INTERNATIONAL JOURNAL OF HYDROGEN ENERGY 39 (2014) 3061–3071

Available online at www.sciencedirect.com

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journal homepage: www.elsevier.com/locate/he

Thermodynamic modeling and assessment of a combined coal gasification and alkaline water electrolysis system for hydrogen production

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ARTICLE INFO

Article history:
Received 10 September 2013
Received in revised form
29 November 2013
Accepted 7 December 2013
Available online 6 January 2014

Keywords:
Hydrogen production
Coal gasification
Alkaline electrolyzer
Thermodynamic modeling
Exergy analysis

ABSTRACT

The performance of a clean energy system that combines the coal gasification and alkaline water electrolyzer concepts to produce hydrogen is evaluated through thermodynamic modeling and simulations. A parametric study is conducted to determine the effect of water ratio in coal slurry, gasifier temperature, effectiveness of carbon dioxide removal, and hydrogen recovery efficiency of the pressure swing adsorption unit on the system hydrogen production. The exergy efficiency and exergy destruction in each system component are also evaluated. The results reveal that the overall energy and exergy efficiencies of this system are ~58% and ~55%, respectively. The weight ratio of the hydrogen yielded to the coal fed to this system is ~0.126. Although this system produces hydrogen from coal, the greenhouse gases emitted from this system are fairly low.

1. Introduction

Energy demand is one of the major concerns in the world and will remain as one of the top-ten global concerns in this century [1]. The production of large amount of energy with low cost is the key to solve the energy requirements and also solving other top global concerns from the increase of new sources of clean water requirement to growing population. Production of energy with low cost is important, but concerns about environmental issues and availability of the energy sources should be considered to produce sustainable solutions of global energy issue. Hydrogen can be used as an energy carrier in the future to provide increasing global energy demand because it does not have any negative impacts on the environment and can be obtained by using primary energy sources. Since hydrogen is not available naturally, the main challenge about using hydrogen is production of it. Hydrogen can be obtained from renewable energy sources with no emissions; however, production of large amount of hydrogen

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http://dx.doi.org/10.1016/j.ijhydene.2013.12.068

and the hydrogen production cost are two important issues about employing renewable energy sources for hydrogen production. Therefore, fossil fuels are largely used (as ~96%) for hydrogen production [2].

Coal is one of the major fossil fuels and can be used for a long time due to the large coal reservoirs in the world. According to the World Coal Association estimation, there are more than 861 billion tons of proven coal reserves in the world [3]. Although coal is usually employed to produce power, it may have significant negative impacts on the environment. However coal gasification system is a promising technology to produce electricity, fuel and hydrogen with minimum adverse impact on the environment because this technology has a potential for carbon capturing.

Many studies have been undertaken on various aspects of coal gasification systems. Chiesa et al. [4,5] investigated the economic and technical performance of coal gasification system to produce H_2 and electricity, with CO_2 capturing and storage. They used different methods of syngas heat recovery and evaluated effects of the electricity/H_2 ratio, gasifier pressure, and hydrogen purity on the system performance. Adams and Barton [6] suggested a novel process to produce electricity with zero emissions and high efficiency. They integrated solid oxide fuel cell (SOFC) and the gasification process to increase the system efficiency. The efficiency of the SOFC-based system with cooling towers was found to be ~44.8%, while the efficiency of the integrated gasification combined cycle systems was about 38.2%. Moreover, they achieved capturing and sequestering almost 100% of CO_2 and other pollutants (e.g. $SO_{x,}$ NO_x). Xu et al. [7] proposed coal partial gasification with CO_2 capture system for co-production of hydrogen and electricity. They could attain the system overall exergy efficiency of ~54.3%, and the ratio of hydrogen to electricity (kW H_2/kW electricity) of ~4.76. Liszka et al. [8] analyzed hydrogen-oriented coal gasification system for two different cases, namely coal only and coal and biomass operation systems. In addition, they evaluated exergy losses for in the main components of the system. The highest exergy loss was calculated for the gasifier. Cosmos et al. [9] investigated technical performance of hydrogen production based on coal gasification with carbon dioxide capturing technology. To increase syngas pressure, they proposed the use of a syngas compressor for the dry feed gasifier after the gas quench and before the shift conversion. Siefert and Lister [10] compared two different gasification systems. The first system is an integrated gasification combined cycle with advanced H_2–O_2 membrane separation including CO_2 sequestration (IGCC-CCS). The second system is an integrated gasification fuel cell cycle with a catalytic gasifier as well as a pressurized SOFC including CO_2 sequestration (IGFC-CCS). They accomplished the exergy and economic analyses of these systems. The novel membrane and syngas chemical looping processes for production of coal-based hydrogen and electricity were examined by Li et al. [11]. They found that the novel membrane and syngas chemical looping strategies are promising methods to reduce the energy and cost penalties for CO_2 capture from coal conversion systems. Ghosh and De [12] performed an exergy analysis of a cogeneration plant using coal gasification and SOFC. They found the exergy destruction of different components of the system. Their results show that the highest exergy destruction takes place in the gasifier and SOFC. The present study is different from the other studies because the system that we suggested produces hydrogen using coal gasification and alkaline water electrolyzer.

In the present study, a novel integrated hydrogen production system which combines coal gasification and alkaline water electrolyzer systems is thermodynamically modeled, and its performance is evaluated through exergy efficiency. The power required for this system is completely generated in the system; thus no need to connection to electric grid. The carbon dioxide produced is also captured in this system; thus this system is an environmentally friendly system. Prediction of the effects of water ratio in coal slurry, gasifier temperature, hydrogen recovery efficiency of the pressure swing adsorption unit, and carbon dioxide removal ratio on the hydrogen production as well as prediction of the exergy efficiency and exergy destruction in each component of this system is the main objectives of this study.

2. System and process description

As illustrated in Fig. 1, the main components of this system are an air separation unit (ASU), a coal gasifier, a low and a high temperature water gas shift (WGS) reactor, H_2S and CO_2 removal units, a pressure swing adsorption (PSA) unit, a combustor, an alkaline water electrolyzer, a heat recovery steam generator (HRSG), and a power generation unit.

The gasifier size may be reduced, smaller gas handling and equipment and heat exchangers can be employed, and higher syngas heating value can be obtained if oxygen is used instead of air in the gasification process [13]. For such reasons, an ASU is used in this system to produce oxygen. Once oxygen is produced in the ASU, its pressure increases to 1.2 times the gasifier pressure in a multistage-compressor [4]. The pressurized oxygen is utilized during partial oxidation of the coal slurry in the gasifier. It is noted that the ASU consumes high amount of power. Of course, this power can be minimized by optimization of the oxygen product volume, purity and pressure, which is beyond the scope of this paper.

The main component of a coal gasification system is the gasifier. GEE entrained flow gasifier with radiant and convective cooling is selected as the gasifier of the system. Coal/water slurry with a ratio of 60%–70% and oxygen with a purity of 95%, provided by the ASU, and are fed to this gasifier to produce syngas [14]. The GEE gasifier can operate at pressures in excess of 62 bars and a temperature in the range of 1230 °C–1595 °C [13,15]. Operation at high pressures is beneficial for the gasifier because it decreases the gasifier volume, and as a result reduces the capital cost [13]. Typical syngas composition for a slurry feed gasifier consists of CO (35%–45%), CO_2 (10%–15%), H_2 (27%–30%), H_2O (15%–25%), H_2S and COS (0.2%–1%) [16]. Quench, radiant or combination of radiant and convective cooling methods can be used to decrease the temperature of hot syngas and heat recovery. Heat exchangers are used for the radiant and convective cooling, while water is sprayed onto the hot syngas in the quench design. The quench design is more reliable and cheaper than other radiant and convective designs [4]; however, it has lower thermal efficiency, because high pressure steam cannot be