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Off-design performance analysis of a combined cooling and power system driven by low-grade heat source

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ABSTRACT

The combined cooling and power (CCP) system integrating the organic Rankine cycle with the ejector refrigeration cycle is a modern solution for low-grade geothermal water. This paper conducts a quantitative analysis of the off-design performance of a CCP system based on a specially designed combination of a radial inflow turbine, an ejector and plate heat exchangers. The CCP system operating at a vapor split ratio of 0.5 is studied, and a novel preliminary design and off-design simulation process are presented. The sliding pressure operation strategy is used to achieve good off-design performance. The results indicate that the CCP system produces 153.76 kW cooling and has a cooling to net power ratio of 1.58 at the design point. The increasing geothermal water mass flow rate ratio could lower thermal efficiency, exergy efficiency and cooling to net power ratio. Higher geothermal water inlet temperature results in lower thermal efficiency. Among the geothermal water inlet temperature, the saturated condensing temperature and the evaporator saturated temperature, the net power is affected mostly by the saturated condensing temperature while the cooling and thermal efficiency are mostly influenced by the evaporator saturated temperature.

1. Introduction

In the industrial production and daily life, power and cooling are in great demand. The combined power and cooling (CCP) system has higher energy conversion efficiency than that of a separated power and cooling system. Most of the conventional power and cooling cogeneration systems are driven by fossil energy. With the escalating concerns of primary energy shortage and pollutant emission, it is necessary to use low-grade thermal energy such as geothermal resource, solar energy, and industrial waste heats. The CCP system for low-grade heat source has attracted increasing attention in recent years.

Goswami et al. [1] constructed a cogeneration system using ammonia-water (called Goswami cycle). They combined a Rankine cycle with an absorption refrigeration cycle. The thermodynamic performance of the Goswami cycle was analyzed [2,3]. However, the cooling output of the Goswami cycle was relatively small because only the sensible heat was transferred when the turbine exhaust flowed through the cooler.

In order to have a stronger cooling effect, a phase change of working fluid in the cooler is needed. Some researchers combined a Kalina cycle with an absorption refrigeration cycle to produce power and cooling simultaneously [4–10]. Wang et al. [11] developed a new CCP system by integrating the Kalina cycle with the absorption refrigeration cycle. The turbine exhaust passed through a separator for purer ammonia vapor. Then the purer ammonia vapor was guided into an evaporator to produce cooling. In order to generate refrigeration, Cao et al. [12] introduced an ammonia-water absorption refrigeration cycle to absorb the poor ammonia-water heat from a Kalina cycle. Kumar et al. [13] established a CCP system by coupling the Kalina cycle with the absorption refrigeration cycle. The results showed that the proposed system could produce 15 kW cooling and 2 kW net power when the ammonia-water vapor split ratio was 0.5.

In addition, various types of the CCP systems driven by low-grade heat source were also investigated. The ejector refrigeration cycle has been widely studied theoretically and experimentally [14–19]. Due to the advantages of low operating and maintenance cost, a large number of researchers investigated the combined power and ejector refrigeration system. Ghaebi et al. [20] proposed a combined power and ejector refrigeration system based on the Kalina cycle, in which the turbine exhaust could entrain the low pressure secondary flow from the evaporator. Barkhordarian et al. [21] developed a new power and cooling cogeneration system by combining a Kalina cycle and an ejector

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Nomenclature

a	sonic velocity (m/s)
b	blade height (mm)
Bo	boiling number
c	absolute velocity (m/s)
cd	channel distance (mm)
D	hydraulic diameter (m)
E	exergy (kW)
F	area (m^2)
G	mass velocity (kg/m^2 s)
h	enthalpy (J/kg)
H	head (m)
J	convection heat transfer coefficient (W/m^2 K)
K	loss efficient
L	loss (J/kg)
m	mass flow rate (kg/s)
M	loss model multiplier
Ma	Mach number
n	incidence angle (°)
N	rotational speed (rpm)
N_s	specific speed
Nu	Nusselt number
P	pressure (kPa)
Pl	plate length (m)
Pr	Prandtl number
Pt	plate thickness (mm)
Pw	plate width (m)
q	volumetric flow rate (m^3/s)
Q	heat transfer rate (kW)
r	radius (mm)
Re	Reynolds number
s	entropy (J/kg K)
T	temperature (°C)
u	circus velocity (m/s)
U	overall heat transfer coefficient (W/m^2 K)
U/C_0	velocity ratio
w	relative velocity (m/s)
W	power (kW)
X	vapor quality
Z	blades number

Greek letters

α	absolute fluid velocity angle (°)
β	relative fluid velocity angle (°)
χ	cooling/net power ratio
δ	clearance (m)
η	efficiency
θ	chevron angle (°)
λ	thermal conductivity (W/m K)
ρ	density (kg/m^3)
μ	viscosity (N s/m^2)
ω	angular velocity (rad/s)
ζ	ejector entrainment ratio
ΔP	pressure drop (kPa)
ΔT_{lmtd}	log mean temperature difference (°C)

Subscripts

01,02,03,04	state point in the radial inflow turbine
1,2,3,4,5,6,7,8	state point of working fluid
c	back
ce	constant area region exit of ejector
$cold$	cold
con	condenser
cr	critical
de	diffuser exit of ejector
des	design
eq	equivalent
eva	evaporator
ex	exergy
f	friction
gas	gas
gw	geothermal water
hot	hot
hub	hub
i	incidence
in	inlet
is	isentropic
liq	liquid
m	mean
mi	location where two streams of ejector finish mixing
min	minimum
ne	nozzle exit of ejector
net	net
opt	optimum
out	outlet
p	ejector primary flow
pa	passage
pum	pump
r	radial component
$rotor$	rotor
s	ejector secondary flow
$stator$	stator
sh	shock location
t	ejector nozzle throat
th	thermal
tur	turbine
tip	tip
u	tangential component
vap	vapor generator
$wall$	plate wall
y	location where two streams of ejector begin to mix
z	axial component

refrigeration cycle. This novel cogeneration system could generate refrigeration at two temperature levels.

Most of the previous CCP systems used ammonia-water as working fluid. However, ammonia-water was toxic and dangerous. Therefore, a combination of an organic Rankine cycle and an ejector refrigeration cycle using environmentally friendly organic working fluid has become the interest of a large number of researchers. Wang et al. [22] established a novel CCP system based on an organic Rankine cycle and an ejector refrigeration cycle. An extraction turbine was added between the vapor generator and the ejector. They found that the exergy destruction mostly occurred in vapor generator, ejector and turbine. Dai et al. [23] optimized the thermodynamic parameters of a new combined power and ejector refrigeration system using R245fa. The maximum exergy efficiency of their system was 27.10% under the studied conditions. Zheng et al. [24,25] integrated an organic Rankine cycle with an ejector refrigeration cycle to produce power and cooling. The results revealed that the expansion ratio across turbine could influence the ratio of power to cooling. Xia et al. [26] recommended a novel CCP system including an organic Rankine cycle and an ejector refrigeration cycle to utilize the waste heats from the internal combustion engine.