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Performance assessment and optimization of a novel multi-generation system from thermodynamic and thermoeconomic viewpoints

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ABSTRACT

Multi-generation systems are promising technologies for multiple production applications to reduce the waste heat of the basic system. For this purpose, a novel multi-generation system using geothermal heat source is proposed which produces different commodities of cooling, heating, power and freshwater, simultaneously. The system comprises of a Kalina cycle, an absorption refrigeration cycle, a humidification-dehumidification desalination system, and a domestic water heater unit system. Exergoeconomic optimization of the proposed system is conducted, showing that the optimum thermal efficiency, exergy efficiency and total SUCP (sum unit cost of the product) can be obtained 94.84%, 47.89%, and 89.95 $/GJ, respectively. Moreover, a comprehensive parametric study showed that the Gained-Output-Ratio, freshwater, thermal efficiency and exergy efficiency can be optimized based on the desalination mass flow rate ratio. In addition, it is demonstrated that a higher thermal efficiency can be obtained by increasing vapour generator pinch point temperature difference, turbine inlet pressure, and evaporator temperature or decreasing condenser temperature, absorber temperature, basic ammonia concentration, desalination top temperature, desalination bottom temperature, and heater terminal temperature difference. Whereas, a higher exergy efficiency can be attained at high evaporator temperature, basic ammonia concentration, and desalination bottom temperature or low vapour generator pinch point temperature difference, turbine inlet pressure, condenser temperature, absorber temperature, desalination top temperature, and heater terminal temperature difference.

1. Introduction

Optimization and performance enhancement of thermal systems are considered as a challenging scenario worldwide. The issues mainly related to the supply and consumption of energy sources along with their side effects which are concerned with global issues. In this manner, improvement in the energy consumption and conversion may lead to more efforts [1]. One way to enhance the performance of energy systems can be their integration in appropriate forms for multi-generation purposes, using low-temperature heat sources such as waste heat from industrial processes, renewable energies (e.g., solar energy, geothermal energy, biomass, etc.) and so on [2]. Cycles which use organic or multi-component working fluids, such as Kalina cycle (KC), organic Rankine cycle (ORC), absorption chiller cycle (ACC), can use these low-temperature heat sources to produce single production or multiple productions. For example, Saffari et al. [3] presented a new geothermal-based KC for single-production purposes which was employed in Husavic power plant. For multiple productions purposes, Han et al. [4] proposed a combined power/refrigeration cycle using a low-grade heat source.

Proposal and assessment of novel combined/integrated energy systems based on the well-known thermodynamic systems is one method to improve the performance of basic systems. With this respect, multi-generation systems provide more efficient way by using different kinds of primary energy resources [5].

1.1. Kalina cycle

Many investigations are focused on performance evaluation of well-known power-based cycles. Among all these power-based cycles, Kalina cycle (KC) has gained more popularity in recent years due to its simple as well as efficient mechanism. KC which is actually a modified organic Rankine cycle uses the ammonia-water mixture as working fluid. Because evaporation and condensation of ammonia-water mixture do not occur at a constant temperature, so in the condenser and evaporator of the KC a high temperature exists which improves the cycle performance [6]. In addition, KC performs much better than the ORC at moderate pressures [7]. Lolos and Rogdakis [8] presented and analyzed a Kalina-type cycle using the stored solar energy of 70 °C as the main

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Nomenclature

Symbols

A	area (m^2)
ARC	absorption refrigeration cycle
c	cost per exergy unit ("\$" GJ^{-1})
$\dot{C}$	cost rate ("\$" yr^{-1})
COD	cost optimal design
CRF	capital recovery factor
DWH	domestic water heater
ex	exergy per unit mass (kW kg^{-1})
$\dot{Ex}$	exergy rate (kW)
EEOD	exergy efficiency optimal design
GA	genetic algorithm
GOR	gained-output-ratio
h	specific enthalpy (kJ kg^{-1})
HCR	heat capacity ratio
HDH	humidification-dehumidification
k	interest rate
LMTD	logarithmic mean temperature difference (K)
$\dot{m}$	mass flow rate (kg s^{-1})
mr	mass flow rate ratio
MG	multi-generation
MOF	multi-objective function
MOOD	multi-objective optimal design
N	annual number of hours (h)
n_r	components expected life
P	pressure (kPa)
$\dot{Q}$	heat transfer rate (kW)
R	universal gases constant (J kg^{-1}K^{-1})
s	specific entropy (kJ kg^{-1} K^{-1})
SUCP	sum unit cost of the product
T	temperature (K)
TEOD	thermal efficiency optimal design
TER	turbine expansion ratio
TTD	terminal temperature difference
T.V	throttlin valve
U	overall heat transfer coefficient (kW m^{-2}K^{-1})
v	specific volume (m^3 kg^{-1})
w	weight coefficient
$\dot{W}$	power (kW)
X_B	ammonia mass fraction of basic solution (%)
Z	investment cost of components (\$)
$\dot{Z}$	investment cost rate of components ("\$" yr^{-1})

Greek symbols

η	efficiency (%)
ω	humidity ratio
ϕ_r	maintenance factor
ε	effectiveness

Subscripts and superscripts

a	air
Abs	absorber
CD	condenser/desorber
ch	chemical
CI	capital investment
Cond	condenser
c.v.	control volume
D	destruction
da	dry air
De	desorber
Dhum	dehumidifier
DWH	domestic water heater
Eva	evaporator
ex	exergy
F	fuel
FW	freshwater
Geo	geothermal
Hum	humidifier
in	inlet
is	isentropic
i	ith component
L	loss
max	maximum
mix	mixer
net	net value
OM	operating & maintenance
out	outlet
P	product
Pc	precooler
ph	physical
PP	pinch point
Pum	pump
Q	heating
R	reference
Rec	rectifier
Reg	regenerator
s	constant entropy
Sep	separator
SHE	solution heat exchanger
sw	seawater
system	overall system
th	thermal
total	total value
Tur	turbine
TV	throttling valve
v	vapor
VG	vapor generator
W	work
wb	wet-bulb
1, 2, …	cycle locations
0	dead state

source and a low-temperature external heat source of 130 °C for power production purposes. They evaluated their system by considering following operating conditions: cycle minimum temperature of 20 °C, evaporator temperature of 70 °C, and low pressure of 0.18–2 bar. Considering different values of ammonia-water concentration, they demonstrated that the thermal efficiency and output power can be maximized, while heat ratio can be minimized. They also presented a couple of equations between operational and performance parameters to estimate the cycle performance under given initial conditions. In another study performed by Sun et al. [9], an auxiliary superheater used in a solar-driven KC showing that the mass flow rates of KC and solar collector sub-cycle and also ammonia-water concentration are important parameters for optimization. The significant operating conditions assumed in their work were included ammonia mass fraction (95%), solar collector efficiency (60%), and sampling month of August. Fallah et al. [10] presented conventional and advanced exergy analysis of the Kalina cycle driven by a low-temperature geothermal source. The results of conventional exergy analysis by this group revealed that evaporator accounts for the highest exergy destruction among all components; however, advanced exergy analysis showed that condenser had the