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Development and analysis of an integrated system with direct splitting of hydrogen sulfide for hydrogen production

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ABSTRACT

This paper analyzes the thermodynamic performance of the combination of a water gas shift membrane reactor and an integrated coal gasification unit with a combined cycle, a carbon capture unit, and a unit for direct splitting of hydrogen sulfide into hydrogen and sulfur. The latter operates as an alternative process for disposing of hydrogen sulfide, while producing hydrogen. The purpose of the thermodynamic analysis is to determine whether the integration proposed is beneficial to the system in terms of thermodynamic performance, compared to the proposed systems in the open literature. The proposed system is simulated using Aspen Plus software, with two models for gasification. Some parametric studies are performed on the system to determine the effect of type of coal, steam flow rate in the single reheat supercritical Rankine cycle, and the main parameters of the membrane reactor on the overall energy and exergy efficiencies of the proposed system. The overall energy and exergy efficiencies of the proposed system are found to be 66.9% and 62.0% for Illinois #6 coal, and 60.7% and 57.0% for the Turkish coal Tuncbilek.

Introduction

Energy is an important aspect of modern life. Energy sources play a major role in living standards and lifestyles as well as the economic development of countries. Energy demand tends to increase with both increasing population and enhanced living standards. According to International Energy Agency (IEA), global primary energy demand is expected to increase by 50.0% by 2030 [1]. Currently the dominant source of energy is fossil fuels, but they have two main disadvantages: the finite nature of them make them a decreasing resource over the long term, and they produce large amount of carbon dioxide, the main greenhouse gas involved in global warming and climate change. An important option to address this problem is to use renewable sources of energy such as wind, solar, wave, and hydroelectric. However, current renewable energy sources are unable to meet all of society's energy demands. It is important to use sustainable energy carriers as a means of facilitating renewable energy use.

Hydrogen and electricity are carbon free energy carriers. Hydrogen has various advantages over fossil fuels and is very clean in terms of emissions if it is obtained from renewable

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sources [2]. Hydrogen can be produced from fossil fuels, such as natural gas by steam reforming, oil products, coal, and from biomass [3]. Coal has economic advantages compared to the other types of fossil fuels like natural gas [4]. However, when burned to produce electricity, coal leads to large emissions of carbon dioxide and other greenhouse gases compared to other fossil fuels. It nonetheless is likely to continue to play a major role in energy production due to its large availability worldwide [5]. Currently, 18% of hydrogen is produced from coal worldwide, even though the process of producing hydrogen from coal has higher costs, i.e. the capital investment in the gasification plant, than units for producing hydrogen from other fossil fuels, for example natural gas reforming. However, due to the lower cost of the coal, the net result in terms of cost is less expensive hydrogen [6]. Coal gasification, i.e., partial oxidation of coal, is important in the field of hydrogen and electricity production. In coal gasification, coal is partially burned rather than completely burned. Thus, the process converts coal to a syngas with high H_2 and CO concentrations. The syngas can be cleaned, and then hydrogen can be extracted from the syngas and the remaining syngas burned [7].

Integrated energy conversion systems are becoming increasingly employed in energy production due to various advantages. Sometimes these systems have higher efficiencies than equivalent independent systems. A wide variety of integrated systems exist that can produce more than two types of energy (e.g., electricity, hydrogen, heat) [8]. One attractive integrated energy conversion system is integrated gasification combined cycle (IGCC). It produces a syngas, mainly from coal but also sometimes from other sources such as biomass. The composition of the syngas depends on the gasification method, the amount of oxygen supplied to the gasifier and its purity, the type of inputs/coal, the temperature and pressure of the gasifier, and other inlets to the gasifier, which depend on the type of the gasification process [9]. There are numerous gasification methods and technologies. A common one for coal gasification is the pressurized entrained flow gasifier, which is the preferred choice for large-scale power production IGCC plants. This is due mainly to their high capacity and small size based on the given thermal input. Since the first installations of this type of gasifier in the USA and the EU, the number of operating units for both power production and/or co-production has increased worldwide. The pressurized entrained flow gasifier is based on oxygen-blown gasification, which operates at elevated temperatures to ensure fast and complete conversion of carbon, without the need to heat the nitrogen and other inert gases in air as is done with air-blown gasifiers. An extra step is required for oxygen- compared to air-blown gasifiers: air separation, which consumes a large percentage of the gross power produced by the IGCC power plant part [10].

Much current research on using coal in an environmentally benign is focused on gasification technology, largely because it can be integrated with other systems to enhance the overall energy conversion to useful forms. Some have examined underground gasification of coal integrated with other systems such as solid oxide fuel cells to increase the process efficiency reduce its environmental impact [12], [13]. El-Emam et al. [8] proposed a gasification system integrated with a solid oxide fuel cell cycle to increase the conversion of conventional energy sources to environmentally friendly energy carriers. Ozturk et al. [14] proposed a multigeneration system integrating a solar power tower with a coal gasification system, and then analyzed it thermodynamically based on the first and second laws. The thermodynamic analyses resulted in energy and exergy efficiencies of 54.0% and 57.7% respectively.

Membrane technology use is growing rapidly, since it can increase the reaction rate by continual selective removal of one of the products; this continuously drives the chemical reaction in the direction of the products, leading to a higher conversion fraction. Although the technology needs advances in material science, using a passive component in place of an active component increases the exergy efficiency by reducing the irreversibility from friction of the moving parts.

Gnanapragasam et al. [15] compared systems for the generation of two energy carriers, hydrogen and electricity. They found that system for hydrogen production has higher energy and exergy efficiencies. An IGCC system was shown to have an exergy efficiency of 53% and around 25% of the total exergy destruction occurred in the gas turbine combustion chamber, 17% in the steam reheat combustor, and 12% in the condenser. Seyitoglu et al. [7] proposed and analyzed a trigeneration system based on IGCC for electricity, hydrogen, and Fischer–Tropsch (FT) synthesis products. Aspen Plus software was used to simulate a large-scale plant with an input rate of 30 kg/s for five types of Turkish lignite, and demonstrated that the use of low-grade coals can be beneficial in terms of energy and exergy efficiencies, economics and environmental impact. The overall energy and exergy efficiencies of the system were found to be 53% and 46%, respectively. Cohce et al. [16] analyzed thermodynamically a gasification system for hydrogen production using Aspen Plus software with an idealized model based on Gibbs free energy. An idealized gasification model was found to provide a good representation of the real process for hydrogen production. Giuffrida et al. [11] analyzed the thermodynamic performance of IGCC power plants that utilize air-blown gasifiers and compared them to plants using oxygen-blown gasifiers, under similar circumstances. It was found that using the air-blown gasifier increased the overall power plant efficiency by 1.5%, and that the initial investment was reduced, lowering the electricity cost. The oxygen blown gasifier had an energy efficiency of 47.3% and the air-blown gasifier 48.9%, about 1.5% higher. Liszka et al. [19] analyzed an IGCC plant for hydrogen production with zero carbon dioxide emissions. Two fuel cases were analyzed: coal and a coal/biomass combination. The energy and exergy efficiencies respectively were found to be 64.7% and 56.7% for the first case and 65.5% and 57.0% for the second case. Zhu et al. [18] used first and second law of thermodynamics perspectives to assess the production of electricity and hydrogen through coal gasification, simultaneously with dual chemical looping processes. The latter include chemical looping air separation and water gas shift calcium looping CO_2 absorption. Three major factors were considered: oxygen to coal ratio, steam to coal ratio, and CaO to coal ratio. Four systems were analyzed: conventional processes including integrated gasification combined cycle (IGCC),

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