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Development and multi-objective optimization of geothermal-based organic Rankine cycle integrated with thermoelectric generator and proton exchange membrane electrolyzer for power and hydrogen production

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ABSTRACT

The aim of this study is to enhance the performance of a geothermal-based organic Rankine cycle by proposing two novel systems in which some part of the waste heat is recovered employing thermoelectric generator for power and/or hydrogen production (using proton exchange membrane electrolyzer). Accordingly, two novel systems are proposed and analyzed along with the basic organic Rankine cycle (configuration (a)). In the first proposed system, some part of the waste heat is recovered by employing thermoelectric generator (configuration (b)), while in the second one the additional power generated by thermoelectric generator is used in the proton exchange membrane electrolyzer for hydrogen production (configuration (c)). The performances of the proposed systems are investigated and compared with that of the basic cycle from energy, exergy and exergoeconomic viewpoints and are optimized using genetic algorithm via a multi-objective optimization strategy. The results indicate that, at the best solution point obtained from multi-objective optimization, the exergy efficiencies of the proposed systems (configurations (b) and (c)) are higher than that of the basic organic Rankine cycle by 21.9% and 12.7%, respectively. Furthermore, another interesting result is found which reveals that the specific product cost for the proposed configurations (b) and (c) is lower than that for the basic organic Rankine cycle, despite the higher total cost rate for the proposed configurations.

1. Introduction

The environmental problems resulting from fossil fuels have forced the researchers to explore alternative (especially renewable-based) energy sources and to design and optimize novel integrated co-generation systems and technologies. Electricity generation from geothermal energy is becoming more and more attractive in recent years, where Organic Rankine Cycles (ORCs) are considered as promising power generation systems. For a given medium heat source temperature, these systems have relatively low efficiency, for which the relatively high turbine exit temperature is the main reason. Thus, their performance can be improved by integrating with other systems and optimizing the performance. Among the major optimization approaches, which are widely considered in the literature for energy conversion systems, maximizing the exergy efficiency and minimizing the total cost rate is an effective one. However, as these two objectives are conflicting each other for the majority of optimization problems, the multi-objective optimization (MOO) is essential.

1.1. Organic Rankine cycle

In the recent relevant literature, employing renewable-based co-generation power plants is becoming a hot topic as they can contribute towards the world energy policy targets such as: sustainable and secure power supply [1]. Among the renewables, geothermal one is considered as a reliable and promising energy source. For power generation from geothermal resources, Organic Rankine Cycles (ORCs) are adopted as favorite technologies for their configuration simplicity, components availability and better economics. Over the last two decades, a large number of studies have been devoted to ORC-based systems' analysis and optimization by single and MOO methods.

Braimakis and Karellas [2] analyzed and optimized different ORC configurations with various working fluids from the energetic viewpoint. They reported relative efficiency gains, ranging from 4.98% to 9.29%, for recuperative configurations over the basic ORC. Sun et al. [3] analyzed and compared two combined ORC based systems driven by low-temperature waste heat employing absorption refrigeration

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Nomenclature

A	area (m^2)
c	specific cost ($/GJ)
$\dot{C}$	cost rate ($/h)
E	energy (J/mol)
$\dot{E}$	exergy rate (kW)
F	Faraday constant (C/mol)
G	Gibbs free energy (J/mol)
h	specific enthalpy (kJ/kg)
i_r	interest rate
J	current density (A/m^2)
J_i^{ref}	pre-exponential factor
K	thermal conductance (W/m K)
$\dot{m}$	mass flow rate (kg/s)
n	operating years
P	pressure (kPa)
$\dot{Q}$	heat rate (kW)
R	resistance (Ω)
$\overline{R}$	ideal gas constant (J/K mol)
s	specific entropy (kJ/kg K)
T	temperature (K, °C)
V	voltage (V)
V_0	reversible potential (V)
$V_{act,an}$	activation over potential of anode (V)
$V_{act,ca}$	activation over potential of cathode (V)
V_{ohm}	ohmic over potential (V)
$\dot{W}$	power (kW)
$\dot{Z}$	investment cost rate ($/h)
Z	figure of merit (1/K)
ΔG	change in Gibbs free energy (kJ/mol)
ΔT	temperature difference between cold and hot side of the TEG (K)
ΔS	change in entropy (kJ/K)
ΔH	change in enthalpy (kJ)

Subscripts

0	dead state
1, 2, 3…	state numbers
an	anode
ca	cathode
Cond	condenser
C.V	control volume
D	destruction
ELEGANT	efficient liquid based electricity generation apparatus inside Thermoelectric
ev	evaporator
H	high
I	first law
II	second law
in	inlet
L	low
ohm	ohmic
p	product
p,p	pinch point
pu	pump
reacted	amount of reacted component
SG	steam generator
t	turbine
sup	superheater
tot	total

Superscripts

CI	capital investment
OM	operating and maintenance

Abbreviations

CRF	capital recovery factor
HHV	higher heating value
MOO	multi-objective optimization
ORC	organic Rankine cycle
PEM	proton exchange membrane
TEG	thermoelectric generator

Greek letters

η	efficiency
$\sigma(x)$	local ionic conductivity (s/m)
$\lambda(x)$	content of water at distance x (1/Ω)
τ	annual operating hours
ψ	seebeck coefficient (V/K)

cycle and ejector refrigeration cycle. The results indicated that the exergy efficiency of the system in which absorption chiller is used is higher than that of the ejector system by around 20%. Yang et al. [4] used the genetic algorithm to optimize the ORC performance employed to recover the waste heat of a diesel engine. They considered the net output power and exergy destruction rate as separate objective functions and reported a value of 13.84 kW for the net output power at the optimal operating condition. Considering the exergy efficiency and specific cost of output power, single and MOO are performed for a novel ORC-based configuration for Sabalan geothermal power plant by Aali et al. [5], who also examined different ORC working fluids. They found R141b as the best working fluid and showed that, for single objective optimization, the specific cost of power is 4.901 $/GJ with an exergy efficiency of 52.56% for the plant, while the MOO leads to an exergy efficiency of 54.87% with a power cost of 5.068 $/GJ. Fiaschi et al. [6] analyzed and compared ORC and Kalina cycles driven by low and medium temperature from exergoeconomic point of view. The results showed that, the ORC has better exergoeconomic performance with lower product cost by 3% as compared to the Kalina cycle. Xi et al. [7] accessed and optimized the performance of three different ORC configurations for various working fluids using genetic algorithm for low grade waste heat recovery considering the exergy efficiency as the single-objective function. Their results indicate that the double-stage regenerative system has the highest energy and exergy efficiencies and R141b is one of the recommended working fluids. The ORC performance for low temperature heat sources accessed thermodynamically by Wang et al. [8], who implemented genetic algorithm to conduct a single objective optimization considering the net output power as the objective function. At the optimal operating condition, they reported a value of 49.88 kW for net output power and showed that the best system performance could be achieved using isobutene as the ORC working fluid. Ozahi et al. [9] analyzed and optimized an ORC-based system integrated with a solid waste power plant. The results showed that toluene would be the best working fluid with the maximum power output of 584.6 kW and exergy efficiency of 15.69%. The multi-objective optimization results revealed that the power output and total cost rate of the system using toluene as the working fluid are 550 kW and 51 $/h, at optimum solution point. To compare the performance of various ORC configurations for binary geothermal power plants, Zare [10] conducted an exergoeconomic analysis and single-objective optimization considering the total product cost rate as the objective function. He concluded that, from the thermodynamic point of view, the ORC with