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Development and assessment of a novel integrated nuclear plant for electricity and hydrogen production

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ABSTRACT

A novel nuclear-based integrated system for electrical power and compressed hydrogen production is proposed. The hydrogen is produced through the four-step Cu-Cl cycle for water decomposition. A Rankine cycle is used to generate the power, part of which is used for the electrolysis step in the hybrid thermochemical water decomposition cycle and the hydrogen compression system. In the proposed design of the four-step thermochemical and electrical water decomposition cycle, only the hydrolysis and the oxygen production reactors receive thermal energy from the nuclear reactor. The nuclear thermal energy is delivered to the integrated system in the form of a supercritical fluid. The nuclear reactor, which is based on the supercritical water-cooled reactor, is responsible for delivering the thermal energy to the system, which is simulated using Aspen Plus and assessed with energy and exergy analyses. It is determined that the energy and the exergy efficiencies of the proposed system are 31.6% and 56.2% respectively, and that the integrated system is able to produce 2.02 kg/s of highly compressed hydrogen and 553 MW of electrical power.

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1. Introduction

To maintain a comfort and living standards, various services are required such as electricity, hot water, cold water, air conditioning, and many chemicals. Conventional methods for producing these necessities use fossil fuels, which are the main contributors to carbon-based emissions, which in turn are a major contributor to global warming. The increasing demand for the above-mentioned services results has resulted in an increase in the use of fossil fuels, affecting the environment greatly [1]. According to the International Energy Agency, energy demands of the world will increase by 50% in the coming 14 years (2016–2030) and, since energy production nowadays is directly related to fossil fuel use, increased carbon-based emissions will be released to the environment [2].

The present situation is motivating the world to find and develop cleaner energy sources and hence more efficient processes. Eventually, it is expected that current fossil fuels will be replaced with sustainable energy sources. One method of reducing carbon emissions is through hydrogen production from renewable or non-carbon based resources such as solar, hydro, wave and nuclear energies. Hydrogen is a clean energy carrier that, when produced from renewable energy sources and/or non-carbon based fuels such as nuclear energy, can be used with little or no carbon emissions [3]. Hydrogen can be converted to electricity, heat, chemical fuels and other useful chemicals and the only byproduct is H_2O (water) [4]. Production of hydrogen from nuclear energy leads to few or no carbon emissions [1]. Another advantage of hydrogen production from nuclear energy now and in the future is that hydrogen will develop its own market where it can be converted to electricity through fuel cells and then sold as electricity during peak periods, or sold as a chemical fuel for transportation or chemical plants. Another advantage of nuclear-produced hydrogen is that it can help match the electrical production curve with the demand curve through either producing hydrogen as an energy storage medium during off-peak periods and or through the generation of electricity from hydrogen through fuels cells. Nuclear hydrogen production can increase the cost competitiveness of nuclear plants and make them more secure by integrating them with thermochemical cycles or hybrid thermochemical and electrical cycles or high-temperature electrical water decomposition cycles [1].

Hydrogen can be produced from nuclear energy either through electrolysis or thermochemical water decomposition or hybrid thermochemical water decomposition. Hybrid thermochemical and electrical water decomposition cycles are attracting increased attention due to their lower temperature requirements compared

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Nomenclature

c_p	specific heat capacity at constant pressure (kJ/kg K)
ex	specific exergy (kJ/kg)
$\dot{E}x$	exergy rate (kW)
h	specific enthalpy (kJ/kg)
$\dot{m}$	mass flow rate (kg/s)
P	pressure (kPa)
$\dot{Q}$	heat rate (kW)
R	universal gas constant (kJ/mol K)
s	specific entropy (kJ/kg K)
T	temperature (°C)
$\dot{W}$	work rate (kW)

Greek letters

η	energy efficiency
ψ	exergy efficiency

Subscripts

Cu-Cl	copper-chlorine cycle
C	compressor
d	destruction
e	electrical
f	formation
gen	generation
H_2	hydrogen
HCS	hydrogen compression system
is	isentropic
in	input (flowing into system boundary)
max	maximum
net	net result
ov	overall
out	output (flowing out of system boundary)
o	reference environment conditions
$\dot{Q}$	heat flow rate
PSR	power supporting rankine cycle
ST	steam turbine
bs	boundary where heat transfer occurs
W	work
@P&T	at pressure P and temperature T

Superscripts

$\cdot$	rate
LP	Low pressure
HP	High pressure

Acronyms

SCWR	Supercritical water cooled reactor
HCS	hydrogen compression system
PSR	power supporting Rankine cycle

to thermal water decomposition. Various types of hybrid thermochemical and electrical water decomposition cycles exist, and these are often differentiated based on the chemical compounds they employ and the number of steps in the cycle [1].

Investigations of hybrid thermochemical and electrical water decomposition cycles for hydrogen production have been reported, as have efforts to integrate them with other systems. One type of hybrid thermochemical and electrical water decomposition cycle uses magnesium and chlorine (the Mg-Cl cycle) [5,6]. Ozcan and Dincer [5,6] modeled and analyzed the performance of this cycle and investigated its thermal energy and electrical energy requirements. Ozcan and Dincer [6] found that the Mg-Cl cycle has energy and exergy efficiencies that allow it to compete with the other hybrid thermochemical and electrical water decomposition cycles. The Mg-Cl cycle has been integrated with a nuclear reactor, a Rankine cycle and a liquid hydrogen storage [7]. Energy and exergy analyses were performed of this integrated system and the energy and exergy efficiencies were found to be 18.6% and 31.4%, respectively [7]. An exergoeconomic analysis of the Mg-Cl cycle was also reported [8].

Another promising hybrid thermochemical and electrical water decomposition cycle is based on copper and chlorine compounds (the Cu-Cl cycle), particularly due to its relatively low-temperature requirements which permit it to be integrated with various thermal energy supply systems. Various Cu-Cl cycles exist, based on the number and type of steps comprising it [1]. Orhan et al. [9,10] examined the performance of several Cu-Cl cycles with energy and exergy analyses. The Cu-Cl cycle has also been evaluated using exergoeconomic analysis [11]. Furthermore, investigations have been reported on the integration of the Cu-Cl cycle with other hydrogen production processes [12–14]. The integration of the Cu-Cl cycle with nuclear plants that provide thermal energy has been examined [13,14], and the system energy and exergy efficiencies were found to be 45% and 10%, respectively [14]. In [14] a Cu-Cl cycle containing five main steps is considered, while a four-step Cu-Cl cycle is examined in [15].

The various Cu-Cl cycles have been investigated extensively over the last decade, using energy, exergy, exergoeconomic, exergoenviromental, analyses, and other costing methods. For example, [9,10,12,13] studied the Cu-Cl cycle itself in terms of energy and exergy analyses and evaluated its efficiency. Some examples of work done on economic aspects of the Cu-Cl cycle include the studies of [11,16]. Ref. [11] used the specific exergy costing (SPECO) method, while [16] used another costing method, exergoeconomic analysis, integrated with an enviromental viewpoint, in the form of exergoenviromental analysis. Other investigations have focused on optimizing the Cu-Cl cycle operating conditions [17,18]. In [17], a new heat exchanger network is proposed to increase the heat recovery and decrease the overall energy requirement of the cycle, while in [18], a multi-objective optimization is carried out on the cycle including energy and exergy efficiencies. However few have proposed realistic conceptual designs of the overall cycle and how the thermal energy is delivered to its reactors [19]. Some research has focused on specific parts of the overall cycle, such as reducing the auxiliary power requirements by integrating the pathways between the hydrolysis reactor and the electrolysis reactor. Also, Ref. [20] assessed the oxygen production process with energy and exergy analyses. Other reseachs proposed integrating the material flows betweenthe hydrolysis reactor and the electrolysis reactor, since both flows share the main chemical components [21]. Ref. [22] proposed and analyzed a new method for recovering the thermal energy from molten CuCl salt through casting. Experiments were carried out on different parts of the cycle, such as scaling up a reactor [23]. Other experiments have been performed on different parts of the cycle [24,25]. A number of integrated systems have been proposed, with such thermal energy sources as nuclear [14,26], solar [27–29], fossil fuels [30,31], renewable energy (only) [28], renewable energy with nuclear energy [32], and systems that integrate more than one technology [33]. Finally several review papers [34–36] have been published to inform of the most recent advances regarding the Cu-Cl cycle. Nevertheless, more work is required on integrating these cycles into systems to determine how well they perform after integration.

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