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Influence of working fluid properties on system performance and screen evaluation indicators for geothermal ORC (organic Rankine cycle) system

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ABSTRACT

The ORC (organic Rankine cycle) system is one of the most effective approaches for recovering energy from low grade heat sources like geothermal water. This paper describes the screen of fluids for geothermal ORC system. This study analyzed the influence of the working fluid properties of HC (hydro carbon) and HFC (hydro fluorine carbon) working fluids on the system performance and relates the properties to the molecular structures. HC and HFC working fluids were adopted. A theoretical ORC model was used to optimize the evaporating temperature to maximize the work output for each working fluid. The optimal working fluids are given for heat sources at 383.15 K, 403.15 K and 423.15 K. The results show that for a specific source temperature, the optimized evaporating temperatures for all the working fluids are almost the same. Based on the influence of working fluid property on system performance, two indicators are given for screening working fluids. Fluids like R32, R134a and propylene with GWP (global warming potential) value less than 1500 provide better performance than others, by extracting more energy from the heat source.

1. Introduction

Low temperature heat sources are abundant on the earth. Turning low temperature energy into work effectively is one of the most promising approaches for relieving the pressure of the energy crisis. The ORC (organic Rankine cycle) is an effective way to convert low temperature heat into work and has attracted the attention of many researchers. Geothermal resources are renewable low temperature heat sources with geothermal water generally range between 353 K and 623 K [1]. High quality resources produce dry vapor or a water-vapor mixture at temperatures of more than 450 K. Medium and low quality sources with temperatures below 450 K must use binary power plants such as ORC systems to improve their efficiency. Guzović, Z., et al. [2] compared the Kalina and ORC system to recover geothermal energy in Republic of Croatia. Results show that ORC has better performance both in the thermal efficiency and the exergetic efficiency and gives more net power. Rašković, P [3].,who is in the same research group with Guzović, Z., made a more detailed Velika Ciglena medium temperature (448.15 K) geothermal case study and indicated that the plant design based on the ORC cycle has a higher thermodynamic efficiency and lower cost of equipment than Kalina cycle.

There are various opinions about the best working fluids and evaluation criteria for geothermal sources. Borsukiewicz-Gozdur et al. [4] hold the view the best method to produce more work was to increase the geothermal water flow rate to increase the work output. Hettiarachchi et al. [5] set the heat transfer area per unit work output as the optimum design criteria and recommended PF5050, R123 and n-pentane. T. Guo et al. [6] found that R236ea was the best working fluid for maximizing the work output per unit mass heat source flow rate while E170, R600 and R141b were the best working fluids when minimizing the heat transfer area per work output. Besides the working fluids, the turbine is also an important part of ORC systems. When radial-inflow turbines in an ORC system, R134a provides the highest network output while n-pentane provides the lowest network output among five high-density working fluids [7].

Most working fluid selection studies have compared all possible working fluids with a given criterion to screen suitable working fluids. Ghasemi, H., et al. [8] and Cheng, W.L., et al. [9] have made detailed study on the modeling and optimization for geothermal

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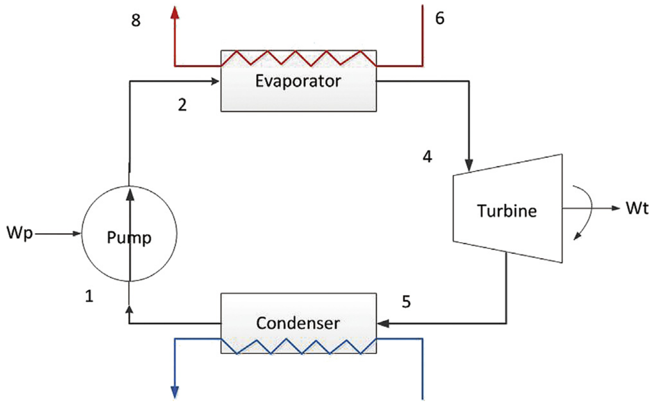

Fig. 1. Schematic diagram of a simple geothermal ORC system.

ORC system. However, the relationship between system performance and working fluids are not mentioned. Some researchers have also begun to make a connection between the working fluids properties and system evaluation indicators [10] with CAMD (computer aided molecular design) and process optimization [11]. These methods enable active working fluid designs for different ORC systems. However, these studies only consider universe ORC system. In reality, each ORC system has its own working fluid requirements, especially for medium and low temperature geothermal ORC systems.

This paper focuses on geothermal ORC systems. The study analyses the influence of the working fluid properties on the system performance and connects the properties and the molecular structures. The results provide guidance for mixture working fluid design. Unlike waste gas or liquid discharged from industrial sources, geothermal water is pumped from deep under the ground which consumes work. The heat source utilization efficiency is then very important for geothermal ORC systems. The optimize objective is to maximize the work output per unit mass of geothermal water. Liu, B. T. et al. [12] referred that the maximum value of the total heat-recovery efficiency occurs at the appropriate evaporating temperature between the inlet temperature of waste heat and the condensing temperature. In this paper, a theoretical ORC model was used to optimize the evaporating temperature to maximize the work output per unit mass of geothermal water for each working fluid. HC (hydro carbon) and HFC (hydro fluorine carbon) are chosen as the working fluids. The optimal working fluids were found for heat sources of 383.15 K, 403.15 K and 423.15 K.

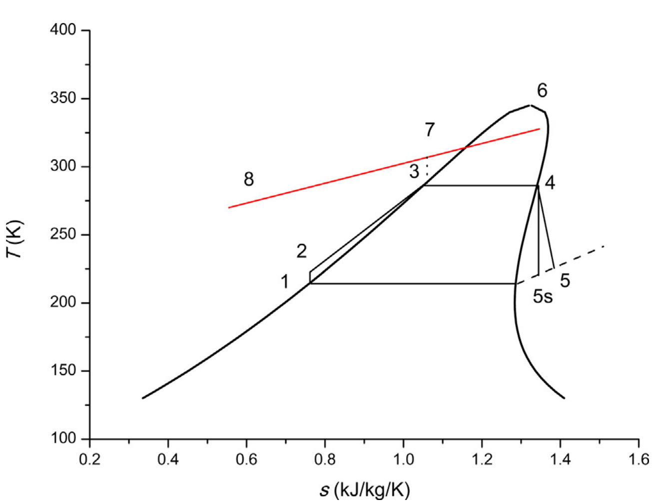

Fig. 2. T–s diagram for geothermal ORC system.

Table 1
Simulation parameters and boundary conditions for the geothermal ORC model.

Parts	Items	Quantities
Heat source	Inlet temperatures	383.15 K/403.15 K/423.15 K
	Pipe pressure	0.5 MPa
	Heat carrier mass flow rate	1 kg/s
Cycle	Pinch evaporator	20 K
	Condenser temperature	283.15 K/293.13 K/303.15 K
	Isentropic pump efficiency	1
	Isentropic turbine efficiency	0.8

2. Geothermal ORC system model

2.1. Description of geothermal ORC systems

The basic cycle without reheating or preheating includes a pump, an evaporator, a turbine and a condenser. A pump pressurizes the organic working fluids to the evaporating pressure. Then, the working fluid is injected into an evaporator and heated by the geothermal hot water to produce vapor. The vapor is expanded in a turbine to produce work. Finally, the exit vapor is condensed to liquid in the condenser to start a new cycle as shown in Fig. 1.

The state points corresponding to the points in Fig. 1 are shown in the *T*–*s* diagram in Fig 2. The organic working fluid is heated from point 2 to point 4 while the geothermal hot water is cooled from point 6 to point 8. In addition, the heat absorbed by the latent heat, Q_{el}, is in the process from point 6 to point 7 while the heat absorbed by the sensible heat, Q_{es}, is from point 7 to point 8. The pinch temperature difference is between point 3 and point 7.

2.2. Assumption and model

The simulation parameters and boundary conditions of the geothermal ORC model are shown in Table 1. To simplify the calculation, the pump isentropic efficiency was set to 1 while the turbine isentropic efficiency was set to 0.8. The condensing temperature was set to 293.15, 298.13 and 303.15 K. The condensing temperature was fixed to 303.15 K when compare of the various working fluids. And condensing temperature 283.15 and 293.13 are calculated to analyses the condensing temperature influence on the cycle performance.

The evaporating temperature was varied in the analyses. One restriction was that the evaporating pressure had to be lower than 0.9 times the critical pressure to guarantee a subcritical cycle. If the critical temperature of the working fluid is much higher than the source inlet temperature (point 6 in Fig. 2), the other restriction is that the evaporating pressure must be lower than the saturate pressure of the evaporating temperature which is equal to the source temperature minus the pinch temperature difference. The lower limit of the evaporating temperature is the condensing temperature.

The working fluid should operate at saturated conditions to reduce the total irreversibility of the process [13]. The thermal efficiency can be improved to some extent if the fluid is superheated at the turbine inlet. However, it increases the system cost as well [14]. Thus, the simulation set the working fluid to be saturated at the turbine inlet. This paper was only subcritical cycles because they are less expensive than supercritical cycles [15].

On the working fluid side, the total cycle efficiency is defined as:

$$\eta = \frac{w_t - w_p}{q_e} \tag{1}$$

where:

$$w_t = h_4 - h_5 \tag{2}$$