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An integrated optimization for organic Rankine cycle based on entransy theory and thermodynamics

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A B S T R A C T

The organic Rankine cycle has been one of the essential heat-work conversion technologies nowadays. Lots of effectual optimization methods are focused on the promotion of the system efficiency, which are mainly relied on engineering experience and numerical simulations rather than theoretical analysis. A theoretical integrated optimization method was established based on the entransy theory and thermodynamics, with the ratio of the net power output to the ratio of the total thermal conductance to the thermal conductance in the condenser as the objective function. The system parameters besides the optimal pinch point temperature difference were obtained. The results show that the mass flow rate of the working fluid is inversely proportional to the evaporating temperature. An optimal evaporating temperature maximizes the net power output, and the maximal net power output corresponds to the maximal entransy loss and the change points of the heat source outlet temperature and the change rates for the entropy generation and the entransy dissipation. Moreover, the net power output and the total thermal conductance are inversely proportional to the pinch point temperature difference, contradicting with each other. Under the specified condition, the optimal operating parameters are ascertained, with the optimal pinch point temperature difference of 5 K.

1. Introduction

The global energy shortage urges the promotion of the heat-work conversion for low- and medium-temperature heat sources, such as geothermal energy, solar energy, the waste heat and so on. Among the numerous technologies, organic Rankine cycle (ORC) has attracted much attention due to its simple system structure and convenient operating maintenance in the past few decades [1–4]. However, the main problem is that the ORCs driven by relatively low heat sources show lower system efficiencies.

Researchers have made great efforts to enhance the system performance, focusing on the parameter matching of the ORC with the heat source and the cold source, which can be categorized into two broad types. One is the optimization of the working fluid selection due to that the working fluid is a key factor; and the other is the simulation-based parameter optimization mainly by the first and second laws of thermodynamics. Tamamoto et al. [1] investigated the performance of the ORC with R123 and water theoretically and experimentally, and R123 is preferable. Hung et al. [5] compared the efficiencies of ORCs using benzene, ammonia, R11, R12, R134a and R113. Saleh et al. [6] presented a thermodynamic screening of 31 pure working fluids for ORCs, showing that fluids with slightly lower critical temperatures are to be preferred. Aljundi [7] analyzed the influence of dry fluids on the efficiencies of the ORC. Hung [8] investigated benzene, toluene, p-xylene, R113 and R123 in recovering low enthalpy heat sources. Yari [9,10] investigated several dry fluids for the ORC by first and second law analyses. Liu et al. [11] investigated the effects of various working fluids on the thermal efficiency and on the total heat recovery efficiency. Arosio et al. [12] found that PP50 and R134a appear to be the most promising working fluids. Lakew et al. [13] considered are R134a, R123, R227ea, R245fa, R290, and *n*-pentane.

Many researchers have been done a lot of work to optimize the ORC parameters. Hettiarachchi et al. [2] presented an optimum design of an ORC driven by low-temperature geothermal water, with the screening criterion of total heat transfer area to the net power out. Roy et al. [14] conducted a parametric optimization of a waste heat recovery system and considered the power output and efficiencies. Rashidi et al. [15] presented a parametric optimization

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of the regenerative ORCs, with efficiencies and specific work as the objective functions. Guo et al. [16] showed that optimum evaporation temperature and fluids vary with screening criteria. Chao et al. [17] proposed the optimal evaporation temperature and working fluids. Wang et al. [18] optimized a thermodynamic parameters using genetic algorithm. Cayer et al. [19] and Zhang et al. [20] conducted a parametric investigation for transcritical and subcritical ORC systems.

The brief reviews presented above are mainly based on the first and second laws of thermodynamics, and these literature did not take the pinch point temperature difference and the heat transfer in the evaporator and condenser in account at the same time. Actually, the two factors have significant effect on the ORC performances. The pinch point temperature difference directly determines the net power output, however, the heat transfer in the evaporator and condenser can illustrate the system investment. Most of the previous just studies fixed the value of the pinch point temperature difference based on experience. Moreover, the heat transfer in the evaporator and condenser for the ORC are always simplified due to that it differs with the working fluid properties and the working condition. Luckily, researchers have introduced and developed a new theory, the entransy theory, to optimize some typical energy utilization systems containing a number of heat transfer processes in heat exchangers, such as evaporative cooling [21], heat exchanger networks in buildings [22,23] and thermal management systems in spacecrafts [24].

Based on the entransy theory and thermodynamics analysis, a theoretical integrated optimization method for the ORC systems is established. The entransy theory is mainly used for the heat transfer processes and the thermodynamic analysis for the expansion process in the turbine and compression process in pump. Furthermore, a novel objective function, $W_{net}/((KA)_{total}/(KA)_c)$, was defined to optimize the pinch point temperature difference. The main objective of this study was focused on optimizing the ORC system parameters. The cycle parameters, W_{net}, S_g, G_{dis}, G_{loss}, $t_{gw,out}$, t_e, η_{th}, η_{ex}, $(KA)_e$, $(KA)_c$, and $(KA)_{total}$, were calculated, and the optimal operating parameters were also ascertained.

2. Analysis of an ORC system

A typical ORC system for power generation can be categorized in three loop circuits according to the working media: the heat source, the working fluid, and the heat sink. The ORC mainly consists of an evaporator, a turbine, a generator, a condenser, a pump, a cooling tower, a cooling pump, and a hot water pump.

The heat source transfers heat to the organic fluid, which absorbs heat to generate high-pressure vapor in the evaporator (Figs. 1 and 2, state 1), then the vapor flows into the turbine and its enthalpy is converted into shaft work to drive the generator. The vapor exits the turbine (Figs. 1 and 2, state 2) is led to the condenser where it is liquefied by cooling water. The liquid working fluid at the condenser outlet (Figs. 1 and 2, state 3) is pressurized by the pump and flows into the evaporator (Figs. 1 and 2, state 4). Then a new cycle begins. The T–s diagram of the ORC is shown in Fig. 2.

The analysis of an ORC based on thermodynamics and the entransy theory were performed for the working fluids investigated. For simplicity, the following assumptions were made:

(1) Geo-plants are operated in a steady state, with a heat source of 105 °C.
(2) Superheated vapor is considered at the turbine inlet, with a degree of superheat of 5 K, and saturated liquid at the condenser exit.
(3) The kinetic and potential energy changes are negligible.

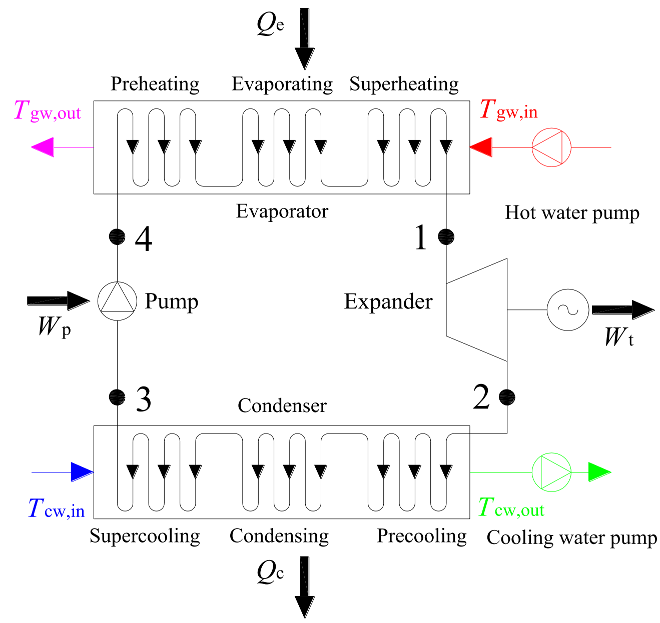

Fig. 1. Schematic diagram of an ORC system.

(4) The thermal loss and the friction loss in the pipes are neglected. There are only two pressures: an evaporating pressure p_e, and a condensing pressure p_c.
(5) The isentropic efficiency of the turbine η_t, the pump η_p, the how water pump $\eta_{p,hw}$, and the cooling water pump $\eta_{p,cw}$ is set to be 0.8, 0.6, 0.75, and 0.75, respectively.
(6) Electrical generator efficiency is taken as 0.90.
(7) Atmospheric condition is taken as 0.101325 MPa and 25 °C.
(8) The temperature at the condenser outlet t_3 is 30 °C.

In an ORC, there are two different categories of thermodynamic processes as the heat transfer processes in both evaporator and condenser and heat-work conversion processes in both pump and turbine. The temperature differences between the heat source/sink and the working fluid drive the heat transfer in both evaporator and condenser, whereas the absolute temperatures of the working fluid impel the heat-work conversion processes. The heat transfer processes are analyzed by entransy theory and heat-work conversion processes by thermodynamic analyses entransy theory.

2.1. Entransy analysis of the heat exchangers

The entransy represents the potential energy of heat in an object corresponding to the analogy of the electrical energy in a capacitor, and it is defined as follows [25]:

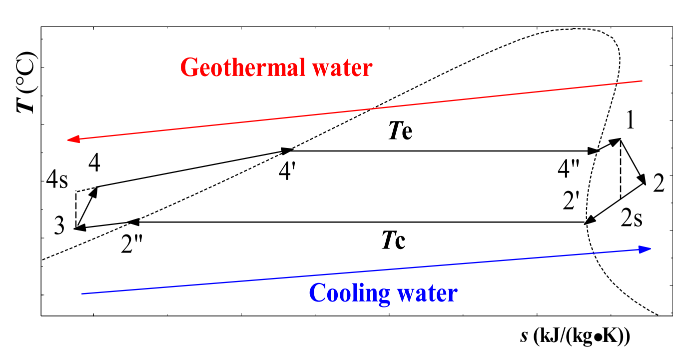

Fig. 2. T–s schematic diagram of an ORC system.