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Strengthening mechanisms of two-stage evaporation strategy on system performance for organic Rankine cycle

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A B S T R A C T

The ORC (organic Rankine cycle) technology has been found promising for heat recovery, but the major problem is its low efficiency, and the evaporator is a major contributor to the total irreversible losses. The heat source is segmented in two temperature ranges. The TSORC (two stage organic Rankine cycle) was put forward. The objective of this paper is to evaluate the performance enhancement of the TSORC with a reference to the ORC. The system performances (mass flow rate, evaporating temperature, VFR (volumetric flow ratio), net power output, system efficiency, and thermal conductances) for the ORC and TSORC were simulated and compared using R245fa. The objective function is the ratio of the net power output to the total thermal conductance, reflecting both the system earnings and the cost. The results show that the TSORC can enhance the net power output, and the growth rate differs with IGWT (intermediate geothermal water temperature) and GWIT (geothermal water inlet temperature) (GWIT). The TSORC exceeds the ORC and enhances the systematic performance with the GWIT. Optimal IGWT and evaporating temperatures of the TSORC maximize the net power output. The TSORC presents excellent systematic performance, which should be popularized in engineering applications.

1. Introduction

The population boom together with social progress accelerates the energy demand, which is predicted to ascend with 33% by 2020 and 84% by 2035 [1]. The electricity price has increased by about 12% over the past decade [2,3]. Furthermore, serious environmental issues heavily influence the energy policy. The energy gap has been becoming larger and larger, motivating the technologies for power generation from renewable sources and waste heat recovery. Among the cycles, ORC (Organic Rankine cycle) has been focused on due to its simple cycle configuration, high reliability and flexibility, and convenient maintenance [4]. The ORC-based plants have successfully been adopted in recovering the geothermal resources [5], solar energy [6], ocean thermal energy [7], and other waste heat from different industries [8].

The ORC has been proven promising in converting low and medium grade heat sources (from 90 to 150 °C) into power, but the thermal efficiency is only 8–12% [9]. Mago et al. [10] calculated the exergy destruction in ORC using an exergy wheel. The results show that the evaporator has the highest exergy destruction rate, around 77%. Numerous studies have been carried out to reduce the system irreversible loss, thereby improving the system performance. The correlative publications can be summarized as the cycle configuration improvement. Based on the basic ORC, the RORC (regenerative organic Rankine cycle) has been proposed and analyzed. Mago et al. [11], Pei et al. [12], Xi et al. [13], Roy and Misra [14], Fernández et al. [15], Franco [16], and Li et al. [17] analyzed the RORC. They found that the RORC can increase the system performance but within a limited extent. RORC not only decreases the thermal load of the condenser, but also reduces the irreversible loss in the evaporator. However, the system performance is improved indeed, but only to a small extent.

On the premise of the minimal temperature difference at the pinch point, the single-evaporating characteristic between the heat source and the working fluid in the evaporator is the major factor in bringing about the system irreversible loss. Kosmadakis et al. [18] and Kosmadakis et al. [19], Wang et al. [20], Liu et al. [21], Zhang et al. [22], Shu et al. [23–25], Yang et al. [26], and Li et al. [27] analyzed dual-loop ORC, and they found that the dual-loop ORC can enhance the system performance. Mohammadkhani et al. [28] utilized a gas turbine-modular helium reactor by two ORCs, and the

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precooler, intercooler and condensers all three perform poorly. The unit cost of electricity increases with the turbine inlet temperature but decreases as the other above mentioned parameters increase. Moreover, Stijepovic et al. [29] proposed an exergy composite curve to explore potential improvements in ORC process by introducing multiple pressure configurations. They found that the multiple pressure system indicates significant improvements in system performance.

From the above-mentioned references on the ORC, it can be obtained that the two or multi stage ORC can indeed improve the system performance. However, it should be pointed out that the cycle configurations in Refs. [18,19] are all parallel systems in essence, which may also generate much irreversibility for the high-stage loop due to the high temperature difference between the heat source and working fluid at the inlet of evaporator for the working fluid side. Moreover, no reference has been found to discuss such a cascade-evaporating ORC for geothermal power generation driven by the low and medium temperature geothermal resources.

The present paper focuses on the evaluation of the systematic performance improvement of the ORC driven by geothermal water of 90–120 °C. The heat source is utilized in two different segmented temperature ranges. The series double cascade-evaporating organic Rankine cycle TSORC (two stage organic Rankine cycle) are put forward to decrease the irreversible loss, especially in the evaporator, thereby enhancing the systematic performance. R245fa is adopted as the working fluid. The main objective is to compare the system performance for TSORC and to optimize the system parameters, so such the preferable cycle configuration as well as the optimal parameters can be obtained, with the dimensionless ratio of the exergetic efficiency to the total thermal conductance as the objective function. Moreover, the parameters, the mass flow rate of the working fluid, the optimal evaporating temperature, the optimal IGWT (intermediate geothermal water temperature), the VFR (volumetric flow ratio), the net power output, the exergetic efficiency, the thermal conductance, and the objective function of the TSORC were compared with those of the traditional ORC.

2. System description

The heat source is utilized in segmented temperature ranges. Geothermal water from the production wells flows through the evaporator 1 and evaporator 2 successively. It is identified as *a*–*b*–*c*, shown by red lines (in the web version) from Figs. 1–2.

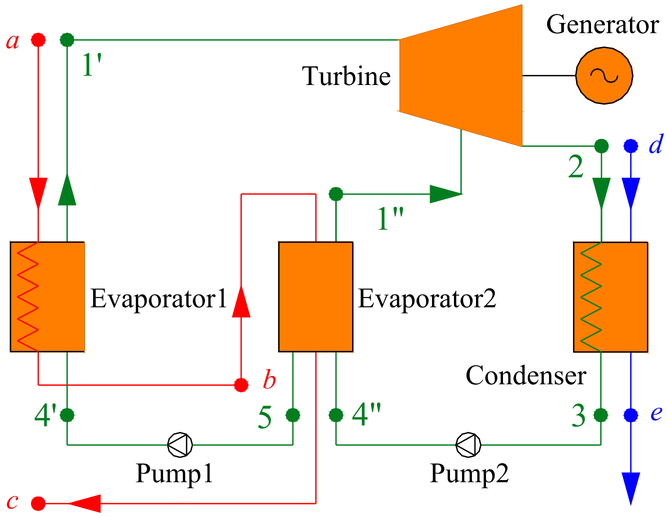

Fig. 1. Schematic diagram of the TSORC.

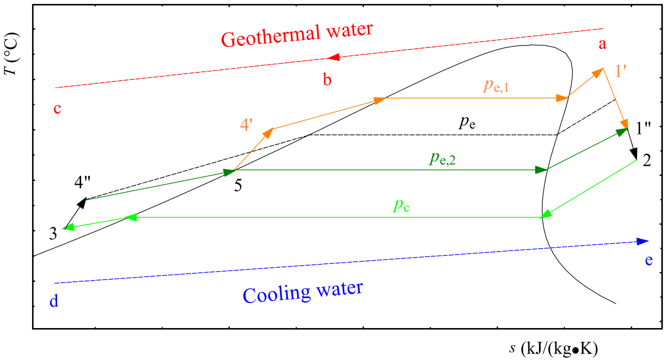

Fig. 2. T-s diagram of the TSORC.

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*, shown by green lines. The heat source and heat sink in the TSORC remain unchanged. Moreover, the counter-current flow between the heat source and heat sink with the working fluid are adopted.

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 series 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. 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 it is heated by geothermal water (process *b*–*c*) coming from the evaporator 1 to generate low-pressure saturated or superheated vapour (process *4″*–*1″*). With the help of the phase separator and a superheater, a portion of the saturated liquid at the saturated pressure in the evaporator 2 is pumped to the evaporator 1 to be heated by 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 TSORC can be identified as *1′*(*1″*)–*2*–*3*–*4′*(*4″*)–*1′*(*1″*), shown by green lines.

3. Mathematical modelling

The energetic and exergetic analysis based on the first and second laws of thermodynamics were carried out for the working fluid investigated. For simplicity, the following hypotheses were made:

(1) Geothermal power plants operate in a steady-state condition.
(2) Superheated vapour is considered at the outlet of the evaporator, with a degree of superheat of 5 °C. The subcooled liquid is considered at the condenser exit, and the subcooled degree is 5 °C.