gasification, the content of N_2 in the syngas is very high and can reach up to 50%. Normally, N_2 is seen as an unharmful gas to the fuel cell, and even used to dilute the hydrogen in some experiments [19, 11]. But a diluted hydrogen gas by using N_2 mixes with a contaminant gas such as CO, will amplify the problem of CO poisoning.

NH_3 is also an important contaminant, which is harmful to the PEMFC and is a result of the hydrogen production from fossil fuel gasification, ammonia reforming, or the digestion of organic substrates [20-21]. The NH_3 will poison the fuel cell severely even with a trace amount such as 13 ppm, and till now its poisoning mechanism is not understood well [12]. However, it is found that operating the fuel cell by using pure hydrogen after NH_3 poisoning will recover the performance, but it cannot be recovered completely and needs much longer recovery time than after CO poisoning [20-21].

2.2. System investigation of the biomass-fuelled PEMFC

Anaerobic digestion, steam reforming and PEMFC

For the biogas-fuelled PEMFC system, the main issues are related to the determination of the parameters for the fuel processes including the steam reforming, the CO water shifting and the preferential oxidation, the integration of the fuel processors and PEMFC, and the perspectives for the system applications.

The complete biogas-based PEMFC system is shown in Figure 1 [23]. The main parameters of the steam reformer, high-temperature WGS reactor, low-temperature WGS reactor and selective CO oxidizer were tested and defined by a series of experiment work using the H_2S-free model biogas [23-24]. The mode biogas consists of 60 % CH_4, 40 % CO_2. Based on the defined fuel processor system, a 50W PEMFC is integrated with the fuel processor was tested [23]. The results indicated that the PEMFC could be operated stably using the hydrogen-rich gas consisting of 70 vol. % H_2, 30 vol. % CO_2, and residual CH_4 (1.0 vol. %) [23].

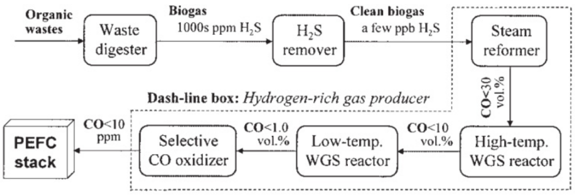

Fig.1. PEFC system using anaerobic digestion biogas of organic wastes as fuel proposed by Xu GW et al.[23]

A PEMFC stack was tested fed by the reformate gas produced from the native biogas which was produced by a small-scale anaerobic digester. It was found that the hydrogen-rich gas containing more than 60 vol. % hydrogen was sufficient for the stable operation of the PEMFC [25]. The thermal efficiency of the fuel processor was 47 % and the electric efficiency of the stack was 22.9% [25]. This group later released another study also for biogas-fueled PEMFC, which tested how the H_2S concentration in the biogas depended on the digestion mode, the operation temperature and the substrate type of the digestion [26].

This system is most suitable to the decentralized energy systems in livestock farm, olive oil plant, and individual homes. For a dairy farm, biogas plant can appropriately treat livestock waste through methane fermentation, as well as supply the heat and power regionally using the biogas-fuelled PEMFC. Based on the simulation work in [27], it was indicated that a dairy farm with 300 milked cows may produce enough manure for the self-sufficiency of an integrated PEMFC, dairy farm and biogas plant system while the PEMFC has 40 % of electric efficiency. For a case study in a Japanese dairy farm, it is estimated that the hydrogen yield capacity from 1000 milk cows will be 400 Nm^3/day which is possible to generate 480 kWh/day of power with PEMFC using this hydrogen [28].

Gasification and PEMFC

For the PEMFC system combined with gasification, till now there is no experimental work carried out. However, some simulation works has emerged for the system level investigation. For the biomass gasification, the wood waste is seen as the favored substrate. As mentioned, the gasification converts the biomass to gaseous fuels by thermochemical methods in the presence of air, oxygen, and/or steam as gasifying agent. Using steam as gasifying agent is an effective method for hydrogen-rich gas production; however, the steam gasification is an extremely endothermic process. Thus, the addition of air to gasifiers seems to be more practical, which enhances the biomass combustion reaction and supplies additional heat to the steam gasification process [29]. Utilizing both of the air and steam as gasifying media can make the gasification process achieve a self-sustainable operation [30]. Simulation results of biomass gasification and PEMFC integrated system utilizing wooden waste as biomass sample while choosing steam and air as the gasifying agents showed that the thermal and electric efficiencies of the gasifier could reach 51 % and 22 %, respectively [30]. The hydrogen content in the hydrogen-rich gas was around 33 vol. % [30]. A decentralized power production system based on biomass gasification and PEMFC using the wooden waste, water and air as the substrates could reach 35 % of total efficiency after considering the different methods of recovering the useful heat [31].

3. Conclusion

The paper reviews research on the biomass-fuelled PEMFC systems, focusing on the anaerobic digestion, and gasification for hydrogen production. Anaerobic digestion needs to be combined with biogas steam reforming. Since the biomass-derived hydrogen from the steam reforming and gasification contains many kinds of contaminants including CO, CO_2, H_2S, NH_3 and N_2, there are extensive work done on the mechanism and the mitigation methods for their poisoning of the PEMFC. CO is seen as the severest contaminant to the fuel cell, so it has received the highest research interest, while for NH_3 the poisoning mechanism is not understood well and for H_2S the mitigation method is not defined as well as that of CO poisoning. However, the current cleaning technologies are good enough to make the biomass-derived hydrogen useable to PEMFC.

For PEMFC systems combining with the anaerobic digestion and steam reforming, the system viability had been proven by experiments, which also showed acceptable system efficiency. Some simulation work evaluated the system application and then defined the expectation on these systems for a sustainable energy system. For the PEMFC systems combined with gasification, to date, there are no experiments that have been done although simulation work on the system level study has shown its feasibility. For biomass-fuelled PEMFC, further work and demonstrations are severely required to improve the system efficiency and reliability.

Acknowledgements

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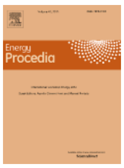

Biography

Tingting Guan is a PhD candidate from the group of Energy processes in the department of Chemical Engineering and Technology in KTH, Sweden. Her research is about the application of the biomass-fuelled proton exchange membrane fuel cell system for residential application.