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Thermodynamic optimization of organic Rankine cycle using two-stage evaporation

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ABSTRACT

Organic Rankine cycle (ORC) is a promising technology to recover low-grade heat, but it leads to a low efficiency due to the highest irreversible loss caused by the single-stage evaporation. The present work concerns the performance enhancement of a two-stage serial organic Rankine cycle (TSORC) for geothermal power generation. The heat source is divided into two separate temperature ranges. The main goal of the current simulation is to evaluate system performance of TSORC, as well as, to calculate the influence of two-stage evaporation on system performance. The ratio of the net power output to the total thermal conductance was chosen as the objective function. Results show that the system performance is coupled with geothermal water inlet temperature (GWIT), intermediate geothermal water temperature (IGWT), and evaporating temperatures. The two-stage evaporation significantly reduces the irreversible loss, thereby enhancing the net power output. The TSORC presents excellent systematic performances and deserves to be popularized in engineering applications.

1. Introduction

With the improvement of the living standards, the global population growth results in the energy demand acceleration. The energy demand is predicted to increase faster [1]. Moreover, the electricity price has increased by about 12% over the past decade [2,3]. Furthermore, serious environmental issues greatly influence the energy policy, and the energy gap has been becoming larger, which motivates the technologies for power generation from low-temperature sources. The available solutions include organic Rankine cycle (ORC), Stirling cycle, Kalina cycle et al. Among these cycles, ORC has been attracted much attention due to its simple cycle configuration, high reliability and flexibility, and convenient maintenance [4]. The ORC-based plants have been successfully adopted in recovering the geothermal energy [5], solar energy [6], ocean thermal energy [7], and waste heat [8].

The ORC has been proven promising in converting low-grade heat into power, but the thermal efficiency is low, only 8–12% [9]. Mago et al. [10] calculated the exergy destruction to show that the evaporator has the highest exergy destruction rate, around 77%. Numerous studies have been carried out in order to reduce the system irreversible loss, thereby improving the system performance. The correlative literatures can be summarized as the parametric optimization, and the main research topics can be classified into two aspects, i.e., the cycle configuration and the zeotropic mixture. The zeotropic mixtures have non-isothermal phase shift to decrease the irreversibility in exchangers. The screening of the working fluids have been studied by Wang et al. [11], Garg et al. [12], Borsukiewiczgozdur and Nowak [13], Chys et al. [14], and Heberle et al. [15]. However, we do not focus on the working fluid selection, with R245fa used as the working fluid in this paper. The cycle configuration, evaporating strategy, is another aspect that should be improved in order to enhance the system performance.

Based on ORC, the regenerative organic Rankine cycle (RORC) has been proposed and analyzed. Mago et al. [16], Pei et al. [17], Xi et al. [18], Roy and Misra [19], and Fernández et al. [20] analyzed RORC and found that the supercritical RORC is preferable for high temperatures heat source. The system efficiency is related to the internal heat exchanger. Franco [21] utilized two different configurations, two basic and two recuperated cycles. The system performance increased a little, but significant reduction was found in cooling system surface area (up to 20%). Li et al. [22] constructed and experimentally analyzed the RORC and found that the efficiency of the RORC is higher than that of the ORC by 1.83%. RORC not

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only decreases the thermal load of the condenser, but also reduces the irreversible loss in the evaporator. However, the system performance was improved only to a small extent.

On the premise of the pinch point temperature, the single-stage is the major factor affecting the system irreversible loss. Many researchers have studied double loop ORC to increase the system performance. Kosmadakis et al. [23] and Kosmadakis et al. [24], Wang et al. [25], Liu et al. [26], Zhang et al. [27], and Shu et al. [28–30] proposed a new dual-loop organic Rankine cycle (DORC). They found that DORC performs better. Yang et al. [31] designed a set of dual-loop ORC to recover exhaust energy. The authors showed that the thermal efficiency of the combined system is increased by 13%. Mohammadkhani et al. [32] utilized a gas turbine-modular helium reactor by two ORCs. The results showed that the precooler, the intercooler, and the ORC condensers exhibit the worst exergoeconomic performance. Li et al. [33] put forward a parallel double-evaporator organic Rankine cycle (PDORC) to decrease the system irreversibility and enhance the power output for geothermal power generation. They found that the PDORC lowers the total irreversible loss, so that enhancing the net power output. Moreover, Stijepovic et al. [34] proposed an exergy composite curve to explore potential improvements in ORC process by introducing multiple pressure configurations. Their research indicates that the multiple pressure system could have significant improvements in system performance.

From the above-mentioned studies, the two-stage ORC can improve the system performance. However, it should be pointed out that the cycle configurations in literature [23–34] are parallel to each other, and these configurations could adversely generate much more irreversible loss for the high-stage. Moreover, no literature has been found to discuss such a TSORC for geothermal power generation.

The present paper concerns the two-stage evaporation on the systematic performance. The heat source is utilized in two different temperature ranges. On one hand attention has been focused on the single- and two-stage systems in term of optimizing the system parameters and on the other performance evaluation has been developed and improved for the two-stage system, so that a more preferable TSORC can be achieved. For the latter purpose, it is crucial to distinguish which parameters and in what extent influence the system performance. The dimensionless ratio of the exergetic efficiency to the total thermal conductance is selected as the objective function. The final scope of the ongoing study is the improvement, TSORC, of the ORC.

2. System description

The heat source is divided into two temperature ranges. Geothermal water from the production wells flows through the evaporator 1 and evaporator 2 successively. It is identified as *a*-*b*-*c*, which is shown by red lines (in web version) from Figs. 1 and 2. Geothermal water from the outlet of the evaporator 2 will be reinjected. The cooling water goes into the condenser driven by the cooling water pump, and it can be identified as *d*-*e*-*d*, which is shown by green lines. The heat source and heat sink in the TSORC are totally the same. Moreover, the counter-current flow between the heat source and heat sink with the working fluid are adopted.

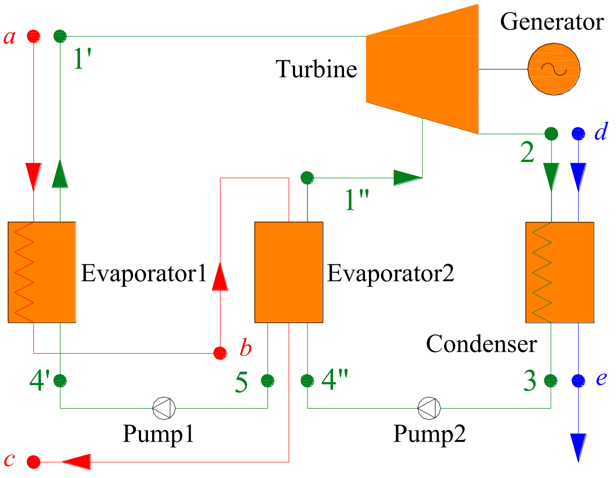

Fig. 1. Schematic diagram of the TSORC.

The TSORC is subcritical, and R245fa was chosen as the working fluid. Figs. 1 and 2 show the schematic diagram and the corresponding *T*-*s* diagram of the TSORC. The TSORC is almost the same with the basic ORC, and the main difference between them two is that the TSORC adopts serial double cascade-evaporating strategy whereas the basic ORC has only one. The TSORC consists of a high-pressure evaporator 1, a low-pressure evaporator 2, a high-pressure pump 1, a low-pressure pump 2, an induction turbine, a generator, a condenser, a cooling pump, and a cooling tower. Due to the two-stage evaporation strategy, the TSORC has two evaporators and two pumps. The exchangers, evaporators and condenser, can be plate or tube-shell depending on the scale of the geo-plant. For an installed generating capacity of lower than tens of kilowatts, the plate heat exchanger can be used. For an installed generating capacity of higher than hundreds of kilowatts, the shell and tube heat exchanger can be used. Sliding vane pumps are selected, and a multi-pressure turbine is chosen in the TSORC and it has two inlets with two different pressures.

The specific flowchart for the working fluid is as follows: The liquid working fluid from the condenser is first pressurized to flow into evaporator 2 where absorbs heat from geothermal water (process *b*-*c*) coming from the evaporator 1 to generate low-pressure saturated or superheated vapour (process 4″-1″). A portion of the saturated liquid at the saturated pressure in the evaporator 2 is pumped to the evaporator 1 to absorb heat from geothermal water (process *a*-*b*) coming from production wells to generate high-pressure saturated or superheated vapour (process 4′-1′). The vapour at the state points 1′ and 1″ flow into the corresponding stages of the induction turbine where its enthalpy is converted into mechanical energy to drive the generator to produce electricity (process 1′ (1″)-2). The discharging steam from the turbine outlet is led to the condenser where it is liquefied by the cooling water (process 2-3). The liquid available at the condenser outlet divides into two parts pressurized by the pumps 1 and 2, and then another new cycle begins. The PDCORC can be identified as 1′(1″)-2-3-4′(4″)-1′(1″), shown by green lines.

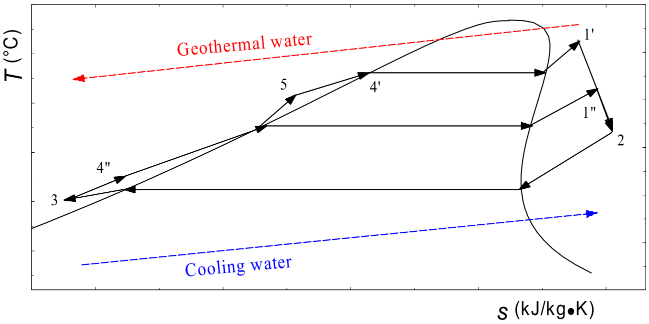

Fig. 2. *T*-*s* diagram of the TSORC.