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Energy and exergy analyses of integrated hydrogen production system using high temperature steam electrolysis

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ABSTRACT

In this study, thermodynamic performance assessment of solar-driven integrated HTSE for hydrogen production is discussed in detail. The system consists of a solar tower, Brayton cycle, Rankine cycle, organic Rankine cycle (ORC) and high temperature steam electrolysis (HTSE). The required heat energy for power generation cycles are supplied from solar energy while produced electricity is used for the necessary energy demand of HTSE. For the analyses, the inlet and outlet energy and exergy rates of all subsystems are calculated and illustrated accordingly. From the results of the analyses, the overall energy and exergy efficiencies of the considered system are found to be 24.79% and 22.36% for power generation section and 87% and 88% for hydrogen production section respectively. Also it is found that without any auxiliary equipment, the considered hydrogen production process consumes 1.98 kWh_e at 230 °C, generates 0.057 kg/s H_2.

Introduction

Since the Industrial Revolution, the world depends on fossil fuels to provide energy needed to run factories, for transportation, or electricity generation, for homes and buildings. In parallel to the increase in the consumption of energy, life standards are increased. But, the utilization of fossil fuels in different applications has caused global warming, climate change, melting of ice caps, and increase in sea levels, ozone layer depletion, acid rains, and pollution [1]. Due to fluctuating oil prices, depletion of fossil fuel resources, global warming and local pollution, and growth in energy demand, alternative energies have become much more important [2]. In this aspect, the energy usage is important in many processes, such as power generation, heating and cooling, drying, desalination and air conditioning.

Hydrogen is presently used predominantly for the production of methanol and ammonia and in the refining industry. Nevertheless, hydrogen production has become a subject of interest for many global companies for its broad application and ecological aspects, and in a number of

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Nomenclature

$\dot{E}$	energy rate, kW
$\dot{E}_x$	exergy rate, kW
e_x	specific exergy, kJ/kg
ex^{ph}	specific physical exergy, kJ/kg
ex^{ch}	specific chemical exergy, kJ/kg
G	Gibbs function, kJ
H	total enthalpy, kJ
h	specific enthalpy, kJ/kg
$\bar{h}$	specific enthalpy, kJ/kmol
$\bar{h}^\circ$	specific enthalpy at reference state, kJ/kmol
$\bar{h}_f^\circ$	specific enthalpy of formation, kJ/kmol
HHV	higher heating value, kJ/kg
M	molar mass, kg/kmol
$\dot{m}$	mass flow rate, kg/s
n	number of moles, kmol
$\dot{Q}$	heat, kW
P	pressure, kPa
S	total entropy, kJ/K
s	specific entropy, kJ/kg K
T	temperature, K or °C
$\dot{W}$	work, kW

Greek letters

η	energy efficiency
ψ	exergy efficiency

Subscripts

dest	destruction
HE	heat exchanger
in	input, inlet
out	output, outlet
P	product
R	reactant;
sys	system
0	reference or dead state

countries an intensive R&D of the methods of obtaining hydrogen through affordable technologies is being conducted. The annual production of hydrogen is now ca 55 million tons, with its consumption increasing by approximately 6% p.a. Hydrogen can be produced in many ways from a broad spectrum of initial raw materials. Hydrogen is produced predominantly from fossil fuels; roughly 96% of hydrogen is produced by steam reforming of natural gas [3–5]. Approximately, about 4% of hydrogen is produced by the electrolysis of water. Electrolytic and plasma processes demonstrate a high efficiency of hydrogen production but unfortunately consume the most energy [3,6,7].

Hydrogen production via renewable energy sources is becoming more prominent. Hydrogen generation from renewable energy sources emerge as a proper way to store, as chemical energy, the energy coming from the sun [8]. Concentrated solar energy is used as the source of high-temperature process heat for driving endothermic reactions. Concentrating solar technologies such as; solar towers and dishes, applied commercially for large scale power generation – coupled to chemical reactors, have the potential of reaching solar-to-fuel energy conversion efficiencies exceeding 50%, and consequently, producing solar fuels at competitive costs [9]. Solar energy based-hydrogen production techniques are seemed to be more simple and convenient than other methods because of the sustainability and availability of the solar energy [10].

High temperature steam electrolysis (HTSE) is still considered in the early developmental stage. The HTSE offers a promising method for highly efficient hydrogen production. From the thermodynamic viewpoint of water decomposition, it is more advantageous to electrolyze water at high temperature (800 °C −1000 °C) because the energy is supplied in mixed form of electricity and heat. Compared with conventional water electrolysis, operation at high temperatures reduces the electrical energy requirement for the electrolysis and also increases the efficiency.

The enthalpy is given as the sum of the minimum work needed and the temperature-entropy term;

$$\Delta H = \Delta G + T\Delta S \tag{1}$$

where ΔH is the enthalpy change or total energy demand, ΔG is the Gibbs free energy or the minimum work, T is the absolute temperature and Δ S is the entropy change. The term TΔS can be considered as the total amount of thermal energy needed to split water [11].

In literature, most used solar hydrogen production methods are mentioned as photovoltaic, photoelectrolysis, photobiolysis, solar thermal energy, and solar thermochemical energy. Zhang et al. [12] have presented the results of 4 kW HTSE long-term test completed in a multi-kW test facility. The experimental unit was consisted of two solid oxide electrolysis stacks electrically connected in parallel. They reported that the HTSE stacks were successfully operated for 830 h with low degradation. Kasai [13], investigated the effectiveness of hydrogen for energy storage by highly efficient HTSE. The HTSE system was coupled with solar energy and nuclear energy for electrical energy storage. Zhang et al. [14] presented a solar-driven high temperature steam electrolysis system for hydrogen production. They carried out a detailed thermodynamic-electrochemical modeling of the solid oxide steam electrolysis. They also determined the electrical and thermal energy required by every energy consumption process are determined. Giraldi et al. [15] investigated a high temperature electrolysis process coupled to a high temperature gas nuclear reactor. Their system was capable of production of hydrogen using electricity and heat from nuclear power. Houaijia et al. [16] developed a solar tube-type receiver to superheat steam to 700 °C for HTE. In their system, the receiver was operated in German Aerospace Center solar simulator with up to 5 kg/h of steam reaching an outlet temperature of about 700 °C at a thermal efficiency of 40% and a solar power of about 4 kW. Buttler et al. [17] investigated the effect of high temperature heat utilization in solid oxide electrolysis on efficiency and hydrogen specific cell area. In their work, a detailed numerical electrochemical 1D model was implemented in the commercial equation-solving program EES. Mingyi et al. [18] examined the overall efficiency of the HTSE system through electrochemical and thermodynamic analysis. For this aim, they established a