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OPTIMAL FLASH EVAPORATION TEMPERATURES FOR GEOTHERMAL FLASH RANKINE CYCLES USING PENTANE

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ABSTRACT

Organic Flash Cycles (OFCs) are preferred to convert low temperature geothermal energy to electricity. In this work, comparative studies on two kinds of systems aiming to recover the heat of the saturated liquid after flash evaporation are presented. Modified OFC (MOFC) mixes the saturated liquid after flashing with the cold working fluid to recover the heat of liquid after flashing. Regenerative OFC (ROFC) that use an internal heat exchanger to recover the part of heat of saturated liquid after flashing. The flash temperatures for Basic OFC (BOFC), ROFC and MOFC using pentane were optimized to maximize the net power outputs at various condensation temperatures. Results shows that recovering the heat of liquid after flashing leads to system performance improving, irreversible loss decrease and change of locations of pinch points.

Keywords: Organic Flash Cycles, geothermal energy, internal heat exchanger, flash evaporation temperature, condensation temperature

1. INTRODUCTION

Geothermal energy is abundant worldwide and independent of weather conditions and suitable for continuous production [1-6]. Organic Flash Cycle (OFC) is a state-of-the-art technology that can generate power using medium and low temperature geothermal energy. OFCs have the advantage of better temperature matching during heat addition compared to organic Rankine cycles, which can reduce exergy losses [7], but additional irreversible loss caused by flash process. Basic OFCs separate the vapor from the liquid after the throttling process, the left saturated liquid which accounts for half of total heat input or even more would be wasted. Thus, the system efficiency of basic OFCs are quite low, more research on improving system performance of OFCs is needed. As previous studies mentioned, recovering the part heat of liquid after flash realized cascade utilization that will make great sense for improving system performance.

NONMENCLATURE

Abbreviations	
GW	Geothermal water
CW	Cooling water
WF	Working fluid
IHE	internal heat exchanger
WFP	Working fluid pump
Symbols	
η	efficiency
Q	Heat flow (kW)
h	Specific enthalpy (kJ kg^{-1})
s	Specific entropy (KJ kg K^{-1})
W	Power (kW)
m	Mass flow rate (kg s^{-1})
I	Exergy destruction (kW)
E	Exergy
C_P	Isobaric heat capacity (kJ $kg^{-1}K^{-1}$)

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Refer to literatures of organic Rankine cycles, regenerative configurations could improve system performance[8-11]. Mago et al. [12] compared the energetic and exergetic performance an open-type regenerative ORC with that of the standard cycle. He concluded that the regenerative ORC can lead to improved energetic and exergetic performance. Mehrpooya et al. [13] performed an exergoeconomic analysis and optimization of a regenerative solar ORC combined with a recuperator.

Research on OFCs with modified configurations could realize cascade utilization of energy, and be superior to other systems driven by low-grade energy have been reported by [14-19]. And Boccoili et al. [20] reported that regeneration of OFC allowed to recover part of the enthalpy of the liquid phase from the flash evaporator increasing the temperature of the liquid at the exchanger inlet, thus reducing the exchanger size. Kim [21] presented comparative exergy analysis of organic flash cycle with and without regeneration, results showed that exergy efficiency of OFC with regeneration was higher than that of OFC without regeneration.

At present, the influence of mechanism of regeneration configurations on OFCs are not clearly stated. In this paper, two kinds of modified OFC systems to recover the part of heat of liquid after flashing are discussed. A modified OFC (MOFC) [22] that mixes the saturated liquid after flash with the cold working, which improves the evaporator inlet temperature of working fluid. ROFC are regenerative systems that use internal heat exchangers to recover the part of heat of saturated liquid after flashing. Condensation temperature [23] and flash temperature [24] have great impact on system performance. In the present, thermodynamic analysis on Basic OFCs (BOFC), ROFC, and MOFC at various condensation temperatures are carried out. Furthermore, the effect of condensation temperature and flash temperature on the systems are investigated.

2. MODELS

The schematics using pentane as working fluid for BOFC, ROFC and MOFC are shown in Figs. 1-3. As Fig.1 shows, the working fluid after flashing of BOFC is throttled into condensation pressure, which produce great irreversible loss. As Fig.2 shows, the working fluid of ROFC preheated by the hot liquid after flashing through an internal heat exchanger that the evaporator inlet temperature is increased. As Fig.3 shows, the cold working fluid form pump 2 is mixed with the hot liquid after flashing, which has also recovered part of the heat of liquid after flashing. The parameters and boundary conditions are listed in Table 1. The flash evaporation temperatures of the systems are optimized for maximum net power outputs at each condensation temperature.

Table 1 Boundary conditions of the systems.

Parameters	Value
Geothermal water inlet temperature	150 ℃
Geothermal water reinjected temperature	70 ℃
Geothermal water pressure	2 MPa
Cooling water inlet temperature	25 ℃
Reference dead state temperature	25 ℃
Pinch point difference in the evaporator	10 ℃
Pinch point difference in the IHE and condenser	5 ℃
Turbine mechanical efficiency	98%
Generator efficiency	97%
Isentropic efficiency of working fluid pump	80%
Circulating pump efficiency	80%
Isentropic efficiency of turbine	80%
Circulating pump head	20 m
Mass flow rate of geofluid	1 kg/s

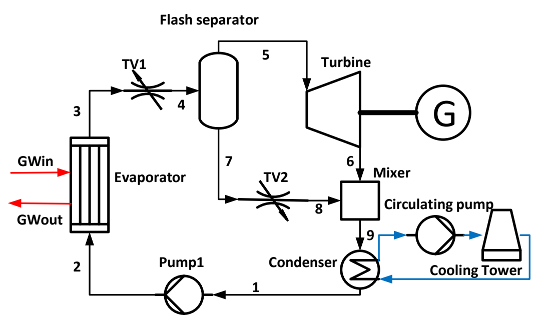

Fig. 1 Schematic of a BOFC with a wet cooling tower

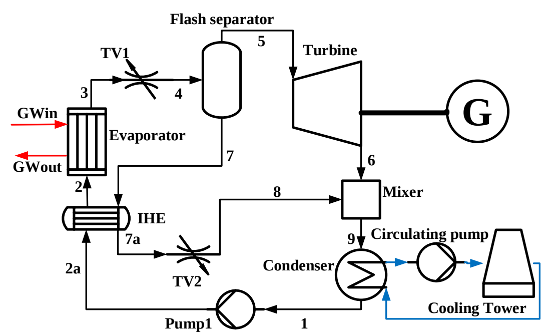

Fig. 2 Schematic of a ROFC.

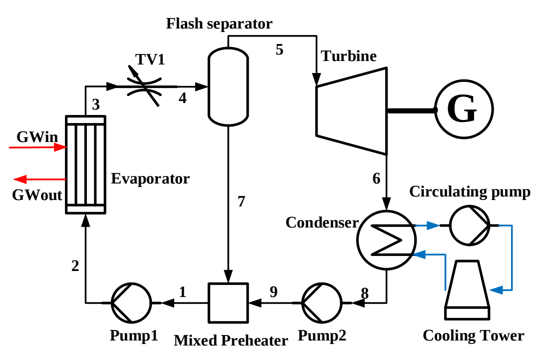

Fig. 3 Schematic of a MOFC.

Mass, energy, exergy balances for any control volume at steady state with negligible potential and kinetic energy changes can be expressed as

$$\Sigma m_{in} = \Sigma m_{out} \quad (1)$$

$$Q - W = \Sigma m_{in} h_{in} - \Sigma m_{out} h_{out} \quad (2)$$

$$E_{heat} - W = \Sigma E_{out} - \Sigma E_{in} - I \quad (3)$$

The net power outputs are calculated as

$$W_{net} = W_{T} - W_{WFP} - W_{CP} \quad (4)$$

where W_T is turbine power output, W_{CP} is circulating pump power consumption, and W_{WFP} is working fluid pump power consumption.

The exergy destruction rate in each component of the system is defined as

$$\Omega_i = \frac{I_i}{E_{GWin}} \quad (5)$$

3. RESULTS AND DISCUSSION

3.1 Optimal flash evaporation temperature

Note that the geothermal water inlet temperature and the reinjection temperature are fixed at 70 ℃ and 150 ℃, respectively. As Fig. 4 shows, the optimal flash temperatures of ROFC and MOFC are greatly decreased compared to BOFC. The optimal flash temperatures for ROFC and MOFC are decreased 5.08 ℃-13.04 ℃ and 8.15 ℃-16.52 ℃, respectively. Because the optimal flash temperatures of ROFC and MOFC are limited by the reinjection temperature. If the optimal flash temperature is so high that evaporator inlet temperature could be preheated even higher than the reinjection temperature, which is unreasonable. The optimal flash temperatures for BOFC increase when condensation temperature increases. However, the optimal flash temperatures of ROFC and MOFC decrease as condensation temperature increases.

Noted that increase of optimal flash temperatures for OFCs would increase the specific enthalpy drop in the turbines that produces more turbine power outputs, but the pressure drop in the throttle valve would be decreased that reduces production of vapor.

3.2 Net power output

Fig. 5 shows that net power outputs first increase as condensation temperature increases and then decreases for condensation temperatures above the optimal condensation temperature. As Fig. 6 shows, W_T decreases almost linearly as the condensation temperature increases, because specific enthalpy drop in the turbine decreases as the condensation temperature increases. As Fig. 7 shows, the slope of W_{CP} decreases as the condensation temperature increases. There is not much change in working fluid pump power consumptions at each condensation temperature. According to eq. (4), there must be an optimal condensation temperature for maximum net power output. Compared to BOFCs and ROFC, the heat of liquid after flashing of MOFC is recycled that leads to the least circulating pump power consumption. Results show that optimal condensation temperatures of BOFCs, ROFC and MOFC are 37.5℃, 34.5℃, and 34℃, respectively. Maximum net power outputs of ROFC and MOFC are relatively improved 22.28% and 23.14% compared with BOFCs at optimal condensation temperature, respectively. MOFC produce the most net power output because of the least circulating pump power consumption.

Furthermore, net power outputs for ROFC and MOFC sharply decrease after the maximum, and net power outputs for BOFC decrease slowly after the maximum as Fig.5. Because turbine power outputs of ROFC and MOFC decrease sharply when condensation temperatures are above the corresponding optimal condensation temperatures. but turbine power outputs of BOFC decrease slowly when condensation temperatures are above the optimal condensation temperatures.

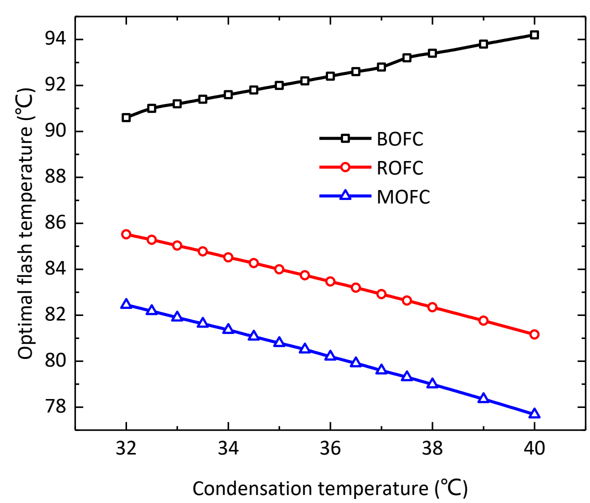

Fig. 4 Optimal flash temperature for the systems.

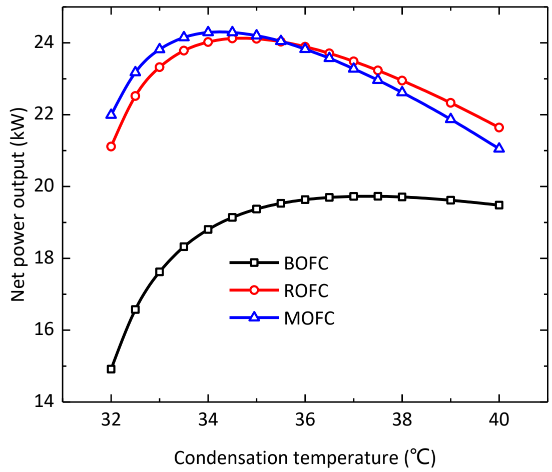

Fig. 5 Net power outputs for the systems.

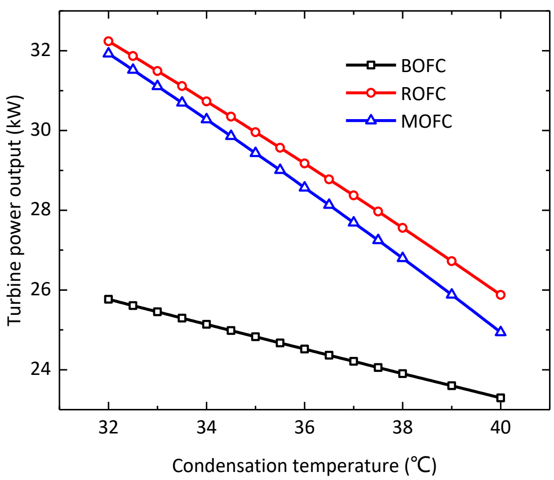

Fig. 6 Turbine power output for the systems.

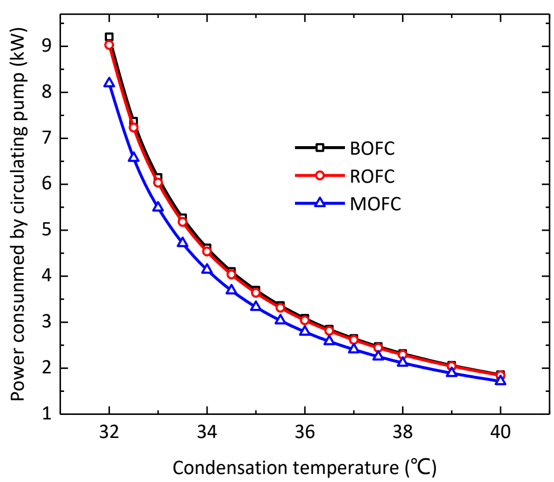

Fig. 7 Circulating pump power consumption for the systems.

3.3 Temperature matching and pinch points analysis

As Fig.8 shows, temperature matching of ROFC and MOFC during heat addition process are better than BOFC. Recovering the part of heat of liquid after flashing increases the evaporator inlet temperatures of ROFC and MOFC, which decrease the heat transfer temperature difference between working fluid and geothermal source. Thus, the irreversible loss during heat addition process is decreased compared to BOFC.

Furthermore, the pinch points of BOFCs happen in the end of heat addition, while that of ROFC and MOFC happen during the heat addition process as shown in Fig.8. Recovering the part of the heat of saturated liquid after flashing has resulted in change of locations of pinch points.

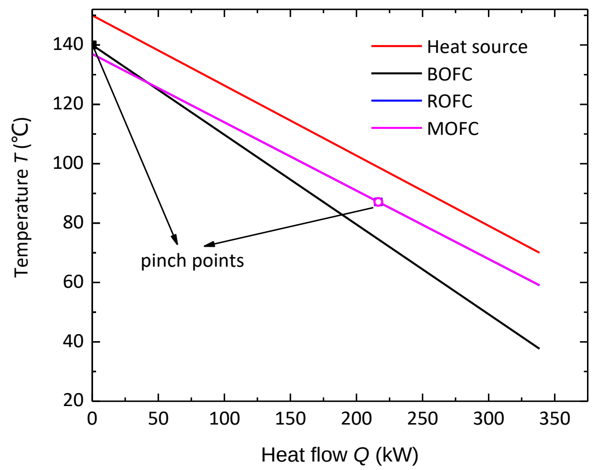

Fig. 8 Diagram of pinch points for the systems.

4. CONCLUSIONS

In this work, comparative thermodynamic performance of two kinds of modified OFCs that recover the heat of liquid after flashing are presented. The evaporation temperature of the systems BOFC, ROFC and MOFC using pentane as working fluid were optimized for maximum net power output at each condensation temperature. The results are as follow:

(1). The optimal flash temperatures of ROFC and MOFC are greatly decreased compared to BOFC. Because the optimal flash temperatures of ROFC and MOFC are limited by reinjection temperature.

(2). Recovering the heat of liquid after flashing can decrease the optimal condensation temperatures of the systems and improve system performance.

(3). Recovering the part of heat of liquid after flashing significantly increases evaporator inlet temperatures for ROFC and MOFC, which decreases heat transfer temperature difference between working fluid and source and decreases irreversible loss.

(4). Recovering the part of heat of liquid after flashing has led to change of positions of pinch points.

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