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Study on off-design performance of transcritical CO_2 power cycle for the utilization of geothermal energy

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A B S T R A C T

Exploiting renewable energy could greatly alleviate current severe energy situation. Transcritical CO_2 (tCO_2) cycle system as a type of competitive and promising energy converter could utilize low temperature geothermal energy effectively. In this paper, the methodology for the off-design operation of tCO_2 system has been proposed and the quantitative performance analysis is carried out for the utilization of geothermal energy. With the aim at obtaining better thermodynamic and economic performance, the optimal power cycle parameters can be determined by the non-dominated sorting genetic algorithm-II (NSGA-II) in the design stage. The models of exergoeconomic analysis and main system components including turbine, pump and heat exchangers are established. The sliding pressure control strategy is applied to respond to the varieties of heat source and heat sink conditions in the off-design stage. Results show that there exists an optimal value of geothermal resource mass flow rate to maximum the thermal efficiency. The pump rotational speed increases linearly with the increasing geothermal resource temperature and geothermal resource mass flow rate while the pump rotational speed is gradually sensitive to the increase of heat sink temperature. The guideline listed in the table for pump could provide effective reference for practical operation.

1. Introduction

Energy is the driving force of a country. Severe energy situation urgent to be solved is presented in front of people all over the world. Energy conversation and emission consumption has been the theme of the world for decades in the energy field. Exploiting and utilizing renewable energy is an effective way to relieve this situation as well. Renewable energy contains solar energy, geothermal energy, wind energy, biomass energy and so on. Among them, geothermal energy with bright prospect has been investigated extensively for a good many of advantages, such as large-scale reserves, cleanliness, relative stability and cost-effective (Avtar and Kumar, 2016). According to the available literature, the total energy output of The Earth, including solar energy, geothermal energy, wind energy, fossil energy etc., is about 4×10^{13} W, which is more than three times of the world total energy consumption (Tchanche et al., 2011).

The research on efficient energy conversion systems for geothermal energy has drawn more and more scholars' attention. Organic Rankine cycle (ORC), Kalina cycle and transcritical CO_2 (tCO_2) cycle are all common effective and promising energy converters to recovery low grade heat source. ORC with low-boiling organics as working fluid absorbs heat from the heat sources and convers to electric power (Lecompte et al., 2015). The cost of investment for working fluid, however, is high and the leakage is inevitable. Furthermore, most of the organics are toxic. Low temperature Kalina cycles, such as Kalina Cycle System-34, are other alternative cycles for exploiting geothermal energy (Zhang et al., 2012). Nevertheless, the mixture of ammonia and water as the working fluid requires additional apparatus in the system-separator and mixer, which increases system complexity and technological requirements.

CO_2 is a type of promising working fluid for its abundance, stability, low cost, non-toxicity. Moreover, tCO_2 cycle is an ambitious and powerful competitor for exploiting low-grade heat source (Sarkar, 2015). Much attention has been devoted to this cycle recently. Chen et al. (Chen et al., 2006) conducted an investigation on the comparison of tCO_2 cycle and ORC with R123 as working fluid in waste heat recovery. They found that more net power output could be gained by tCO_2 cycle system under the same heat source conditions. Cayer et al. (Cayer et al., 2009; Cayer et al., 2010) made a parametric analysis and optimization on a tCO_2 power cycle and ORC using six performance indicators for a low temperature source. The system using CO_2 as working fluid had a higher total product of the overall heat transfer coefficient and much less heat exchange surface than the case of ethane. Li et al. (Li et al., 2014a) carried out a thermo-economic analysis and comparison of a

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Nomenclature

A	Heat transfer area, m^2
b	Channel spacing, m
C	Perimeter, m; cost rate, $ h^{-1}
$\dot{C}$	Cost rate, $ h^{-1}
c	Distance from neutral axis to extreme fiber, m; cost per exergy unit, $ GJ^{-1}
c_p	Specific heat, J kg^{-1} K^{-1}
$c_{p,total}$	Total product unit cost, $ GJ^{-1}
D	Diameter
de	Hydraulic diameter, m
E	Joint factor; exergy, kJ
$\dot{E}$	Exergy rate, kJ h^{-1}
f	Friction factor
G	Mass velocity, kg m^{-2} s^{-1}
h	Convection heat transfer coefficient, W m^{-2} K^{-1}; channel width, m
H	Pump head, m; channel depth, m
I	Moment of inertia, m^4
l	Channel length, m
m	Mass flow rate of working fluid, kg s^{-1}
P	Pressure, MPa
q	Volumetric flow rate, m^3 s^{-1}
Q	Heat transfer rate, kW
R_w	Fouling resistance, m^2 K W^{-1}
s	Entropy, kJ kg^{-1} K^{-1}
S	Design stress, MPa
T	Temperature, °C
t	Edge width, m
U	Overall heat transfer coefficient, W m^{-2} K^{-1}
W	Channel width, m; power, kW
Yd	Stodola's constant of the turbine, m^{-2} s^{-2} K^{-1}
Z	Capital cost of a component, $
$\dot{Z}$	Capital cost rate, $ h^{-1}
ΔP	Pressure drop, J kg^{-1}
Δh	Enthalpy drop, J kg^{-1}
ΔT_{lmtd}	Log mean temperature difference, K
ΔT_{endreg}	Temperature difference of the regenerator bottom end, K
ΔT_{endcnd}	Temperature difference of the condenser left end, K

Greek symbols

η	Efficiency, %
Φ	Mass flow coefficient, m s $K^{1/2}$
λ	Thermal conductivity, W m^{-1} K^{-1}
β	the chevron angle of the plates, °
δ	Smoothness, m
ρ	Density, kg m^{-3}
ω	Pump rotational speed, rpm

Subscripts

1,2…6	State points
b	Bending
cold	Cold side in heat exchanger
d	Design operating condition
env	Environment
eva	Evaporating
f	Fluid
fir	First value
g	Gas
gs	Geothermal resource
hot	Hot side in heat exchanger
in	Inlet
l	Liquid
m	Membrane
off	Off-design operating conditions
out	Outlet
pump	Working fluid pump
rel	Reletive
s	Isentropic process
T	Total
tub	Tube channel
tur	Turbine
well	Geothermal well
wf	Working fluid

Acronyms

GA	Genetic algorithm
ORC	Organic rankine cycle
PCHE	Print circuit heat exchanger
Pr	Prandtl number
Re	Reynolds number
tCO_2	Transcritical CO_2

tCO_2 cycle and an ORC with R123, R245fa, R600 and R601 as working fluids using the low temperature geothermal resource. They suggested that the tCO_2 cycle showed a better economic performance than ORC. Li et al. (Li and Dai, 2014) explored the performance of a tCO_2 system and a Kalina system driven by low temperature geothermal water. They observed that the exergetic efficiency of the tCO_2 system is more than that of the Kalina system. Besides, Li et al. (Li et al., 2014b) combined an ejector with the tCO_2 power cycle to utilized the low-grade heat to generate power.

The tCO_2 cycle has been thoroughly investigated by many researchers in the past few years. They primarily devoted their efforts to the cycle thermodynamics and economics. As we know, the geothermal resource mass flow rate and geothermal resource temperature influenced by some uncontrolled factors are variable at any moment. In addition, the requirement of variable power load can be met by adjusting the system operating parameters, such as the pressure ratio and working fluid mass flow rate, on the basis of the off-design mechanisms. More and more attention about investigating the power cycles has switched from the views of thermodynamics and economics to the off-design analysis. However, little work has been conducted on the off-design performance of tCO_2 cycle. Furthermore, the corresponding control strategies have seldom been discussed. Hence, it is significant to investigate the off-design performance analysis of tCO_2 cycle for low temperature geothermal resource, especially the recuperative configuration.

In this paper, the operation parameters of the recuperative tCO_2 cycle are optimized by thermodynamic and economic analysis in the design stage. Exergoeconomic analysis regarded as a type of reasonable, effective, accruable and popular method is adopted. Exergoeconomic model is established for the tCO_2 power cycle. The system components can be preliminarily designed based on the optimal design parameters gained by NSGA-II. Multi-stage axial turbine model is utilized to expand working fluid and generate power. Affinity laws are adopted to the pump to meet the acquirements of different system flow rates and pressures. The print circuit heat exchanger (PCHE) is applied as the evaporator, regenerator and condenser to realize heat exchange. The sliding pressure control strategy is adopted to respond to the varieties of geothermal resource temperature, geothermal resource mass flow rate