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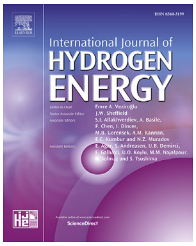

A conceptual design of a dual hydrogen-power generation plant based on the integration of the gas-turbine cycle and copper chlorine thermochemical plant

Hoseyn Sayyaadi

Faculty of Mechanical Engineering-Energy Division, K.N. Toosi University of Technology, P.O. Box: 19395-1999, No. 15-19, Pardis St., Mollasadra Ave., Vanak Sq., Tehran 1999 143344, Iran

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ABSTRACT

The Cu–Cl hydrogen production plants are one of the promising hydrogen production plants that have a higher conversion efficiency compared to water electrolyzing system. However, these plant requires a high-temperature source of thermal energy in the order of 530–560 °C. Such high-temperature source of thermal energy is aimed to be provided from the fourth-generation nuclear reactor. Due to a shortage in the technology of the fourth-generation nuclear reactors in developing countries, one alternative to provide such high temperature of thermal energy is the exhaust gasses of gas-turbine stations. In this paper, a conceptual design for dual production cycle of power and hydrogen-based on the integration of gas cycles into the Cu–Cl thermochemical hydrogen plant was examined. The main product of the cycle was supposed to be 130,000 kg per day. However, the gas cycle is the upper cycle of the dual production plant; the electric power was considered as the byproduct of this plant. The aim was to present a conceptual design of the combined plant with the lowest cost of produced hydrogen and highest conversion efficiency, on the one hand, and the highest and cheapest cost of electric power, on the other hand. In this regard, the concept of pinch analysis and multi-objective optimization was conducted. Moreover, a decision-making tool was employed to find the best combination of gas turbines for the configuration of the upstream cycle. Different configurations of the upper gas cycle were examined by 39 types of commercial gas turbine. The final design of the combined plant could generate hydrogen with 51.3% thermal efficiency, 55.2% exergetic efficiency, and the cost of 4.02 \$ kg^{-1}. This plant used four gas turbine's model Mitsubishi HI 501 F with 735 MW capacity of electric power generation at the cost of 0.10 \$ kWh^{-1}.

E-mail addresses: sayyaadi@kntu.ac.ir, hoseynsayyaadi@gmail.com.

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Nomenclature

AFR	Air-fuel ratio
c	The unit cost of an exergy stream ($\$\cdot kJ^{-1}$)
$\overline{Ex}_d$	Exergy destruction of the plant per mole of generated hydrogen ($kW\cdot mol^{-1}$)
$\dot{E}x$	Exergy rate (kW)
ex	Specific exergy ($kJ\cdot kmol^{-1}$)
$\overline{h}$	Specific molar enthalpy ($kJ\cdot kmol^{-1}$)
$\overline{h}^o$	Specific molar enthalpy at reference state ($kJ\cdot kmol^{-1}$)
$\overline{h}_f^o$	Enthalpy of formation ($kJ\cdot kmol^{-1}$)
$\overline{LHV}$	Molar lower heat value ($kJ\cdot kmol^{-1}$)
$\dot{m}$	Mass flow rate ($kg\cdot s^{-1}$)
$\dot{n}$	Molar flow rate ($kmol\cdot s^{-1}$)
PEC	Purchase equipment cost ($)
$\dot{Q}$	Heat transfer rate (kW)
s	Specific entropy ($kJ\cdot kmol^{-1}\cdot K^{-1}$)
s^o	Specific entropy at reference state ($kJ\cdot kmol^{-1}\cdot K^{-1}$)
T_0	Reference-environment temperature (°C or K)
T	Temperature (°C) or (K)
TRR	Total revenue requirement
$\dot{Z}_k$	The total cost rate of kth component including capital investment and operating-maintenance cost ($\$\cdot h^{-1}$)
$\dot{W}$	Power (kW or MW)

Greek letters

$\eta_{th,\ overall}$	Energy (thermal) efficiency of the plant (%)
$\eta_{ex,\ overall}$	Exergy efficiency of the plant (%)
λ	Excess air
τ	Annual operating hours (h)

Subscripts

0	Reference state
a	Average
ac	Air compressor
c	cold
CI	Capital investment
e	Exit (Outlet)
fg	Flue gases
gt	Gas turbine
h	hot
i	Inlet
k	kth component
q	thermal
reac	Reaction
sys	System
step1,2,3,4,5	Related to reaction step #1 to #5 in CCC

Superscripts

$\dot{}$	Quantity per unit time
$^{\circ}$	Standard reference-state
CH	Chemical
PH	Physical
OM	Operating and maintenance

Acronyms

CCC	Cu–Cl Cycle

Introduction

Hydrogen with a high calorific value is a source of energy that can be used in fuel cells and transportation sector. In addition, hydrogen is widely used in petrochemical industries. One dominant technology for generating hydrogen is various classes of methane reforming. However, this technology depends on the usage of fossil source of fuels. Another alternative for generating the hydrogen is water splitting process. Nevertheless, this technology is not dependent on the usage of fossil fuel as the source of hydrogen, it suffers from low conversion efficiency. Thermochemical processes for water splitting have been introduced as alternatives to the electrolyzing method. These methods depend on water as the feed into the process while they have a higher conversion efficiency compared with the water electrolyzing process. They employed a number of intermediate reactions of chemicals in a way that those chemicals are used in some step reactions and recovered by others. The net outcomes of these processes are split the water molecules into the hydrogen and oxygen through the number of intermediate reactions. More than eight hundred thermochemical cycles have been proposed [1]; however, only a few of them have the potential to be scaled-up into the industrial scale. This is due to the fact that these numerous methods require their own intermediate chemicals, reaction temperature, consumed energy, and conversion reaction. The most promising one needs to be involved with the cheapest and safest chemicals as well as having the lowest reaction temperatures, less energy consumption, and the highest conversion efficiency. In addition, the lowest number of step reactions as well as the simplest form of chemical reactors are highly desired. Among numerous thermochemical cycles, only a few cycles have these potentials to be converted from the laboratory scale into the industrial one. The Copper–Chlorine (Cu–Cl) cycle called as CCC hereinafter is among those few promising thermochemical cycles. Its highest reaction temperature is in the range of 530–560 °C making it as an ideal option to be coupled with small nuclear reactors, renewable energy such as solar energy, and waste heats. Tolga Balta et al. [2] provided a comparative assessment on different chlorine family, including (Cu–Cl), magnesium-chlorine (Mg–Cl), iron-chlorine (Fe–Cl) and vanadium-chlorine (V–Cl) cycles from the energy and exergy analysing aspects and found that the V–Cl cycle was one of the most promising low-temperature cycles due to a high efficiency; however, the Cu–Cl cycle was still among the desired thermochemical cycles.

The copper and chlorine compounds attained several intermediate reactions in the CCC, and the outcomes are splitting the water molecules into the hydrogen and oxygen in such a way that all copper and chlorine compounds are recovered in subsequent reactions. Therefore, the feed to the plant is water and products are hydrogen and oxygen. In CCC, through a series of chemical reactions with the interference of chlorine and copper compounds, water is decomposed into hydrogen and Oxygen. The CCC family employs 3–5 steps of intermediate reaction depending on the type of the cycle. A most efficient and famous one is the five-step cycle which includes (1) HCl production step, (2) O_2 production reaction, (3)