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Exergoeconomic analysis of a hybrid copper–chlorine cycle driven by geothermal energy for hydrogen production

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ABSTRACT

In this study, we conduct an exergy, cost, energy and mass (EXCEM) analysis of a copper–chlorine thermochemical water splitting cycle driven by geothermal energy for hydrogen production. We also investigate and illustrate the relations between thermodynamic losses and capital costs. The results show that hydrogen cost is closely and directly related to the plant capacity and also exergy efficiency. Increasing economic viability and reducing the hydrogen production costs will help these cycles play a more critical role in switching to hydrogen economy.

1. Introduction

Hydrogen is an attractive alternative to carbon-based fuels when considering the use of renewable energy for hydrogen production. In today's hydrogen economy, hydrogen is mostly produced from non-renewable energy sources and emits greenhouse gases to the atmosphere which leads to the global problems. But a sustainable hydrogen economy requires hydrogen to be produced with environmentally benign and renewable energy sources such as solar energy, wind energy, hydropower, biomass and geothermal. For this reason, we need to develop new methods to produce hydrogen in cleaner ways.

In the literature, there are a few methods identified for producing hydrogen as free of greenhouse gas emissions since they are driven by non-fossil energy sources. Thermochemical water decomposition and electrolysis of water are the most promising processes for such hydrogen production for hydrogen economy.

In this case, geothermal-based hydrogen production using thermochemical cycles appears to be a promising solution for the sustainable hydrogen economy to be run on renewable, and also it will help reduce environmental impact, by reducing greenhouse gas emissions, and hence beneficial for sustainable development.

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Nomenclature

$\dot{E}$	Energy rate, kW
$\dot{E}x$	Exergy rate, kW
K	Capital cost of system, $/GJ
L	Thermodynamic loss, GJ/kg
$\dot{L}$	Thermodynamic loss rate, kW
$\dot{m}$	Mass flow rate, kg/s
R	Ratio of thermodynamic loss rate to capital cost, GJ/$

Subscripts

a	Accumulation
C	Creation
con	Consumption
eq	Equipment
en	Energy
ex	Exergy
gen	Generation
in	Input, inlet
M	Maintenance
out	Output, outlet
P	Product
W	Waste

The authors [1–3] have investigated potential methods for geothermal-based hydrogen production and identified six low-temperature thermochemical and hybrid cycles, which can be coupled with geothermal energy. They [2,3] carried out a thermodynamic analysis through energy and exergy efficiencies of the low-temperature thermochemical and hybrid cycles for geothermal-based hydrogen production. The results of their studies [2,3] showed that low-temperature thermochemical cycles offer a good option for hydrogen production and become attractive due to their overall system efficiencies over 50% based on a complete reaction approach. They concluded that, the copper–chlorine (Cu–Cl) cycle appears to be the most promising thermochemical cycle for hydrogen production efficiently and effectively, without releasing any greenhouse gases to the atmosphere, and thereby help overcome numerous energy and environment concerns.

In the literature, numerous studies have been undertaken on hydrogen production using Cu–Cl cycles by many researchers and recent ones are presented below [4–11]. Many of these studies, the prime purpose were to find ways to improve its overall efficiency. For example, Orhan et al. [4–8] have examined the steps of the Cu–Cl cycle for nuclear-based hydrogen production in detail using exergy analysis approach. Naterer et al. [9] have analyzed the heat requirements for the steps and studied the ways to recover heat in order to minimize the net heat supply for the overall cycle which will improve its overall efficiency. Lewis et al. [10,11] have optimized the Cu–Cl cycle's performance and extending the process to obtain estimated hydrogen production costs. It is necessary to point out that the number of the studies conducted on economic assessment of Cu–Cl cycle [12–14] is relatively low, but no studies have appeared on exergoeconomic analysis of hydrogen production through Cu–Cl cycle driven by geothermal resources in the open literature to the best of the authors' knowledge. This was a key motivation behind the present study.

In this paper, we conduct a comprehensive exergoeconomic analysis of a hybrid Cu–Cl cycle driven by geothermal energy for hydrogen production. The thermodynamic loss rates are studied in detail for the cycle for its economic performance assessment.

The exergoeconomic analysis, which is essentially based on the exergy along with cost accounting, gives better perspective on the energy systems. It gives a true picture of the production cost of a process. In the recent years, various exergy-based economic analysis methodologies have been used by many investigators [14–21]. The exergoeconomic analysis in this study is based on the methodology as proposed and used by Rosen and Scott [22] and Rosen and Dincer [15,16]. The methodology provides a comprehensive assessment by accounting for the quantities exergy, cost, energy and mass. According this methodology it is possible to assess the cost of hydrogen in the Cu–Cl cycle.

2. Description of Cu–Cl cycle

The copper–chlorine cycle was originally proposed in the 1970s and has recently been proven at laboratory level. The Cu–Cl cycle is thus considered the most promising low-temperature cycle and offers a number of potential advantages over other cycles, such as [3,23]:

- The maximum cycle temperature (500 °C) allows the use of a wider range of heat sources such as geothermal, nuclear or solar.
- The recycling chemicals are relatively safe, inexpensive and abundant.
- All reactions have been proven in the laboratory and no significant side reactions have been observed.

The Cu–Cl cycle is a hybrid process using heat essentially and some electricity to split water to produce hydrogen at a maximum process temperature of 550 °C. The overall reaction for decomposition of water is given below:

$$H_2O + \text{Heat and Electricity} => H_2 + \frac{1}{2}O_2 \quad (1)$$

In the current literature there are two different Cu–Cl cycles under investigation, such as a five-step cycle as studied by several researchers [e.g., [4–8]] and a four-step cycle [e.g., [10,11]]. In this paper, a four-step cycle has been considered for exergoeconomic analysis. A simple conceptual layout of four-step Cu–Cl cycle is shown in Fig. 1. This cycle consists of two thermochemical reactions and one electrochemical reaction, involving different chemical reactions.

A chemical reaction takes place in each step, except the drying step. These chemical reactions form a closed internal