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Optimization and applicability of compound power cycles for enhanced geothermal systems☆

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HIGHLIGHTS

- Optimizations of 3 compound power cycles have been carried out thermodynamically.
- Five maps are obtained for selecting optimum geothermal power generation cycles.
- Different ORC working fluids are investigated in generating the maps.
- Techno-economic performance of each power cycle has been analyzed in detail.

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ABSTRACT

Both thermodynamic performance and techno-economic analysis of compound power cycles for enhanced geothermal systems have been investigated in this study. Thermodynamic analysis were carried out for four power generation systems: single-flash (SF) system, double-flash (DF) system, flash-ORC (FORC) system; and double-flash-ORC (DFORC) system. By choosing the maximum net power output as an objective function, optimization is done based on comparisons among the four systems with a goal of increasing the net power output by 20% under the condition that the SF is replaced by one of the compound systems (DF, FORC, and DFORC). As an original contribution, five maps useful for real applications have been generated for selecting optimum geothermal power cycles under different geofluid's conditions, with consideration of five ORC working fluids (R123, R152a, isobutane, *n*-pentane and R245fa). The boundaries that determine whether the compound systems have advantages over the SF system are functions of the geofluid temperature, geofluid dryness, and the type of the working fluid used by the ORC. In the techno-economic study, Levelized Electricity Cost (LEC) and Payback Period (PBP) analyses were carried out. The results from the LEC and PBP studies show good agreement. For the three scenarios analyzed, each of the compound power systems has a better engineering economic performance than the SF system. For the "common" heat source condition investigated, comparison among the three compound systems shows that the DF system has a lowest levelized electricity cost and the shortest payback period; the FORC and DFORC show similar techno-economic performance and have advantages over the SF system.

1. Introduction

An enhanced geothermal system (EGS), also known as an engineered geothermal system, is a man-made geothermal reservoir which is created where there is hot rock with little natural permeability and insufficient fluid saturation. In an EGS, fluid is injected into the subsurface under carefully controlled conditions, causing pre-existing fractures to re-open and creating permeability [1]. Such an enhanced system allows fluid to circulate throughout the hydraulically-fractured rock and to transport heat to the surface for power generation [2].

The resource base of EGS is huge. Unlike a naturally formed geothermal system (hydrothermal system) which can be found only in areas with geothermal activities, EGS could be built in many places with electricity demand in the world [3]. In the US, for example, the

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Nomenclature

g	gravity coefficient (m/s^2)
h	specific enthalpy (kJ/kg)
i	bank rate
m	mass flow rate (kg/s)
n	running years of power station
p	pressure (MPa)
Q	heat rate (kW)
T	temperature (°C)
V	volume flow rate (m^3/h)
W	power (kW)
x	geofluid dryness
ΔH	head of pump (m)
ΔT	temperature difference (°C)
C_p	heat capacity at constant pressure

Greek symbols

η	efficiency (%)
ρ	density (kg/m^3)
τ	operating time each year

Subscripts

1, 2, 3…	state points
air	air
c	condenser
cw	cooling water
dou	double
e	evaporator
fan	fan
g	generator
gw	geothermal water (brine)
h	high
in	inlet
inc	increase
l	low
m	mechanical
net	net electricity output
orc	organic Rankine cycle
out	outlet
p	pump
s	isentropic
sf	single flash
t	turbine
total	total
wf	working fluid

Acronyms

CNY	China currency unit (Yuan, ¥)
COM	Cost of Operation Maintenance
COST	cost
CRF	Capital Recovery Factor
DF	double flash
DFORC	double-flash-ORC
EGS	enhanced geothermal system
FORC	flash-ORC
GWP	global warming potential
HDR	hot dry rock
LEC	levelized electricity cost
NE	net earning each year
ODP	ozone depletion potential
ORC	organic Rankine cycle
PBP	Pay Back Period
Pro	profit in running years
Rev	revenue each year
SF	single flash

installed EGS power generation capacity is expected to reach approximately 24 GW by 2030, and 100 GW by 2050 [4]. Due to the huge potential of using EGS for power generation, many countries have carried out research on EGS technology.

The geofluid from an EGS usually has lower temperature and less dryness, compared with that from the naturally formed hydrothermal system. Therefore thermodynamic analyses and optimizations of different power generation systems should be carried out in order to determine the most suitable application scope of each system under certain geofluid conditions. In addition, an EGS also has its own cost characteristics, which especially lies in its relatively high capital costs (such as drilling and hydraulic fracturing costs). Therefore, relevant techno-economic analysis of each power generation system associated with an EGS should also be investigated. This research was carried out as part of the prefeasibility study of geothermal power generation in China using geofluids from enhanced geothermal systems.

The aim of the thermodynamic analysis is to generate more maps useful for selecting optimum geothermal power generation systems. Since four more ORC working fluids have been investigated, this study is a substantial extension of our earlier work [5]. In order to obtain the maps, the following geothermal power generation systems were analyzed: (1) single-flash power generation system (SF); (2) double-flash power generation system (DF); (3) flash-ORC power generation system (FORC); (4) double-flash-ORC power generation system (DFORC). Each of the compound systems (DF, FORC, or DFORC) was then analyzed and compared with the SF system.

In selection of an ORC working fluid, both its influence on the ORC's thermodynamic performance [6] and its influence on the environment [7] are considered based on the suggestions from some previous research. Relevant considerations of choosing a working fluid are summarized as follows:

- Environmental friendly (ODP = 0; GWP is low)
- Moderate critical parameters
- Low viscosity and high thermal conductivity
- Moderate latent heat
- Chemical stability and safety
- Low corrosion and low toxicity
- Market availability and cost

Apart from our earlier work [5], no previous studies have been found to generate maps for selecting optimum power cycles associated with enhanced geothermal systems. However, literature survey shows that some preliminary studies in relevant fields have been carried out. In the study of Roy et al., working fluids R12, R123, and R134a were compared [8]; the researchers found that R123 was the most suitable working fluid in order to get the best thermodynamic performance. However, this study was only a numerical simulation for a simple ORC with a constant-temperature heat source; there was no detailed discussion about the specific application of the ORC system. Shengjun et al. [9] analyzed 16 different working fluids for an ORC using low-temperature (80–100 °C) geothermal water for power generation. In their study, isobutane and R245fa are recommended for getting better thermal and exergy efficiencies. Their study also shows that isobutane has low levelized electricity cost; isobutane and R152a correspond to lower heat exchanger area per unit power output. Budisulistyo and Krumdieck [10] carried out an economic analysis for a binary geothermal power plant, and suggested using *n*-pentane as a working fluid. Coskun et al. [11] found that isobutane was suitable as a working fluid of ORC for the geothermal power plant they investigated. Zeyghami [12]