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Performance analysis of a supercritical water-cooled nuclear reactor integrated with a combined cycle, a Cu-Cl thermochemical cycle and a hydrogen compression system

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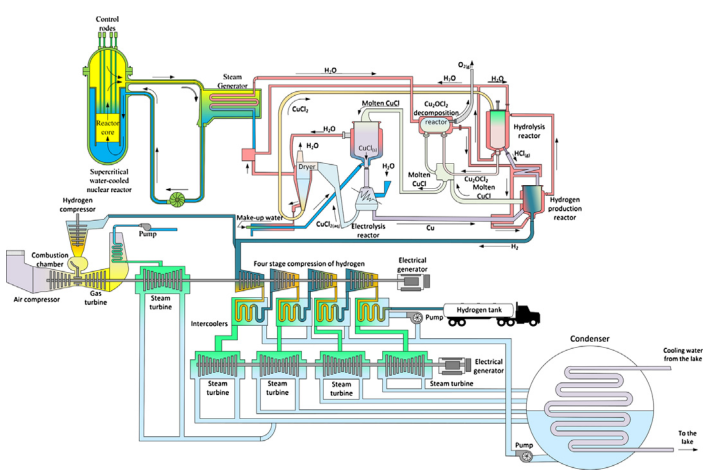
HIGHLIGHTS

- Integrated nuclear-based hydrogen production plant is proposed.
- Performance of the integrated system is measured through thermodynamic analysis.
- New design for the Cu-Cl cycle is proposed for integrating it with SCWR.

GRAPHICAL ABSTRACT



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ABSTRACT

A novel integration is proposed and analyzed of a thermochemical water decomposition cycle with a supercritical water-cooled nuclear reactor, a combined cycle, and a hydrogen compression system. The supercritical water-cooled reactor in the integrated system has been investigated extensively in Canada. The integrated system uses a compression system to compress the product hydrogen. The hydrogen is produced via a hybrid thermochemical and electrical water decomposition cycle that utilizes the chemical couple of copper and chlorine. The integrated system is modeled and simulated on Aspen Plus, except for the steam circuit, which is simulated on Aspen Hysys. The hydrogen production rate from the proposed system is 3.56 kg/s. Both energy and exergy analyses are performed of the integrated system, and its overall energy and exergy efficiencies are, in this regard, found to be 16.9% and 27.8%, respectively.

1. Introduction

Hydrogen is abundant in nature; it accounts for 75% (mass basis) and 90% (by number of atoms) of the total matter in the

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Nomenclature

$\dot{E}x$	exergy rate (kW)
ex	specific exergy (kJ/kg)
LHV	lower heating value (kJ/kg)
h	specific enthalpy (kJ/kg)
h_f	heat of formation
$\dot{m}$	mass flow rate (kg/s)
P	pressure (kPa)
$\dot{Q}$	heat rate (kW)
T	temperature (°C)
$\dot{W}$	work rate (kW)

Greek letters

η	energy efficiency
ψ	exergy efficiency

Subscripts

bs	boundary where heat transfer occurs
c	compressor
Cu-Cl	copper-chlorine
d	destruction
e	electrical
gen	generation
GT	gas turbine
H_2	hydrogen
HCS	hydrogen compression system
is	isentropic
in	input (flowing into the system boundary)
net	net result
ov	overall
out	output (flowing out of the system boundary)
o	reference environment conditions
p	pump
$\dot{Q}$	heat flow rate
RC	Rankine cycle
ST	steam turbine
SCC	supporting combined cycle

Superscripts

HP	hydrogen at high pressure (700 bar)
LP	hydrogen at low pressure

Acronyms

Cu-Cl	copper-chlorine cycle
ER	electrolysis reactor
HCS	hydrogen compression system
RC	Rankine cycle
SC	steam circuit
SCC	supporting combined cycle
SCWR	supercritical water-cooled nuclear reactor

Aspen Plus terms (italic terms)

Rstoic	Aspen Plus reactor model that carries out the reaction based on the stoichiometric balanced chemical reaction equation with a specified reactants conversion percentage
Cisolid	for homogeneous solids that have a defined molecular weight, with the option of entering the particle size distribution
RGibbs	Aspen Plus reactor model that carries out the reaction based on Gibbs free energy minimization approach
Mixed	material stream option in Aspen Plus modeling

universe [1]. On earth, an abundant amount of hydrogen exists connected to an oxygen atom in the form of water (H_2O) [2]. The chemical bond between a hydrogen atom and an oxygen atom in water requires 460 kJ/mol of energy to break [3,4]. Hydrogen in the form of H_2 has the highest energy to mass density of any substance. But hydrogen is not readily available in nature in large amounts in the form of H_2. Hydrogen can serve as an energy storage medium and as a clean energy carrier. Many technologies are available for producing hydrogen from water, such as water electrolysis, thermal water decomposition, thermochemical water decomposition, and thermochemical and electrical water decomposition. Water decomposition is a potentially attractive method for hydrogen production.

Energy demands of the world are continuously rising, with recent reports from the International Energy Agency expecting an increase of 50% from 2016 to 2030 [5]. Energy demands vary yearly, monthly and daily, so it if is challenging for power plants intended to meet the energy demands exactly. The benefits of steady-state conditions are lost, and the efficiency of the power plant is reduced. Another option for maintaining a constant operational rate for a power plant and at the same time not losing energy is by using energy storage. One energy storage option is hydrogen. Hydrogen has one of the highest energy to mass densities of any substance. Also, hydrogen energy can be produced from water using various methods using heat, electricity, and chemical fuels. When produced from water without hydrocarbon fuels, hydrogen is a clean fuel in terms of carbon-based emission, which provides an advantage as an energy storage and energy carrier.

Most hydrogen is produced today from fossil fuels, mainly via steam reforming of natural gas. There are also other processes for obtaining hydrogen from fossil fuels such as coal gasification, and catalytic combustion and partial oxidation of other hydrocarbons [6]. Other methods produce hydrogen from renewable resources, such as biomass gasification [7] and solar hydrogen production [8]. Hydrogen production from fossil fuels is not environmentally benign, since it yields carbon-based emissions, which are greenhouse gases and one of the main contributors to global warming. Hydrogen production from non-carbon based fuels avoids carbon-based emissions. A large percentage of hydrogen on earth is in the form of water, so water decomposition to produce hydrogen using a non-carbon emitting process can be advantageous for reducing carbon emissions.

Thermochemical and electrical water decomposition powered thermally by nuclear reactors is a promising technology for producing hydrogen without carbon-emissions. The thermochemical and electrical water decomposition processes requires heat at lower temperatures than those required when directly decomposing water thermally. The thermochemical and electrical water decomposition cycle that is based on the chemical couple copper and chlorine (Cu-Cl cycle) has one of the lowest temperature requirements for thermochemical water decomposition. Nonetheless, the Cu-Cl cycle requires temperatures higher than available from currently operating nuclear reactors [9]. The relatively low steam temperature of current nuclear reactors is one of the main reasons for their relatively low efficiencies. New nuclear reactors concepts are being introduced that involve higher steam temperatures. One promising concept is the supercritical water-cooled nuclear reactor (SCWR). The SCWR produces steam at an outlet temperature of 625 °C [10]. One reason for coupling a Cu-Cl cycle with a SCWR rather than with a supercritical Rankine cycle where