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Energy, entropy and cost analysis of a combined power and water system with cascade utilization of geothermal energy

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ABSTRACT

This paper proposed a novel combined system to achieve the cascade utilization of geothermal energy for joint power and water production. A regenerative organic Rankine cycle (ORC) is adopted as the top cycle, while a desalination system based on humidification dehumidification (HDH) principle with open-air architectures is applied to further utilize the geothermal energy. Based on the streams within the ORC and HDH units, the corresponding mathematical models with mass and energy conservation are established, and performance simulation according to thermodynamic laws is fulfilled. Furthermore, cost analysis of the combined system is also accomplished to reveal the correlations between the system economy and the involved parameters. The research results show that the actual peak values of net power, water production and gained-output-ratio (GOR) reach 42.68 kW, 236.81 kg h^{-1} and 1.42, and the total efficiency of the entire system is 31.19%. Based on the obtained thermodynamic performance, the bottom cost of the entire system is found as 4983.83$ with a total heat and mass transfer areas of 104.27 m^2 at the balance condition of the humidifier. Furthermore, according to the influence analysis, an elevation of the evaporation temperature of the ORC, which is within the prescribed range, is beneficial to improve the thermodynamic performance and the relevant cost of the combined system.

1. Introduction

Owing to the rapid development of industry in the past several centuries, the problems of energy and environment are becoming more and more serious. As well known, electricity and freshwater are the two important necessities both for life and industrial production, and the traditional producing process will consume large amount of fossil fuel and release contaminant [1]. As a result, renewable energy, such as wind, solar, biomass and geothermal energy, with clean characteristics attracted extensive attentions all over the world [2,3]. Thereinto, geothermal energy, which emerges as geothermal steam, including dry and wet type, and geothermal water, has been investigated and taken into reality to generate power with different types in the relevant abundant space.

A single flash thermal cycle was introduced into power generation to utilize the geothermal energy, with a temperature of 513 K, by Jalilinasrabady [4]. On the basis of the thermodynamic mathematical models, a peak net power of 31 MW can be attained under the applied architecture, with the flashing pressure of 5.5 bar and discharged pressure of 0.3 bar. In order to improve the energy utilization efficiency, a double flashing structure was then proposed, and the maximum net power can be updated to 49.7 MW. A comparative study concerning different styles of geothermal power plant, with the geothermal resources having a temperature of 503 K, was achieved [5]. After building mathematical models for various thermal cycles, the corresponding energetic and exergetic analysis was completed, and the obtained results from different cycle configurations are analyzed and compared. It was concluded that the energy utilization efficiency of the binary structure with a regenerative ORC had a peak value of 15.35%. Fiaschi [6] conducted a energetic and exergoeconomic analysis driven by two geothermal fluid reservoirs, with Kalina, carbon dioxide and organic Rankine cycles, for power generation. The two geothermal resources are a medium-temperature heat source of 485.15 K in Mt. Amiata, Italy, and a low-temperature heat source of 393.15 K in Pomarance geothermal basin, Italy. The analysis results presented that the ORC with R1233zd (E) has the best exergoeconomic performance for the medium-temperature conditions while the Kalina cycle has the best performance compared to other ORC configurations. Yang [7] proposed an organic Rankine cycle to generate power with geothermal resource from abandoned oil wells, with a temperature of 383 K. With R245fa as the cycling working fluid, a four-stage axial turbine was appointed in the ORC, and an onsite test showed that the efficiency of the turbine and entire cycle can reach 78.52% and 5.33%, respectively. The research results and method could give some significant references for the

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Nomenclature

Roman symbols

a	specific area ($m^2 m^{-3}$)
A	heat transfer surface area (m^2)
b	channel height of the plate type heat exchangers (mm)
E	exergy (kW)
h	enthalpy ($kJ\,kg^{-1}$); convective heat transfer coefficient ($WK^{-1} m^{-2}$)
H	total enthalpy (kW)
h_{fg}	latent heat ($kJ\,kg^{-1}$)
k	mass transfer coefficient ($kg\,m^{-1} s^{-1}$)
L_{vg}	length along the vapor generator (m)
L_{sh}	length along the seawater heater (m)
m	mass flow rate ($kg\,s^{-1}$)
Nu	Nusselt number
P_r	Prandtl number
Q	heat load (kW)
Re	Reynolds number
s	specific entropy ($J\,kg^{-1} K^{-1}$);
S	concentration of seawater ($g\,kg^{-1}$); entropy rate (WK^{-1})
T	temperature (K)
U	heat transfer coefficient ($WK^{-1} m^{-2}$)
V	volume (m^3)
W	width of the plate (mm)

Greek letters

β	plate chevron angle (°)
ζ	effectiveness during the humidification or dehumidification
λ	thermal conductivity ($WK^{-1} m^{-1}$)
φ	coefficient of area expansion
ω	humidity ratio ($g\,kg^{-1}$)
δ	Thickness (m)

Subscripts

a	air
b	brine
d	dehumidifier; destruction
da	dry air
ex	exergy
g	generator
gen	generation
gw	geothermal water
h	humidifier
i	inlet
l	liquid
m	mechanical; middle
max	maximum
min	minimum
o	outlet
orc	organic Rankine cycle
p	plate; pump
sh	seawater heater
sw	seawater
t	total
tur	turbine
v	vapor
vg	vapor generator
vr	vapor recuperator
w	water

Abbreviation

GOR	gained-output-ratio
HDH	humidification dehumidification
HMTD	heat and mass transfer device
LMTD	log mean temperature difference
ORC	organic Rankine cycle
PTD	pinch temperature difference
PTHE	plate type heat exchanger
RH	relative humidity
SH	seawater heater
TTD	terminal temperature difference
VR	vapor recuperator
WR	water recuperator
VG	vapor generator

desirable power plants with the geothermal energy from the abandoned oil wells.

In accordance with the previous literature survey, it can be summarized that the specific architecture of the power plant for geothermal energy utilization differed with the temperature of the geothermal resources [8,9]. For a geothermal resource with low temperature, novel power cycles, such as Kalina, carbon dioxide and organic Rankine cycles are suitable choices due to a low boiling point [10–12]. As well known, cascade utilization is the essential principle during energy conversion and management processes. Hence, the discharge geothermal resource from the power plant can be further applied for water production, even for the low temperature geothermal resources, because the temperate demand to drive the desalination system is lower that of the power systems. The remaining problem is to look for a satisfied desalination method to complete the purpose of water production. Desalination system with humidification dehumidification processes [13,14], which simulates the water circulation in the nature environment, is just the appropriate candidate.

A novel HDH desalination system, with half open-air, open-water architecture, was proposed by Mahdizade [15]. Thermodynamic analysis of the novel structured HDH desalination system was accomplished, and the fundamental performance enhancement was also enhanced when the top temperature was fixed. Compared to the ambient humidity, It was found that the ambient temperature is much more critical for the performance of the desalination process. The novel HDH desalination method was proved to have great advantages compared to the general closed air versions due to the elevation of the gained-output-ratio. Chehayeb [16] simulated the thermodynamic performance of the single and two-stage water-heated HDH desalination system, with a packed bed humidifier and a bubble column dehumidifier. The variation trends of the flow rate ratio to affect the entropy generation rate of the entire system and heat and mass transfer forces were explored. Based on the modified definition of energy effectiveness, the measures of air extraction and injection were used to enhance the performance of the humidification dehumidification desalination system. Based on the simulation results, the relevant improvement effect and mechanism were also investigated. An indirect solar dryer was introduced into the HDH desalination system by Kabeel [17], and the relevant system performance was tested. An improvement amplitude of 29% for GOR was obtained through increasing the involved air flow rate. He [18] conducted a thermo-economic analysis of a water-heated HDH desalination unit with waste heat recovery. Based on the thermo-economic analysis, it was revealed that waste heat powered HDH desalination unit have great advantages compared to the