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Sensitivity analysis of system parameters on the performance of the Organic Rankine Cycle system for binary-cycle geothermal power plants

Xiaomin Liu*, Xing Wang, Chuhua Zhang

Department of Fluid Machinery and Engineering, School of Energy and Power Engineering, Xi'an Jiaotong University, No. 28 West Xianning Road, Xi'an 710049, Shaanxi, PR China

HIGHLIGHTS

- Evaporating temperature has significant effect on performance of ORC system.
- Order of system parameters' sensitivity to the performance of ORC is revealed.
- Effect of system parameters on performance indices vary with geothermal temperature.
- Geothermal temperature has no effect on range of six factors to the size of turbine.

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ABSTRACT

The main purpose of this paper is to analyze the sensitivity of system parameters to the performance of the Organic Rankine Cycle (ORC) system quantitatively. A thermodynamic model of the ORC system for binary-cycle geothermal power plants has been developed and verified. The system parameters, such as working fluid, superheat temperature, pinch temperature difference in evaporator and condenser, evaporating temperature, the isentropic efficiencies of the cycle pump and radial inflow turbine are selected as six factors for orthogonal design. The order of factors sensitivity on performance indices of the net power output of the ORC system, the thermal efficiency, the size parameter of radial inflow turbine, the power decrease factor of the pump and the total heat transfer capacity are determined by the range obtained from the orthogonal design. At different geothermal temperatures, the ranges of the six factors corresponding to performance indices are analyzed respectively. The results show that the geothermal temperature influences the range of the factors to the net power output, SP factor of radial inflow turbine, and the total heat transfer capacity, but it has no effect for the range of the factors for the thermal efficiency and the power decrease factor of the pump. The evaporating temperature is always the primary or secondary factor that influence the thermodynamic and economic performance of the ORC system. This study would provide useful references for determining the proper design variables in the performance optimization of the ORC system at different geothermal temperatures.

1. Introduction

The geothermal energy is considered as a worldwide important renewable energy in recent years due to rising environmental pollution concerns. The study carried out by Bertani [1] showed that the globally installed electrical power of 2 GW was achieved in 2007. Furthermore, if the number of low and medium temperature binary-cycle geothermal plant was increased, the installed capacity of geothermal plant would make up 8.3% of the total world electricity production by 2050 [2].

The Organic Rankine Cycle (ORC) is known as one of the efficient technologies for utilizing the low and medium temperature geothermal source. Although the ORC system has been identified as an acceptable technology of power generation by utilizing low-temperature heat sources relatively at high thermal efficiency, some factors such as the heat transfer coefficient of the working fluids adopted in the ORC and the large irreversibilities caused by

* Corresponding author. Tel./fax: +86 29 82663775x308.
E-mail addresses: liuxm@mail.xjtu.edu.cn (X. Liu), wangxing93@163.com (X. Wang), chzhang@mail.xjtu.edu.cn (C. Zhang).

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the bad thermal match between the working fluid and the heat source [3] may limit the amount of energy that can be obtained from the heat source.

In order to improve the performance of the ORC system, the factors influencing the performance of the ORC system needed to be determined firstly. Chen et al. [4] studied 35 working fluids for the Organic Rankine Cycle and supercritical Rankine cycles. The influences of fluid properties on the performance of the two cycles were also analyzed. The results illustrated that the properties of the working fluids were very important in the cycle performance. Wang et al. [5] carried out a working fluids selection and parametric optimization using the simulated annealing algorithm. The result illustrated that the boiling temperature of working fluids greatly affect the optimal evaporating pressure of the ORC system. Wang et al. [6] adopted a thermal efficiency model theoretically based on an ideal ORC to analyze the effect of working fluid properties on the thermal efficiency, the optimal operation condition and exergy destruction at various heat source temperatures. The results indicated that the ratio of evaporating temperature and condensing temperature also had a main influence on the thermal efficiency of ORC.

The equipment used in the ORC system is also a main factor influencing the performance of the ORC system. Pan [7] replaced the constant isentropic efficiency by the internal efficiency adopted to evaluate the nozzle loss, rotor blade loss, friction loss, thus leaving velocity loss and leakage loss in the radial flow turbine in analyzing the performance of the ORC system. The results showed that the differences between the cycle net power output with internal efficiency analysis and that with conventional analysis method should be considered in the performance analysis of the ORC system. Wang et al. [8] adopted a reasonable efficiency of radial turbo expanders by using the preliminary design to analyze the performance of the ORC system used for the binary-cycle geothermal power plants. The results illustrated that the influence of isentropic efficiency on the power output and thermal efficiency of ORC could not be ignored. Li et al. [9] analyzed the influence of the heat exchangers' parameters on the net power output and the heat transfer area of ORC in recovering the low temperature waste heat. The results illustrated that the pinch point temperature difference (PPTD) of the evaporator at the given total temperature difference influences the total heat transfer area and the corresponding cost-effective performance.

The configurations of cycles and other parameters also influence the performance of the ORC system. Yari [10] conducted an exergtic analysis of various types of geothermal power plants. The results illustrated that the binary cycle with the regenerative ORC with an internal heat exchanger and R123 as the working fluid had the highest efficiency (15.35%). However, the efficiency of simple ORC was only 13.0%. A set of parametric studies were carried out by Marion et al. [11] to establish the optimum configuration of a solar the ORC system. The results showed that the expected net mechanical power depends strongly on the fluid mass flow rate of system. A parametric energy analysis was performed by Algieri and Morrone [12] to analyze the energetic performances of ORC for a biomass power plant. The results showed that the internal regeneration and maximum temperature had a significant effect on the power plant performances.

Although many studies have been conducted to reveal the main parameters which influence the ORC system, it is necessary to investigate the effect of system parameters on the performance of the ORC system. One of the reasons is that the influences of system parameters on the ORC system always vary with performance indices. Li et al. [13] studied the effects of the evaporating temperature and the internal heat exchanger on ORC. The results illustrated that the adoption of the internal heat exchanger could improve thermal and exergy efficiency. However, the output power of the ORC system reduced a little bit after its being equipped with the internal heat exchanger and the decrease rate of the output power increased with the increase in the mass proportion. Branchini et al. [14] conducted a systematic comparison of ORC configurations by using comprehensive performance indexes. The results illustrate that higher hot source temperature leads to higher heat recovery efficiency values but make the heat exchange surface areas for the heat exchangers larger. Guo et al. [15] studied the effect of the location of heat transfer pinch point in evaporator on the ORC performance under conditions of different operating parameters and cycle types. The results indicated that the supercritical ORC can obtain better thermal efficiency, exergy efficiency and work output at lower outlet temperature of heat source determined by heat transfer pinch point, with the work output per unit area of the supercritical ORC being much lower.

In the present study, the net power output of the ORC system, thermal efficiency, the size parameters of radial inflow turbine, the power decrease factor of the pump and the total heat transfer capacity are selected as the indices to comprehensively evaluate the performance of the ORC system. The quantitative analysis is conducted of the sensitivity of system parameters, such as working fluids, superheat temperature, the pinch temperature difference in evaporator and condenser, evaporating temperature, isentropic efficiency of the cycle pump and isentropic efficiency of radial inflow turbine on the five performance indices of the ORC system by the range analysis based on the orthogonal design. In order to provide detailed references to the selection of optimization variables in the optimization of the ORC system for binary-cycle geothermal power plant, the orders of the sensitivity of system parameters to the indices at different geothermal temperatures are revealed.

2. System description and modeling

Fig. 1 depicts the schematic of the ORC system adopted in the present study with the geothermal water considered as the heat source. The mass flow rate of geothermal water is 70 t/h. The temperature of geothermal water at inlet of evaporator or superheater (when included) is 363 K and that of the cooling water at the inlet of condenser is 293 K. The ORC system is composed of a

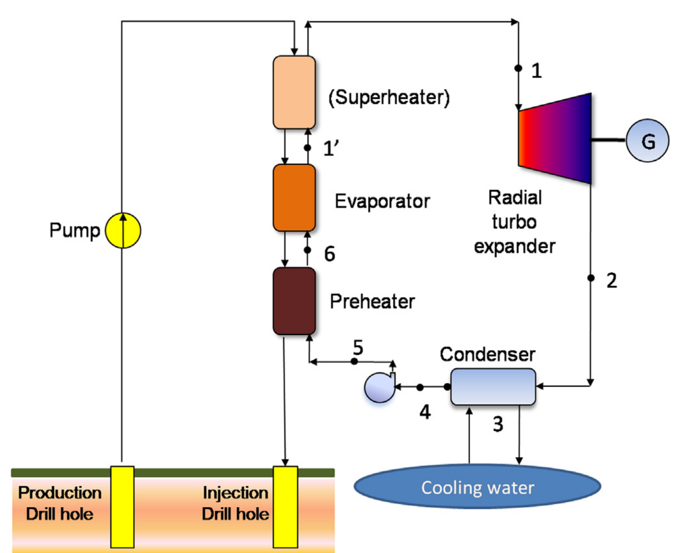

Fig. 1. Schematic diagram of the ORC system.