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Thermodynamic studies of a novel heat pipe evacuated tube solar collectors based integrated process for hydrogen production

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ABSTRACT

In this study, the detailed thermodynamic assessment of an integrated process based on heat pipe evacuated tube solar collectors for hydrogen production is provided for more efficiently process designs. An integrated process consists of the solar heat pipe collector, photovoltaic panels, PEM electrolyzer and Linde-Hampson hydrogen liquefaction process are considered and analyzed thermodynamically for hydrogen production and liquefaction aims. The energetic and exergetic efficiencies of this integrated process are calculated as 0.2297 and 0.1955, respectively. Based on the parametric study, the effectiveness of the solar energy based integrated process is also highly dependent on the solar flux and ambient conditions.

Introduction

The energy need of world increases with increasing living standard, industrialization, quality of life and population. Nowadays, a greater part of energy requirements is supplied by using the fossil fuels i.e. coal, natural gas and petroleum. The fossil fuel utilization for energy generation has negative effects on the environment and on health of human beings. Meeting the importantly escalating global energy needs with no or minimal environmental damage and fossil fuel dependence can only be achieved by utilizing clean energy processes. These renewable energy based processes have considerable environmental, energetic, financial, and societal benefits [1]. The solar energy is a reliable and sustainable energy resource. Based on the environmental view-point, the solar energy processes do not have negative effects and harmful emission to the environment compared to the fossil energy sources, which continuously increase the earth's average ambient temperature and pollution [2]. In order to decrease fossil fuel consumption, the solar energy assisted integrated systems, which make use of the renewable and clean solar energy, should be designed for power, heating, cooling, hydrogen, hot and clean water production aims. Also,

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the discontinuous and inconsistent characteristics of solar radiation need the requirement for effective storing methods. The solar energy can be stored in the chemical form (i.e., hydrogen) or electrical energy form. The electricity is generally exploited as an energy storing way and it is heavily utilized on a daily basis. Hydrogen has been obtaining growing amount of consideration as a result of its favorable characteristics as an energy transporter [3].

The solar heat pipe collector absorbs the solar energy reaching on the collector receiver and transfers the absorbed heat energy into the working fluid, i.e. air, water or thermal oil, circulating through the tubes of the solar heat pipe collector [4]. This working fluid is then directly used or transfers its heat to another fluid for the desired purpose, e.g. hot water or steam generation. With the increasing attention in solar energy technologies, there have been many papers regarding both characterizations of solar photovoltaic, cost and efficiency analyses with the thermodynamic viewpoint. For these approaches, the energy, entropy and exergy concepts as well as their importance and roles for thermodynamic processes have been investigated extensively by Dincer and Cengel [5]. Thermodynamic limitations in energy processes through solar energy conversion with the entropy balance has been investigated by Wurfel [6], illustrating that an upper performance of 0.86 for maximally concentrated solar flux in any conversion process. Classification of radiation and calculation on exergy of the thermal radiation has been investigated by Petela [7]. Caliskan et al. [8] have investigated the exergoeconomic and environmental impact analysis, by using the energetic, exergetic and sustainability assessment methods to analyze the solar energy based hydrogen and power production process.

The evacuated tube solar energy concentrators have several design forms, such as heat pipe, U type tube, direct flow and glass to glass. The first collector type, heat pipe evacuated tube solar concentrator with two phase processes is utilized for absorbing and transferring solar energy to the working fluid is to be heated [9]. Jafarkazemi et al. [10] have analyzed both theoretically and experimentally the efficiency behavior of solar heat pipe evacuated tube concentrators. To investigate an efficiency of solar collector, they have used the energy and exergy analyses. Also, they have noticed that the very adequate results between experiment outputs and theory results. Finally, they have analyzed some different design parameters on the system performance by using theoretical working results. Ribot and McConnell [11] have given the mathematical model and experimental analysis on solar heat pipe evacuated tube concentrators. Based on the experimental analysis outputs, the solar radiation flux has important effect on the collector design. Ng et al. [12] have analyzed the efficiency of the solar heat pipe evacuated tube concentrators and checked with the outputs of experimental works. The proposed mathematical model in this paper has good agreement with experimental results.

The specific outputs of this study are to analyze the thermodynamic studies by using the first and second laws of thermodynamic for the multi-generation system supported by the heat pipe evacuated tube solar collectors with the hydrogen production and liquefaction process, and to decrease the environmental impacts and hydrogen production cost. The other main sub-objectives of this paper can be written as

- To propose and to define with thermodynamic studies a novel integrated process using solar energy
- To investigate the exergy contents for each flow of the integrated system.
- To perform the exergy efficiencies and exergy destruction rates of process parts and whole process.
- To determine the impacts of the varying some significant indicators on the integrated system efficiency.

System design

The proposed integrated hydrogen production and liquefaction system driven by renewable energy is presented in Fig. 1. The integrated system investigated in this paper consists of mainly four sub-systems, such as i) heat pipe collector, ii) photovoltaic system, iii) PEM electrolyzer, and iv) hydrogen liquefaction system.

To generate hydrogen, the PEM electrolyzer sub-system is utilized, which is driven by part of the power produced by using the solar photovoltaic system. On the other hand, the PEM electrolyzer works at the temperature between 60 °C and 120 °C, for this reason the heat pipe evacuated tube solar concentrators are used in the integrated system to produce heat for electrolyzer. The heat pipe evacuated tube solar collector system is composed of two parts, such as i) heat-pipe evaporator, and ii) heat-pipe condenser, and also produces low temperature useful heat by using the solar radiation. The working fluid in the evacuated glass tube of heat pipe transfers its heat power to the working fluid before entering a PEM electrolyzer.

The heated water goes into the PEM electrolyzer at point 2 and is reacted electro-chemically to split H_2O molecule into H_2 and O_2. Also, the part of produced electricity by using the photovoltaic sub-system is used in the proton exchange membrane electrolyzer to generate hydrogen. The produced O_2 exits from PEM electrolyzer at state 3 to be used for further aims. Since it is not possible to directly store or constantly supply solar power, the conversion of solar radiation to useful form of energy that can be stored has very important. The hydrogen liquefaction sub-system is used for more efficiently hydrogen storage.

The produced hydrogen is gaseous form at reference conditions at state 4, and enters the mixer and compressor subcomponent at state 5 and 6, respectively. The temperature of hydrogen is falls in nearly −125 °C at state 7. The hydrogen transfers heat energy of its with heat exchangers between II to V, and also the temperature of hydrogen reduces in −252 °C, exist at state 12. Finally, the liquid hydrogen can be stored at 101.3 kPa pressure and −252 °C temperature in liquid storage tank. The liquid hydrogen at point 21 in the Linde–Hampson hydrogen liquefaction process can be stored and transported to the nearby places for distribution respectively.

The hydrogen liquefaction system is comparatively higher power intensive than compression of hydrogen, whereas, the density of liquid hydrogen is nearly 1120 kg m^{-3} and, also

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