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Exergy analysis and optimization of a combined cooling and power system driven by geothermal energy for ice-making and hydrogen production

Liyan Cao, Juwei Lou, Jiangfeng Wang*, Yiping Dai

Institute of Turbomachinery, Shaanxi Engineering Laboratory of Turbomachinery and Power Equipment, State Key Laboratory of Multiphase Flow in Power Engineering, School of Energy and Power Engineering, Xi'an Jiaotong University, Xi'an 710049, China

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ABSTRACT

This paper investigates a combined cooling and power system driven by geothermal energy for ice-making and hydrogen production. The proposed system combines geothermal flash cycle, Kalina cycle, ammonia-water absorption refrigeration cycle and electrolyser. The geothermal energy can be efficiently converted to storable hydrogen and ice. Based on mathematical model, some key parameters are analyzed to figure out their effect on the exergetic performance. An exergy destruction analysis for all components has been performed to find out the distribution of exergy inefficiency. The system exergetic efficiency is optimized by Jaya algorithm and Genetic algorithm and the optimization results are compared. According to the parametric analysis, the exergy efficiency decreases as the back pressure of steam turbine and the back pressure of ammonia-water turbine increase. The exergy efficiency could increase first and then decline, as flash pressure, ammonia-water turbine inlet pressure and ammonia mass fraction of basic solution increase. The optimization results show that the exergy efficiency reaches 23.59%, 25.06% and 26.25% when the geothermal water temperature is 150 °C, 160 °C and 170 °C. Jaya algorithm has highly precise optimization results.

1. Introduction

In recent years, the demand for fossil fuels increases dramatically, which has aroused great concerns about the environmental pollution, greenhouse gas emission and security of energy supply. Different countries have made plans to achieve diversification of energy supply and increase the proportion of renewable energy. Geothermal energy is one of reliable, sustainable and environmentally friendly renewable energy, which has drawn great attention.

Worldwide, geothermal power generation is the most common and efficient method for geothermal utilization. Geothermal power generation technologies in use mainly include flash cycle, binary cycle and flash-binary cycle. Researchers conducted analysis and optimization of the flash cycle [1–3]. The optimization results exhibited the optimum flash pressure to maximize the power output. But the flash cycle requires a relatively high geothermal water temperature. For the geothermal well with low water temperature, Kalina cycle [4–7] is regarded as reliable technologies, since Kalina cycle take full advantage of ammonia-water mixture. Owing to its low-boiling point and temperature slide character, ammonia-water mixture can achieve better thermal match in evaporator to reduce the irreversible loss. On this basis, Kalina cycle has applied as the bottom cycle of flash cycle to improve the thermal and exergy efficiency [8,9]. The comparison results showed that flash-Kalina cycle generated more power than double-flash cycle did. However, the traditional flash cycle, Kalina cycle or flash-Kalina cycle only generate power, which cannot satisfy the diversified energy demand of users.

The cogeneration systems can supply users with different kinds of energy including electricity, heat and cooling, but more importantly, it has higher energy efficiency. From thermodynamic point of view, cooling is not an easily accessible energy compared to heat. It is usually converted from heat or electricity. Therefore, this brings a focus on the combined power and cooling (CCP) system employing ammonia–water as working fluid. Goswami and Xu [10,11] came up with a CCP system based on ammonia-water absorption refrigeration cycle. They claimed that this system had potential for efficient recovery of low-grade heat source. Rashidi and Yoo [12] proposed a CCP system that combined the Kalina power cycle and the ejector absorption refrigeration cycle. They compared this new system with another CCP system and found the new system had higher refrigeration output and thermal efficiency. Shokati *et al.* [13] came up with a new CCP system. The proposed cycle was the combination of a Kalina cycle and an absorption refrigeration cycle. Han *et al.* [14] conducted experimental investigation on a combined refrigeration/power generation system. The net power output and

* Corresponding author.
E-mail address: jfwang@mail.xjtu.edu.cn (J. Wang).

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Nomenclature

C	cost rate ($·year^{-1})
c	costs per unit of exergy ($·J^{-1});
c_p	specific heat capacity, kJ/(kg·K)
E	exergy, kW
HHV	higher heating value, kJ/mol
h	specific enthalpy, kJ/kg
I	exergy destruction, kW
M	molecular weight, g/mol
m	mass flow rate, kg/s
Q	energy, kW
q	quality
s	specific entropy, kJ/(kg K)
T	temperature, K
t	temperature, °C
V	volumetric flow rate, L/s
VG	vapor generator
W	power, kW
W_y	annual power (J·year^{-1});
x	ammonia mass fraction, %
Z	annually levelized cost value ($·year^{-1})

Greek letters

ρ	density, kg/m^3
η	efficiency, %

Subscript

amb	ambient
awt	ammonia-water turbine
basic	ammonia-water basic solution
elec	electrolyser
exg	exergy
F	fuel
gen	generating
geo	geothermal water
H_2	hydrogen
ice	ice
in	inlet
l	liquid
mech	mechanical
motor	motor
net	net
P	product
poor	ammonia-poor solution
poor2	secondary ammonia-poor solution
pump	pump
ref	refrigeration
rich	ammonia-rich vapor
rich2	secondary ammonia-rich vapor
s	isentropic
st	steam turbine
tot	total
v	vapor
1–28	state point

cooling output were 1.02 kW and 11.67 kW.

However, the energy demand may fluctuate with time. This will trigger the mismatch between energy supply and demand. For lower energy demand, the operation condition of CCP system can be adjusted to meet the change of energy demand, but CCP system will deviate from the design condition and go against the efficient operation. To solve this problem, some researchers try to store electricity energy into hydrogen energy to eliminate the energy mismatch. Yüksel [15] conducted thermodynamic analysis for a combined cooling, power and hydrogen production system driven by solar energy. The high-temperature water from solar collector was the heat source for an Organic rankine cycle and an absorption cooling system to produce electricity and cooling, respectively. A part of electricity was used for hydrogen production by a Proton Exchange Membrane (PEM) electrolyser. Khanmohammadi *et al.* [16] proposed a similar combined cooling, power and hydrogen production system and carried out a parametric study to determine the main design parameters and their effects on the system performance. Akrami *et al.* [17] proposed multi-generation system comprised of a geothermal based organic Rankine cycle, domestic water heater, absorption refrigeration cycle and PEM electrolyser. The geothermal water was used to drive ORC and to heat the domestic water up, successively. A part of power generated by organic turbine was used for hydrogen production and organic turbine exhaust was used as the heat source of absorption refrigeration cycle. Yuksel *et al.* [18] came up with a novel integrated geothermal energy-based system for cooling and hydrogen production. The cooling and hydrogen was produced by an absorption refrigeration cycle and PEM electrolyser, separately. They claimed that the energetic and exergetic efficiencies of the integrated system could reach to 42.59% and 48.24%, respectively. Parham *et al.* [19] proposed a novel multi-generation system including an open absorption heat transformer, an ORC and an electrolyser for hydrogen production. They analyzed the system from both first and second laws of thermodynamics. Boyaghchi and Safari [20] proposed a new designed quadruple energy production system integrated with geothermal energy, which could produce electricity power, heating, cooling and hydrogen. They conducted thermoeconomic analysis and optimization for the system, and found that the total avoidable investment cost rate is improved within 17.4% relative to the base point. Ahmadi *et al.* [21] proposed a multigeneration energy system to produce power, heating, cooling, hot water and hydrogen. They performed multi-objective optimization for the system and determined the optimum thermoeconomic performance.

All the combined cooling, power and hydrogen systems could convert electricity to hydrogen that can be easily stored to counter the mismatch between supply and demand. However, these papers don't take the cooling mismatch into consideration. In addition, all the systems generate electricity and cooling with separate cycles, and different cycles run with different working medium. As a result, the systems have very complex configurations. We believe that the cogeneration system could have a more compact configuration and all the products are storable. Toward this end, we propose a combined cooling and power system driven by geothermal energy for ice-making and hydrogen production in this paper. The system consists of a top geothermal flash cycle, a bottom combined cooling and power cycle as well as an electrolyser. For the bottom cycle, both Kalina cycle and absorption refrigeration cycle can adopt ammonia-water as working fluid, we integrate Kalina cycle with absorption refrigeration cycle by sharing same key components to simplify the system configuration. And electricity and cooling are converted to storable hydrogen and ice, respectively. We also conduct a parametric analysis to study the effect of key parameters on system performance. In addition, we use a novel optimization algorithm named Jaya algorithm to optimize the systems and compare the Jaya algorithm with Genetic algorithm to verify its accuracy.