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Thermodynamic assessment of geothermal energy use in hydrogen production

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ABSTRACT

In this study, geothermal-based hydrogen production methods, and their technologies and application possibilities are discussed in detail. A high-temperature electrolysis (HTE) process coupled with and powered by a geothermal source is considered for a case study, and its thermodynamic analysis through energy and exergy is conducted for performance evaluation purposes. In this regard, overall energy and exergy efficiencies of the geothermal-based hydrogen production process for this HTE are found to be 87% and 86%, respectively.

1. Introduction

Nowadays with the increase in the world population and industrialization, there has been a continuous increase in consumption of fossil fuels, which further causes several problems such as increased carbon emissions mainly from fossil fuel combustion products and leads to the global problems. In this regard, the world has started alarming ''accelerated global warming'', while the need for the clean and renewable energy has become inevitable.

Currently more than 80% of the world's energy supply comes from fossil fuels. The ongoing growth in fossil fuel consumption suggests that global carbon dioxide emissions are still rising [1]. Supplies of energy resources such as fossil fuels are finite. Energy sources such as solar, wind, and geothermal are generally considered renewable and therefore sustainable over the relatively long term [2]. In this regard, renewable energy technologies offer one of the potential solutions to current environmental issues [3,4].

Veziroglu and Sahin [5] suggested that the solution to these global problems would be to replace the existing fossil fuel system by the hydrogen energy system. Therefore, hydrogen energy systems appear to be one of the most effective

Abbreviations: HT, high temperature; HTE, high-temperature electrolysis; HTSE, high-temperature steam electrolysis; HTR, high-temperature helium cooled reactors; LT, low temperature; MT, medium temperature; NHE, Norsk Hydro electrolysers; PEM, proton exchange membrane; *SExI*, specific exergy index; SMR, steam methane reforming.

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Nomenclature

$\dot{E}$	energy rate, kW
$\dot{E}x$	exergy rate, kW
ex	specific exergy, kJ/kg
ex^{ph}	specific physical exergy, kJ/kg
ex^{ch}	specific chemical exergy, kJ/kg
G	Gibbs function, kJ
g	gravity, m/s^2
$\bar{g}_f^o$	specific Gibbs free energy of formation, kJ/kmol
H	total enthalpy, kJ
h	specific enthalpy, kJ/kg
$\bar{h}$	specific enthalpy, kJ/kmol
$\bar{h}^0$	specific enthalpy at reference state, kJ/kmol
$\bar{h}_f^0$	specific enthalpy of formation, kJ/kmol
HHV_{H_2}	higher heating value of H_2, MJ/kg
M	molar mass, kg/kmol
$\dot{m}$	mass flow rate, kg/s
n	number of moles, kmol
Q	heat, kJ
r	recycling ratio
s	specific entropy, kJ/kg K
T	temperature, K or °C
W	work, kJ
$\dot{W}$	power or work rate, kW
v	velocity, m/s
z	elevation, m

Greek letters

ΔG	change in Gibbs function for a reaction, kJ
η	energy or first law efficiency
ψ	exergy or second law efficiency

Subscripts

b	brine
d	destruction
e	electricity
el	electrolyser
g	geothermal
HE	heat exchanger
in	input, inlet
out	output, outlet
P	product
R	reactant
s	system
0	reference or dead state

solutions, and can play a significant role in providing better environment and sustainability [6].

Hydrogen does not exist alone in nature and cannot be produced directly. It is always found in the form of compounds and high value energy needs to be consumed for its production. All hydrogen production processes are based on the separation of hydrogen from hydrogen containing compounds from either fossil fuels or water. In the early 1970s, hydrogen received little as an energy carrier. At that time, the concepts of ‘‘hydrogen energy’’, ‘‘hydrogen economy’’ and ‘‘hydrogen energy system’’ were not in the headlines. In those days, at the landmark THEME (The Hydrogen Economy Miami Energy) Conference, 18–20 March 1974, Miami Beach, Florida, organized and chaired by Veziroglu [7], the consensus developed that the Hydrogen Energy System offers the optimum solution to the interrelated global problems occasioned by the increasingly rapid depletion of fossil fuel sources, as well as the environmental problems caused by their current usage (global warming, climate change, ozone layer depletion, acid rains, pollution, oil spills, oxygen depletion, etc.). Those in attendance at the THEME Conference were in agreement that the Hydrogen Economy would protect the planet earth – the only planet known to be hospitable to human life – while delivering clean, abundant energy, leading to a higher standard of living. This seemed a noble and worthwhile idea, and it was decided to establish an organization dedicated to the ultimate establishment of the Hydrogen Energy System. This organization, the International Association for Hydrogen Energy, was formed by the end of 1974, with Veziroglu as the Founding President. Later some more initiatives have followed this landmark, more recently establishing UNIDO-ICHET (International Center for Hydrogen Energy Technologies) by Veziroglu [7]. These clearly show the level of commitment made internationally on hydrogen energy technologies. Hydrogen appears to be a potential candidate to replace fossil fuels, especially in transportation sector.

The more mature and commonly used hydrogen production techniques include water electrolysis, steam methane reforming of natural gas and coal gasification today [8–10]. Various technologies are being studied, particularly in developed/industrialized countries, including hydrogen production from thermal disassociation of water using other renewable energies [11].

Recently, many more studies have been conducted on the global hydrogen production, in the short-term production of hydrogen from fossil fuels (mainly natural gas), and in the long term, hydrogen will be produced from renewable energy.

Some current hydrogen production technologies are mainly based on processes that mainly extract hydrogen from fossil fuel feedstock [12–14]. Fig. 1 illustrates that 96% hydrogen is currently produced directly from fossil fuels, while about 4% is produced indirectly by electricity utilization. Alternative clean and efficient pathways for the production of pure hydrogen are water electrolysis and thermochemical water-splitting cycles with renewable energy sources.

Hydrogen can also be produced as a clean fuel from the world’s sustainable non-fossil primary energy sources such as solar energy, wind energy, hydropower, biomass and geothermal.

The concept of integrating renewable energy with hydrogen systems was given some serious consideration in the 1970s [15,16]. The aim of the above mentioned concept was to