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Parametric optimization and range analysis of Organic Rankine Cycle for binary-cycle geothermal plant

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ABSTRACT

In this study, a thermodynamic model of Organic Rankine Cycle (ORC) system combined with orthogonal design is proposed. The comprehensive scoring method was adopted to obtain a comprehensive index to evaluate both of the thermodynamic performance and economic performance. The optimal level constitution of system parameters which improves the thermodynamic and economic performance of ORC system is provided by analyzing the result of orthogonal design. The range analysis based on orthogonal design is adopted to determine the sensitivity of system parameters to the net power output of ORC system, thermal efficiency, the SP factor of radial inflow turbine, the power decrease factor of the pump and the total heat transfer capacity. The results show that the optimal level constitution of system parameters is determined as the working fluid of R245fa, the super heating temperature of 10 °C, the pinch temperature difference in evaporator and condenser of 5 °C, the evaporating temperature of 65 °C, the isentropic efficiency for the pump of 0.75 and the isentropic efficiency of radial inflow turbine of 0.85. The order of system parameters' sensitivity to the comprehensive index of orthogonal design is evaporating temperature > isentropic efficiency of radial inflow turbine > the working fluid > the pinch temperature difference of the evaporator and the condenser > isentropic efficiency of cycle pump > the super heating temperature. This study provides useful references for selecting main controlled parameters in the optimal design of ORC system.

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1. Introduction

As an environmentally friendly renewable energy, the geothermal energy has been identified as an important energy in recent years. Bertani [1] studied the development of the geothermal power generation all over the world. The results illustrated that an increase of about 2GW in the five year term 2005–2010 has been achieved. 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 total world electricity production by 2050.

The Organic Rankine Cycle (ORC) is considered as an efficient technology for utilizing the low and medium temperature geothermal source. In order to improve the performance of ORC, a lot of studies about the selection of the working fluid, the main device of ORC, the configurations of systems and the parametric optimization of ORC system have been investigated in recent years.

The working fluids play an important role in the performance of ORC system. Chen et al. [2] reviewed 35 working fluids for the Organic Rankine Cycle and supercritical Rankine cycles and analyzed the influence of fluid properties on the performance of the two cycles. The results illustrated that the properties of the working fluids were very important for in the cycle performance. Bao and Zhao [3] reviewed the selection of working fluids and expander for ORC. It was found that the selection of working fluids was a tedious process and should consider many factors. The isentropic and dry fluids are preferred in Organic Rankine Cycles. He et al. [4] analyzed the optimal working fluid for a subcritical ORC system. According to the maximum net power output, suitable working pressure, total heat transfer capacity and size parameter of the expander, R114, R245fa, R123, R601a, n-pentane, R141b and R113were suited as working fluids for subcritical ORC under the given conditions. Basaran and Ozgner [5] investigated the effects of twelve refrigerants on performances of binary geothermal power plants. The results showed that the dry type fluids R236ea, R600, R600a, and R227ea would increase the energy and exergy efficiencies of binary geothermal power plants. Heberle et al. [6] investigated the zeotropic mixtures in Organic Rankine Cycles for low-enthalpy geothermal resources. The results illustrated

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Nomenclature

T	temperature (K)
P	pressure (MPa)
h	specific enthalpy (kJ kg^{-1})
$\dot{W}$	power output or input (kW)
C_P	specific heat capacity of water at constant pressure (kJ kg^{-1} K^{-1})
v	specific volume (m^3 kg^{-1})
$\dot{m}$	mass flow rate (kg s^{-1})
$\dot{Q}$	heat injected and rejected (kW)
F_{SP}	the SP factor of radial inflow turbine (dimensionless)
F_K	the *K* factor of cycle pump (dimensionless)
$(\mathrm{HA})_{\mathrm{tot}}$	the total heat transfer capacity (kW K^{-1})
$\dot{V}$	volume flow rate of the working fluid (m^3 s^{-1})
ΔH_S	specific enthalpy drop in the radial inflow turbine (kJ kg^{-1})
$\Delta \overline{T}_m$	the logarithmic mean temperature difference (K)
ΔT	the pinch temperature difference (K)
VER	vapor expansion ratio (dimensionless)
M	membership dgree (dimensionless)
I	index of the orthogonal design
S_C	comprehensive score (dimensionless)
R	the range of factors in the orthogonal design

Subscripts

evp	evaporator
con	condenser
o	organic working fluids
out	power output of ORC
tur	radial inflow turbine
turo	outlet of the radial inflow turbine
turi	inlet of the radial inflow turbine
prei	inlet of preheater
S	isentropic process
gin	geothermal water temperature at superheater inlet
gout	geothermal water temperature at superheater outlet
water	geothermal source water
pump	pump used in the cycle
1–6	state points of ORC system
min	minimal
max	maximal
n	number of trial scheme in orthogonal design
super	the superheater

Greek symbols

η_{th}	thermal efficiency of ORC

that the zeotropic mixtures increased the efficiency of ORC system compared to pure fluid.

The main device of the ORC system is another main factor that influences the performance of ORC system. Pan and Wang [7] replaced the constant isentropic efficiency by internal efficiency of optimal radial flow turbine in the ORC analysis. The results showed that the differences between cycle net power output with internal efficiency analysis and that with conventional analysis method cannot be ignored. Sauret and Rowlands [8] presented the rationale for the use of radial-inflow turbines for ORC applications and conducted the design of several radial-inflow machines. The heat transfer capacity of the evaporator is extremely important for a successful ORC system. Zhang et al. [9] conducted heat transfer analysis of a finned-tube evaporator for ORC system used in engine exhaust heat recovery. The results showed that a finned tube evaporator should be selected carefully based on the most typical operating region of engine. It was also found that the heat transfer rate is the greatest in the preheated zone and least in the superheated zone.

The choice of the cycle type was also important for a geothermal power plant. A proper cycle type could improve the performance of ORC system. Walraven et al. [10] conducted the comparison between the different types of ORCs and the Kalina cycle. It was found that the transcritical and multi-pressure subcritical cycles were the best choice for low-temperature geothermal heat sources. Branchini et al. [11] carried out systematic comparison of ORC configurations by using comprehensive performance indexes in their study. When the hot source temperature was 200 °C, the best identified configurations have been obtained with more complicated layouts, namely SH (superheated cycle) with butane and REC + SH (recuperated superheated steam cycle) with R245fa. Baik et al. [12] compared the power optimization between R125 transcritical cycle and HFC (hydrofluorocarbon) ORC for a low-grade heat source of 100 °C. The results showed that the power output of an R125 transcritical cycle was greater than that of subcritical ORCs when total overall conductance (TOC) was higher than 35 kW/K, but the transcritical cycle' s power output was slightly less than that of subcritical cycles when the TOC was lower than 35 kW/K.

Much attention has also been paid on optimization of ORC system. Sun and Li [13] carried out the optimization of an Organic Rankine Cycle (ORC) heat recovery power plant using R134a as working fluid. The results revealed that the relationships between controlled variables (optimal relative working fluid mass flow rate, the optimal relative condenser fan air mass flow rate) and uncontrolled variables (the heat source temperature and the ambient dry bulb temperature) were different when maximizing system net power generation and the system thermal efficiency respectively. Wang et al. [14] carried out a multi-objective optimization of an Organic Rankine Cycle using evolutionary algorithm. The results illustrated that the turbine inlet pressure, turbine inlet temperature, pinch temperature difference, approach temperature difference and condenser temperature difference played an important role in influencing the exergy efficiency and overall capital cost. The optimum turbine inlet pressure and the optimum turbine inlet temperature were also determined. Zhang et al. [15] conducted a performance comparison and parametric optimization of subcritical Organic Rankine Cycle (ORC) and transcritical power cycle system for low-temperature geothermal power generation. The performances of the working fluids were also evaluated and compared under their optimized internal operation parameters. They found that the optimum operation parameters and working fluids were not the same for different indicators. R125 shows excellent economic and environmental performance in transcritical power cycle and can maximize utilization of the geothermal source. R41 also exhibits favorable performance except for its flammability. Dai et al. [16] carried out parametric optimization and comparative study of Organic Rankine Cycle (ORC). The results showed that the cycle with R236ea had the highest exergy efficiency. Adding an internal heat exchanger into the ORC system could not improve the performance under the given waste heat condition.

Although many studies have been done on ORC system, the properly parameters of ORC system for specific condition of heat source still need to be determined. One of the reasons is that the suitable working fluid, parameters of devices and the configuration of the system always varied with condition of the heat source and the performance requirements of ORC system. Furthermore, the order of the system parameters' sensitivity to the thermodynamic

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