Energy 97 (2016) 470–487

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Comprehensive analysis and parametric optimization of a CCP (combined cooling and power) system driven by geothermal source

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ARTICLE INFO

Article history:
Received 16 September 2015
Received in revised form
31 December 2015
Accepted 3 January 2016
Available online 29 January 2016

Keywords:
Exergoeconomic analysis
Exergy analysis
Geothermal energy
CCP
Optimization

ABSTRACT

A CCP (combined cooling and power) system, which integrated a flash-binary power generation system with a bottom combined cooling and power subsystem operating through the combination of an organic Rankine cycle and an ejector refrigeration cycle, was developed to utilize geothermal energy. Thermodynamic and exergoeconomic analyses were performed on the system. A performance indicator, namely the average levelized costs per unit of exergy products for the overall system, was developed to assess the exergoeconomic performance of the system. The effects of four key parameters including flash pressure, pinch point temperature difference in the vapor generator, inlet pressure and back pressure of the ORC turbine on the system performance were evaluated through a parametric analysis. Two single-objective optimizations were conducted to reach the maximum exergy efficiency and the minimum average levelized costs per unit of exergy products for the overall system, respectively. The optimization results implied that the most exergoeconomically effective system couldn't obtain the best system thermodynamic performance and vice versa. An exergy analysis based on the thermodynamic optimization result revealed that the biggest exergy destruction occurred in the vapor generator and the next two largest exergy destruction were respectively caused by the steam turbine and the flashing device.

1. Introduction

The demand for energy is growing at an increasing rate due to the growth of population, and is arousing wide concerns about the security of energy supply for the long term [1]. Energy resources have been divided into three categories: fossil fuels, renewable resources and nuclear resources [2]. Using fossil fuels can result in environmental deterioration and resource depletion. Nuclear energy can cause serious problems for the environment and human health. Renewable energy sources, which are sustainable and environmental friendly, are hence under emerging exploitation [3]. Among all kinds of renewable energies, geothermal energy, which has abundant amount of storage [4] as well as significant base-load potential [1], is expected to make an increasing contribution for energy supply in a near future [5].

Variety of thermal systems have been developed to utilize geothermal energy. Conventional power systems that simply converted geothermal energy into electricity have been widely studied since 1904 when a dry-steam geothermal power system was first built and operated in the Tuscany region of Italy [6]. Although dry-steam power systems can utilize the dry geothermal steam directly to produce electricity, dry steam reservoirs are rare and only found in few fields around the world while most of the remaining conventional geothermal fields worldwide are wet fields [7]. Hence, more attention has been paid to other types of power systems including single-flash steam power systems, double-flash steam power systems, binary cycle power systems and flash-binary power systems to develop wet geothermal fields for power generation [8–12]. Particularly, for temperature of the geothermal water below 180 °C where direct flashing processes are not suitable anymore [13], ORC (organic Rankine cycle) and Kalina cycle, both of which are well proven and reliable technologies for energy conversion, especially for exploiting low-temperature heat sources, have been widely applied as the subsystem in binary cycle power systems [10–12,14–20]. However, conventional power plants can

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http://dx.doi.org/10.1016/j.energy.2016.01.003
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Nomenclature

A	cross sectional area (m^2); heat exchanger area (m^2)
Bo	boiling number
$\dot{C}$	cost rates (\$ $year^{-1}$)
$\dot{C}_{dif}$	fictitious cost rates associated with dissipative components (\$ $year^{-1}$)
CEPCI	chemical engineering plant cost index
CRF	capital recovery factor
c	levelized costs per unit of exergy (\$ $(MWh)^{-1}$)
c_p	specific heat (J kg^{-1} K^{-1})
D	diameter (m)
$\dot{E}$	annual exergy transfer rates (J $year^{-1}$)
$\dot{E}x$	exergy flow rates (J s^{-1})
ex	specific exergy (J kg^{-1})
F	factor
f	friction factor
G	mass velocity (kg m^{-2} s^{-1})
h	enthalpy (J kg^{-1}); convection heat transfer coefficient (W m^{-2} K^{-1})
i_{eff}	effective discount (%)
K	constant
L	length (m)
l_B	baffle spacing (m)
$\dot{M}$	mass flow rates (kg s^{-1})
N	number of the tubes
n	lifetime (year)
Nu	Nusselt number
P	pressure (bar)
Pr	Prandtl number
P_t	distance between tubes (m)
Q_{vs}	volumetric stream flow (m^3 s^{-1})
$\dot{Q}$	heat transfer rate (W)
q_m	average imposed wall heat flux (W m^{-2})
Re	Reynolds number
r	enthalpy of vaporization (J kg^{-1})
s	specific entropy (J kg^{-1} K^{-1})
T	temperature (K)
t	working hours (hours)
U	overall heat transfer coefficient (W m^{-2} K^{-1})
V	volume (m^3)
v_t	terminal velocity (m s^{-1})
$\dot{W}$	power (W)
x	vapor quality
y	exergy destruction ratio (%)
$\dot{Z}$	annually levelized cost value (\$ $year^{-1}$)

Greek letters

δ	thickness (m)
Δt_m	logarithmic mean temperature difference between hot side and cold side (K)
ε	component exergy efficiency (%)
η	efficiency (%)
λ	thermal conductivity (W m^{-1} k^{-1})
ρ	density (kg/m^3)
μ	viscosity (kg s^{-1} m^{-1})

Subscripts

A	upper part
B	lower part
BM	bare module
cond	condenser
cond1	condenser 1
cond2	condenser 2
D	destruction
elec	electricity
es	equivalent diameter
evap	evaporator
ex	exergy
F	fuel
he	heat exchanger
i,j,k	state points
i	inside
in	inlet
ip	inlet pipe
L	loss
l	liquid
M	material factor
m	mean
max	maximum
min	minimum
o	outside
out	outlet
P	product; pressure factor
pump	pump
pump1	pump 1
pump2	pump 2
q	heat transfer; cold exergy output
ref	reference period
s	single-phase
ss	shell-side
sep	separator
system	exergy products produced by the overall system
th	thermal
tot	total
ts	tube-side
turb	turbine
turb1	steam turbine
turb2	ORC turbine
v	vapor
vg	vapor generator
w	power
well	drilling wells
wt1	power produced by steam turbine
wt2	power produced by ORC turbine
y	per year
0	ambient state
1–23	state points

only produce electricity and are not adequate for meeting with diverse consumers' requirements for energy supply. To satisfy the diverse users' demands and to utilize the energy source more efficiently, some cogeneration systems that combines electricity generation with other kinds of energy production have been developed for the exploiting of low- or medium-temperature heat sources such as geothermal water. A number of studies on geothermal cogeneration systems have been concentrated on the CHP (combined heat and power) technologies, which are relatively mature technologies directly using the geothermal water