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Performance analyses of geothermal organic Rankine cycles with selected hydrocarbon working fluids

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ABSTRACT

ORC (organic Rankine cycles) are promising systems for conversion of low temperature geothermal energy to electricity. The thermodynamic performance of the ORC with a wet cooling system is analyzed here using hydrocarbon working fluids driven by geothermal water from 100 °C to 150 °C and reinjection temperatures not less than 70 °C. The hydrocarbon working fluids are butane (R600), isobutane (R600a), pentane (R601), isopentane (R601a) and hexane. For each fluid, the ORC net power output first increases and then decreases with increasing turbine inlet temperature. The turbine inlet parameters are then optimized for the maximum power output. The ORC net power output increases as the condensation temperature decreases but the circulating pump power consumption increases especially for lower condensation temperatures at higher cooling water flow rates. The optimal condensation temperatures for the maximum plant power output are 29.45–29.75 °C for a cooling water inlet temperature of 20 °C and a pinch point temperature difference of 5 °C in the condenser. The maximum power is produced by an ORC using R600a at geothermal water inlet temperatures higher than 120 °C, followed by R245fa and R600 for reinjection temperatures not less than 70 °C. R600a also has the highest plant exergetic efficiency with the lowest turbine size factor.

1. Introduction

Geothermal heat is a renewable energy source with temperatures varying from 50 °C to 350 °C [1]. Compared to other renewable energy sources such as solar energy, biomass energy and wind energy, geothermal energy has the distinctive features of being stable at all times, being independent of the weather conditions, having inherent storage capability and being cost-effectiveness [2,3]. The earth's geothermal resources are huge. The amount of geothermal energy stored at depths up to 3000 m is estimated to be 43,000,000 EJ [4]. Water dominated low-enthalpy geothermal heat resources below 150 °C account for 70% of the geothermal resources available in the world [5]. Geothermal energy has been identified as a good thermal source for electric power generation. The first demonstration of electricity generation from geothermal energy occurred at Larderello, Italy in 1904 [6]. The estimated total installed capacity of geothermal power plants worldwide reached 11,224 MW in May, 2012 [7].

The ORC (organic Rankine cycle) is a state-of-the-art technology that can generate power using low-enthalpy geothermal heat at temperatures lower than 150 °C. There have been a great number of studies addressing geothermal ORC performance, characteristics, design criteria and types for power generation systems [1,3,5,8–17]. The critical challenges for geothermal ORC research are the working fluid selection and the cycle design. An ideal geothermal ORC should have good thermodynamic performance and high heat source utilization.

In the past, HFCs (hydrofluorocarbons) have been commonly used as ORC working fluids. However, the increasing concern about their impact on global warming has lead to calls for green working fluids for ORC. Natural working fluids are expected to be long-term alternative working fluids due to their negligible GWP (global warming potentials). Yari [15] investigated different geothermal concepts and several dry fluids for ORC systems using the first and second laws of thermodynamics. The results showed that a regenerative ORC with an internal heat exchanger and R123 as the working fluid had the highest efficiency. Saleh et al. [18] investigated the thermodynamic performance of 31 pure fluids consisting of alkanes, fluorinated alkanes, ethers and fluorinated ethers as ORC working fluids with a maximum turbine inlet temperature of 100 °C for geothermal applications. Parameters including thermal

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Nomenclature

c_p	isobaric heat capacity (kJ kg^{-1} K^{-1})
g	gravitational acceleration (m s^{-2})
h	enthalpy (kJ kg^{-1})
H	pump head (m)
I	exergy destruction (kW)
m	mass flow rate (kg s^{-1})
p	pressure (MPa)
Q	heat flow rate (kW)
s	specific entropy (kJ kg^{-1} K^{-1})
t	temperature (°C)
W	power (kW)

Acronyms

HFCs	hydrofluorocarbon
IHE	internal heat exchanger
ORC	organic Rankine cycle
VR	turbine outlet/inlet volume flow ratio
SP	turbine size factor

Greek symbols

η	efficiency
Δt	temperature difference

Subscripts

1–5, 2a, 4a	state points in Figs. 1–2
C	condenser
cp	circulating pump
E	evaporator
ex	exergetic efficiency
G	Geothermal water
g	generator
IHE	internal heat exchanger
in	inlet
m	mechanical
net	net power
O	organic working fluid
ORC	organic Rankine cycle
out	outlet
p	working fluid pump
plant	geothermal power plant
s	isentropic
T	turbine
w	cooling water

efficiency, turbine inlet volumetric flow rate and expansion ratio were considered. For higher turbine inlet temperatures, o-fluids with higher critical temperatures were preferred. Tchanche et al. [19] investigated the thermodynamic performance of 20 fluids based on the system efficiencies, volumetric flow rates and pressure ratios. Their results showed that R152a, R600a, R600 and R290 gave good performance. Subbiah and Natarajan [20] investigated the performance of a binary–fluid cycle based on the first and second law cycle efficiencies. They showed that the second law approach helped identify the optimal working conditions for the maximum work output. Angelino and Colonna di Paliano [21] analyzed the performance of multi-component fluids as the working fluid for ORC systems based on the first and second law efficiencies. Guo et al. [22–24] described a cogeneration system driven by a low-temperature geothermal source and investigated the working fluid selection by optimizing the ratios of the total heat transfer area to the net power output and electricity production cost [22]. Their results showed that there were optimum evaporating temperatures for the maximum net power output, the minimum ratio of the total heat transfer area to the net power output and the minimum electricity production cost, with different optimum temperatures for different screening criteria and fluids. Lakew and Bolland [25] investigated the power production capability and heat exchanger and turbine sizes of ORCs with different working fluids. Their results showed that R227ea gave a higher power output than R134a, R123, R245fa, n-pentane or R290. Aljundi [26] investigated the effect of the working fluid on the cycle efficiency and found that hydrocarbons gave better performance than some other refrigerants. Heberle and Brüggemann [27] analyzed the fluid selection for a geothermal ORC that combined heat and power generation. Their results showed that isopentane was suitable for series circuits, while R600a and R227ea were better for parallel circuits. Thus, ORCs using different working fluids have different performance characteristics at different operating conditions [28].

Most previous investigations of the ORC performance characteristics have focused on analyses of the cycle efficiency and optimization of the temperature profiles of the working fluid and heat source with little consideration paid to the influence of the cooling system performance. In particular, the geothermal water reinjection temperature should be high enough to avoid silica oversaturation which can lead to silica scaling and fouling in the heat recovery heat exchanger and mineral deposition in pipes and valves [5,10,29,30], but this problem has been neglected in quite a few studies [30]. The primary goal of a geothermal power plant is to maximize the power output with a low temperature heat source. This paper analyzes the effects of using a wet cooling system where the working fluid is cooled by water and an IHE (internal heat exchanger) on the geothermal ORC performance and studies the power output of ORCs driven by geothermal water temperatures from 100 °C to 150 °C with five hydrocarbon working fluids, butane (R600), isobutane (R600a), pentane (R601), isopentane (R601a) and hexane. Subcritical o2 cycles are studied to match the geothermal source temperature with reinjection temperatures not less than 70 °C. The turbine inlet parameters for the five fluids are optimized to maximize the plant power output. The net power output is maximized rather than the efficiency because at higher turbine inlet temperatures the reinjection temperature is higher so the power output per kilogram of geothermal water is lower even though the efficiency is higher. The influences of condensation temperature and reinjection temperature on the plant power output are analyzed. The thermodynamic performance is analyzed in terms of turbine outlet/inlet volumetric flow ratio and turbine size factor. The results are compared with that of R245fa to find attractive hydrocarbon working fluids.

2. ORC model

Dry fluids with a positively sloped saturation curve in the temperature–entropy diagram have better thermal performance because the fluid does not condense after it goes through the turbine as opposed to wet fluids that condense after expansion [31]. For a subcritical ORC, superheating does not increase the power output for evaporation temperatures below 0.9 T_c but increases the turbine outlet temperature and increases the system complexity. This paper uses the o2 cycle [18] with saturated vapor at the turbine