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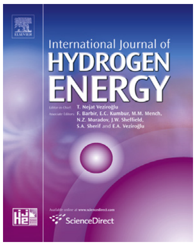

Development and analysis of an integrated photovoltaic system for hydrogen and methanol production

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ABSTRACT

A solar based integrated system for hydrogen and methanol production is investigated. Energy and exergy analyses of a hydrogen production plant, thermodynamic assessment of a methanol synthesis plant, and exergy analysis of the integrated solar based system for hydrogen and methanol production, are performed. The analysis of hydrogen production is performed for the methanol synthesis procedure. The present analysis shows the effects of temperature and current density of the electrolyser on hydrogen production. The optimum temperature of methanol synthesis is obtained for the final design of the methanol plant. It is shown that increasing the pressure improves the methanol synthesis process. Methanol conversion takes place at 493 K. The energy and exergy efficiencies of the system are reduced by 30% if the electrolyser operates at 300 K. The efficiencies of the system are also highly dependent on the solar intensity. The system efficiencies can be tripled if the intensity of solar radiation is increased to 600 W/m^2 instead of 250 W/m^2.

Introduction

The main source of energy in today's society is based on fossil fuels. Carbon dioxide, which is one of the main causes of global warming, is released from the combustion of fossil fuels [1]. As a consequence of the greenhouse gas emissions (GHG), the overall average temperature and sea levels have increased by 0.4 K and 15 cm over the twentieth century, respectively. The results of GHG emissions on climate change are now one of the most important challenges facing humanity. It was reported that 40% of all species will be in danger of extinction if insufficient action is taken for GHGs [2].

Fossil fuels have a key role in today's energy policies. More than 75% of global energy demand is supplied by fossil fuels. The increase in the atmospheric carbon dioxide concentration is directly related to fossil fuel use [3]. Three methods can achieve a significant decrease in carbon dioxide emissions:

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- Enhancement of energy efficiency of equipment;
- Investigation of renewable energy sources;
- Improvement of carbon capture and storage (CCS) technologies and chemical recycling of carbon dioxide to other valuable fuels, such as methanol [4].

The first approach will not resolve the emission issues completely. The strategy of switching to renewable energy sources at a large scale is not easy to achieve in the short term. The last option may be more probable [5]. Converting carbon dioxide to other valuable materials can be applied from any source of flue gas at existing industry emitters. The production of methanol from exhaust carbon dioxide can be one method to recycle carbon dioxide, which can help reduce the amount of carbon dioxide in the atmosphere.

The usage of carbon dioxide as a carbon source for chemical production and fuel synthesis has been examined previously. The recovery of exhaust carbon dioxide could contribute significantly to reducing climate change [3]. Carbon dioxide can be used as a feedstock in the production of many chemicals.

Although methanol synthesis technology is mature and widely available since 1923, the catalytic synthesis of methanol has attracted most attention from industry, academia, and government. Over the years, many researchers have tried to use efficient catalysts that would support the synthesis reaction [6]. Due to the vast volume of methanol needs in a wide diversity of industrial parts, the scope of commercial production has been increasing. The environmental limitations on the process have also held an essential role in the production of methanol.

Solar and wind energy are exceedingly desirable as renewable energy sources, since they can be readily transformed to electricity by wind turbines and solar cells. Nevertheless, the electricity production from these renewable sources suffers from unstable and fluctuating behaviour. The overall required and supplied solar and wind electricity do not provide a consistent supply, so it requires the utilization of energy storage options.

In this paper, a solar based integrated system for hydrogen and methanol production is investigated. Energy and exergy analyses for each part of the system are conducted. The operating conditions, including temperature, pressure and overpotential, are studied parametrically in order to give a better understanding of the system.

System description

A schematic of a system for solar based methanol production is shown in Fig. 1. Carbon dioxide is extracted from a CO_2 capture system. Solar panels are investigated to provide the required electricity for the electrolyser. They are utilized, in order to produce synthetic fuel from a sustainable and renewable source of energy. Part of the required water is supplied by the feedback from the methanol reactor. The supplied water is passed through the chemical reactor, in order to have a role as the reactor cooling system and also to become warm enough ($T = 353\ K$) to increase the efficiency of the electrolyser. The feed gas needs heat input to reach its reaction temperature. This required energy can be obtained from heat recovery from the exhaust gas from the boiler of the plant.

PV panels

The photovoltaic term refers to photons of light stimulating electrons into a higher state of energy, permitting them to act as charge exporters for an electric current. The term photovoltaic states the balanced functioning of a photodiode in which current through the device occurs due to the transduced light energy. The adaptability of the modular PV system permits developers to construct solar power systems that encounter a wide variability of electrical requirements [7].

PEM electrolyser

PEM electrolysers are based on the latest advances in PEM fuel cell technology [8]. The materials of electrodes of PEM electrolysers are typically platinum, iridium, ruthenium, and rhodium. The material of the membrane is usually Nafion, which not only splits the two-half cells, but performs as a gas separator [9]. The protons are transferred via the membrane to the cathode. In the cathode, protons are converted into hydrogen. The oxygen gas is separated and stored for other purposes. The PEM electrolyser has low ionic resistance and consequently high current density.

Through the electrolysis process, electricity and heat are brought to the PEM electrolyser to operate the electrochemical reactions. Water is heated in order to reach the temperature of the PEM electrolyser by passing water through the chemical reactor. Hydrogen is produced at the cathode, while oxygen gas is produced at the anode. A hydrogen storage system will be considered in order to provide the required amount of hydrogen to the methanol production plant during the night and cloudy days. It is assumed that the rate of hydrogen for both the methanol synthesizer and storage are the same.

Methanol synthesis reactor

The schematic of a methanol synthesizer is shown in Fig. 2. This system is modified from Rihko-Struckmann et al. [10]. The methanol synthesis process was examined with the following conditions. Four adiabatic reactor units, in cascade configuration, are considered by assuming equilibrium conversion with the defined stoichiometric reactions. Also, the input temperature is 493 K in each adiabatic reactor. Intermediate cooling between the reactors was simulated by locating heat exchangers between the reactor units.

The direct reaction of carbon monoxide with hydrogen also occurs in order to produce methanol. This reaction is the most important reaction in the presence of $Cu/ZnO_2/Al_2O_3$ catalysts in the large scale production of methanol. The overall reactor pressure is 5 MPa, and a pressure drop of 25 kPa is assumed in each reactor and heat exchanger.

The designated pressure and temperature ranges relate to usual industrial conditions for low pressure methanol synthesis. After the reactor section, the pressure is decreased to 1.2 MPa. The remaining feed compounds (carbon monoxide, carbon dioxide and hydrogen) are separated in the main flash unit; reprocessed and moved back in a second-step to the

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