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Effects of evaporator pinch point temperature difference on thermo-economic performance of geothermal organic Rankine cycle systems

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ABSTRACT

Organic Rankine cycle (ORC) systems are being used to convert medium-low temperature geothermal energy into electricity. However, the ORC system efficiencies need to be increased and the investment costs need to be reduced to further promote this technology. The evaporator pinch point temperature difference (PPTD) is a key parameter affecting the thermodynamic and economic performance. A lower evaporator PPTD leads to higher turbine power output; however, this also increases the heat transfer area and the investment cost. Therefore, this work optimizes the evaporation temperatures to maximize the net power outputs for evaporator PPTDs of 4–15 °C and brine inlet temperatures of 100–150 °C. The heat transfer area per unit power output, the levelized cost of electricity (LCOE) and the dynamic payback period (PBP) at the optimal conditions are also analyzed. ORCs produce 1.7–2.6% more net power with every 1 °C decrease of the evaporator PPTD for brine inlet temperatures higher than 130 °C. The total area per unit power output first decreases to a minimum at an evaporator PPTD of about 7 °C and then increases slightly with increasing evaporator PPTD. The LCOE and the dynamic PBP of a basic ORC reach a minimum at an evaporator PPTD of about 7 °C with the minimum at 5–6 °C for drilling costs higher than 500 $/m.

1. Introduction

Geothermal resources are promising energy sources that can reduce pollutant emissions and fossil fuel consumption. According to the International Energy Agency, 3.5% of the worldwide generated power is expected to be generated by geothermal energy by 2050 (Chagnon-Lessard et al., 2016). The annual amount of geothermal energy used in China is equivalent to 85.3 billion tons of standard coal, 7.9% of the worldwide geothermal resource usage (An et al., 2016). However, the installed geothermal capacity in China was only 0.2% of the global installed geothermal capacity in 2015 (Bertani, 2016) because of the high cost of electricity production using geothermal energy (Franco and Vaccaro, 2014). Therefore, studies are needed to show how to more efficiently and economically convert geothermal energy into power.

Organic Rankine cycle systems have been developed to generate electricity over the past two decades (Astolfi et al., 2011) as an efficient method for such resources (Dipippo, 2004; Vélez et al., 2012; Li et al., 2016). Nevertheless, geothermal ORC system efficiencies are still less than 12% (Basaran and Ozgerer, 2013) for moderate-low temperature geothermal energy sources (below 150 °C) due to the limited temperature difference between the heat source and sink. Most efforts in the literature have sought to maximize the ORC thermodynamic efficiencies by improving the system configurations (Franco and Villani, 2009; Yari, 2010; Sadeghi et al., 2016) and selecting the best working fluids including pure organic fluids or zeotropic mixtures (Liu et al., 2014; Linke et al., 2015; Schuster et al., 2010). The cycle parameters have also been optimized in many studies (Bao and Zhao, 2016; Feng et al., 2017). The evaporator pinch point temperature difference (PPTD) is a key factor influencing the thermodynamic efficiency, the evaporator and condenser heat transfer areas (Pan and Shi, 2016) and the system economics, which PPTD usually set to a constant from 1 to 15 °C (Liu et al., 2017).

Abbreviations: ORC, organic Rankine cycle; PPTD, pinch point temperature difference; LCOE, levelized cost of electricity; PBP, Payback period; LMTD, logarithmic mean temperature difference; EPC, engineering, procurement and construction; O&M, operation and maintenance; t, the tth year

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Nomenclature

A	Heat transfer area (m^2)
$\dot{m}$	Mass flow rate ($kg\,s^{-1}$)
$\dot{Q}$	Heat transfer rate (kW)
$\dot{W}$	Power output (kW)
P	Pressure (MPa)
h	Specific enthalpy ($kJ\,kg^{-1}$)
g	Gravitational acceleration ($m\,s^{-2}$)
H	Pump head (m)
ΔT	Temperature difference (K)
T	Temperature (K)
s	Specific entropy ($kJ\,kg^{-1}\,K^{-1}$)
c_p	Specific heat ($kJ\,kg^{-1}\,K^{-1}$)
U	Overall heat transfer coefficient ($W\,m^{-2}\,K^{-1}$)
d	Tube diameter (m)
R	Fouling thermal resistance ($m^2\,K\,W^{-1}$)
Nu	Nusselt number
Re	Reynolds number
Pr	Prandtl number
r	Latent heat ($kJ\,kg^{-1}$)
u	Velocity ($m\,s^{-1}$)
D_d	Bubble departure diameter (m)
$Cost$	Investment cost
C_E	Cost correlation
CE	Chemical engineering index
N	Number of full load hours (h)
M	Cooling water loss
N_n	Concentration factor
K	Atmospheric temperature factor

Greek symbols

η	Efficiency (%)
α	Heat transfer coefficient ($W\,m^{-1}\,K^{-1}$)
λ	Thermal conductivity ($W\,m^{-1}\,K^{-1}$)
δ	Tube wall thickness (m)
ρ	Density ($k\,m^{-3}$)
θ	Angle (degree)
σ	Surface tension ($N\,m^{-1}$)
μ	Dynamic viscosity (Pa s)
ν	Kinematic viscosity ($m^2\,s^{-1}$)

Subscripts

FP	Working fluid feed pump
CP	Circulating pump
PRE	Pre-heater
E	Evaporator
CON	Condenser
DE	Desuperheater
net	Net power output
n	the nth section
max	Maximum
min	Minimum
i	Inside
o	Outside
L	Liquid
V	Vapor
S	Saturated
W	Tube wall

A lower evaporator PPTD leads to higher turbine inlet temperature, which increases the average heat absorption temperature of the working fluid and the turbine power output (Li et al., 2013; Liu et al., 2017). In addition, a lower evaporator PPTD can change the heat distribution in the preheater and the evaporator. Therefore, the evaporator PPTD has a vital impact on the ORC system efficiency. Several studies have investigated the effects of the evaporator PPTD on the ORC system efficiency. Liu et al. (2017) optimized the evaporator PPTD with consideration of the evaporator and condenser heat transfer rates as well as the turbine performance of a geothermal ORC. They related the optimal evaporator PPTD to the brine inlet temperature. Yu et al. (2015) found a linear relationship between the average temperature difference and the exergy destruction in the evaporator for a trans-critical ORC. Guo et al. (2014) established a model to determine the evaporator PPTD location and the optimal evaporator PPTD based on the thermal efficiency, exergy efficiency, net power output and power output per heat transfer area. Vetter et al. (2013) focused on the influence of the evaporator PPTD on the ORC system efficiency. They found that a trans-critical geothermal ORC system generated 29% less net power output with a PPTD of 20 °C than for 5 °C. Bina et al. (2017) analyzed the effects of the evaporator PPTD on the exergy efficiencies of basic and dual-fluid ORC systems and found that exergy efficiencies decreased 12.3% when the evaporator PPTD was increased from 5 °C to 15 °C for dual fluid ORCs, but decreased less than 5% for single fluid ORCs.

A lower evaporator PPTD increases the evaporator and preheater areas. Jiang et al. (2014) pointed out that the heat exchanger cost is over half of the total investment cost. Thus, the evaporator PPTD should be optimized to improve the economics of an ORC system, but there have been few such studies. Li et al. (2012) analyzed the effects of the evaporator PPTD on the ORC efficiency using the ratio of the net power output to the heat transfer area as a cost indicator. They found that the net power output per heat transfer area first decreased and then increased with decreasing evaporator PPTD for fixed total evaporator and condenser PPTDs and evaporation temperature. Wu et al. (2014) optimized the evaporator PPTD of an ORC system based on the exergoeconomic principle. They pointed out that the optimal PPTD was closely connected to the evaporator investment and that the optimal PPTDs were 1 °C higher when the analysis was based on the exergy recovery than that the exergy destruction.

Most previous investigations have focused on analyses of the effects of the evaporator PPTD on the ORC efficiency with little consideration paid to its effect on the heat exchanger areas and the overall system economics including the cost of the cooling system and the drilling. In particular, the drilling cost often accounts for more than half of the total geothermal power plant cost (Caulk and Tomac, 2017). Thus, the influence of the evaporator PPTD on the system economics should be analyzed with consideration of the drilling cost. The working fluid evaporating temperatures are optimized in this study for brine inlet temperatures from 100 °C to 150 °C and evaporator PPTDs from 4 °C to 15 °C. The analyses determine the heat transfer area per unit power output, the levelized cost of electricity (LCOE) and the dynamic payback period (PBP) for the entire system lifetime. The drilling, working fluid and cooling water costs are taken into consideration.

2. Methodology

2.1. System model

This study considers basic organic Rankine cycles (ORCs) for geothermal power generation. A simplified schematic of a basic geothermal ORC system using isobutane as the working fluid is shown in Fig. 1 with the corresponding *T-s* diagram shown in Fig. 2. The system includes a geothermal brine circuit, an organic fluid circuit and a cooling water circuit.

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