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Research Paper

Parametric study on the effects of a recuperator on the design and off-design performances for a CO_2 transcritical power cycle for low temperature geothermal plants

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HIGHLIGHTS

- Off-design performance comparison of basic and regenerative CDTPCs is conducted.
- The sliding pressure operation control strategy is performed.
- Recuperator can improve overall system performance for CDTPC in design and off-design cases.
- Recuperator might weaken the off-design behavior of some key components.

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ABSTRACT

A CO_2 transcritical power cycle (CDTPC) is a promising power system to utilize low temperature geothermal heat source. Many researchers mainly focus on the thermodynamic and thermo-economic performance analysis or optimization for a CDTPC, or compare the design performance of a CDTPC with that of organic Rankine cycle. The objective of this paper is to study the effects of a recuperator on the design and off-design performances of a CDTPC for low temperature geothermal plants. Detailed off-design mathematical models of the basic and regenerative CDTPCs are built to complete this study under the variable mass flow rates and temperatures of the geothermal water and the cooling water temperatures conditions by a sliding pressure operation control strategy. The results reveal that no matter how the geothermal water mass flow rate and temperature or the cooling water temperature vary, both the overall net power and overall thermal efficiency of the regenerative CDTPC system are higher than those of the basic CDTPC system. Meanwhile, a recuperator can improve the overall system performance of a CDTPC system under the both design and off-design conditions, although the recuperator might weaken the off-design behavior of some key components. In addition, a recuperator can improve off-design behaviors of the CO_2 pump performance under the off-design conditions. The guidelines for the rotational speed listed in the tables for CO_2 pumps might provide some reference for practical operation.

1. Introduction

Energy and electricity demands are increased in the industrial, commercial and utility sectors, leading to the increasing of fossil fuel consumption, and therefore serious environmental pollution and energy shortage. In order to avoid these effects, many studies [1–5] have recently been conducted on the use of the renewable energy to generate power. As a type of the renewable energy, geothermal energy is sustainable, abundant, environmentally-friendly, independent of various weather conditions and easily coupled with the conventional system. Geothermal resources vary in temperature depending on the temperature of the source rock and depth, with the most common brine temperature being in the range of 100–150 °C [6,7]. In recent years, more than 1300 geothermal resource spots have been mainly employed in breeding industry, heat providing and medical service [8]. In order to make full use of the geothermal energy, alternative working such as HCFC123, n-Pentane, PF5050, ammonia-water mixture [9], zeotropic mixtures [10] and carbon dioxide (CO_2) [11] have been used in the power system instead of water. Among all these fluids, carbon dioxide has stood out as one of the most promising working fluids in the power cycle. In addition, it is easy for CO_2 to reach its supercritical state (the critical pressure and temperature of CO_2 are 7.38 MPa and 30.98 °C,

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Nomenclature

A	heat transfer area (m^2)
b	channel spacing (m)
Bo	boiling number
C	wetted perimeter of the cross-section (m)
c_p	specific heat ($J{\cdot}kg^{-1}{\cdot}K^{-1}$)
d_e	hydraulic diameter (m)
f	Fanning fraction factor
g	gravitational acceleration (m/s^2)
G	mass velocity ($kg{\cdot}m^{-2}{\cdot}s^{-1}$)
h	specific enthalpy ($kJ{\cdot}kg^{-1}$); convection heat transfer coefficient ($W{\cdot}m^{-2}{\cdot}K^{-1}$)
H	hydraulic head of pump (m)
L	plate length (m)
$\dot{m}$	mass flow rate ($kg{\cdot}s^{-1}$)
N	rotational speed (rpm)
Nu	Nusselt number
P	pressure (MPa) & (kPa)
$\dot{P}$	power (kW)
Pr	Prandtl number
q	volume flow rate ($m^3{\cdot}s^{-1}$); average imposed wall heat flux ($W{\cdot}m^{-2}$)
$\dot{Q}$	heat transfer rate (kW)
r_{fg}	enthalpy of vaporization ($J{\cdot}kg^{-1}$)
Re	Reynolds number
T	temperature (°C)
U	overall heat transfer coefficient ($W{\cdot}m^{-2}{\cdot}K^{-1}$)
$\dot{W}$	power (kW)
W	channel width (m)
x	vapor quality
Y_d	Stodola's constant of the CO_2 turbine ($m^{-2}{\cdot}s^{-1}{\cdot}K^{-1}$)
Δt_m	logic mean temperature difference (°C)

Greek letters

β	chevron angle (°)
η	efficiency; viscosity ($kg{\cdot}s^{-1}{\cdot}m^{-1}$)
ϕ	mass flow coefficient ($m{\cdot}s{\cdot}K^{1/2}$)
λ	thermal conductivity ($W{\cdot}m^{-2}{\cdot}K^{-1}$)
δ	plate thickness (m)
ρ	density ($kg{\cdot}m^{-3}$)
ΔT	temperature difference (°C)
ΔP	pressure drop (kPa)
Δh	specific enthalpy drop ($kJ{\cdot}kg^{-1}$)

Subscripts

1, 2…10	state points
cold	cold side
cw	cooling water
d	design operating condition
end	end
eq	equivalent
f	fluid
g	gaseous
gen	generator
gw	geothermal water
hot	hot side
in	inlet; input
is	isentropic process
l	liquid
m	mean
net	net power output
out	outlet
off	off-design condition
pp	pinch point
pum	working fluid pump
rec	recuperator
th	thermal
tp	two phase
tur	turbine

respectively). The temperature glide of supercritical CO_2 offers a better temperature profile matching with the temperature of the heat source than fluids with an isothermal subcritical evaporation [5].

In recent years, much research has been devoted to CO_2 transcritical power cycle (CDTPC) with low-grade sources. Chen et al. [12] investigated the CO_2 transcritical power cycle utilizing energy from low-grade waste heat in comparison to an Organic Rankine cycle (ORC) with R123. They found that the CDTPC has a slightly higher power output than the ORC under the same condition. Baik et al. [13] compared the net power outputs of a CDTPC and a transcritical power cycle with R125 for a low-grade heat resource of about 100 °C and parametric optimization was conducted for the two cycles to maximize the net power output under the same conditions. Cayer et al. [14] conducted a detailed analysis of a CDTPC utilizing an industrial low-grade heat source. They found that a recuperator could improve marginally the thermal efficiency, exergy efficiency and the total heat transfer area. Yari [15] also found that a recuperator could increase the system efficiency by investigating seven types of geothermal power plants. Wang et al. [16] analyzed and optimized the thermodynamic parameters of a CDTPC with a low-grade heat resource by using the genetic algorithm (GA) and artificial neural network (ANN). Guo et al. [11] explored a detailed thermodynamic comparison between a CDTPC and an ORC using HFC245fa as the working fluid driven by low-temperature geothermal source. The results showed that the net power output of the CDTPC presents 3–7% higher than that of the ORC using the same geothermal source.

In practice, an energy conversion system cannot always operate under the rated condition. The mass flow rate and temperature of the heat resource may be variable at any moment. Besides, the heat sink condition might also be changeable. Therefore it is significant to investigate the off-design performance of an energy conversion system. The off-design performance of CDTPC has been explored by a few scholars. Walnum et al. [17,18] compared the off-design performances between a CDTPC and an ORC with R123 driven by the low-temperature surplus heat source. However, they didn't develop the detailed submodel of the heat exchangers and investigate the off-design performance of the cycle system under the variable heat sink conditions. The off-design performance analysis on the energy conversion systems utilizing the low temperature geothermal source mainly focuses on the ORCs. Hu et al. [19] conducted a detailed off-design performance of an ORC using R245fa as the working fluid for the low temperature geothermal source based on the preliminary design of turbines and heat exchangers. Their off-design model could be used to provide basic data for future detailed design, and predict off-design performance in the initial design condition. Fu et al. [20] carried out a performance analysis on a 250 kW ORC system under the off-design low temperature conditions. They controlled the operating pressure to meet that R245fa reached the saturation liquid and vapor states at the outlet of the preheater and evaporator, respectively. Ibarra et al. [21] conducted an investigation on the off-design performance of a 5 kWe ORC at part-load operation. They found that the isentropic efficiency of the scroll expander has a great influence on the cycle performance and thermal