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Performance analysis of an organic Rankine cycle for a reverse osmosis desalination system using zeotropic mixtures

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HIGHLIGHTS

- An ORC for RO desalination system with zeotropic mixture is proposed.
- The effects of seawater temperature increase on the cycle performance are analyzed.
- The best composition of mixtures and seawater temperature increase are identified.

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ABSTRACT

The use of low-grade thermal energy to power desalination processes by coupling an organic Rankine cycle (ORC) with seawater reverse osmosis (RO) is a promising technology to reduce the cost and environmental impact associated with the use of fossil fuel sources. A low-enthalpy geothermal ORC for a RO desalination system with zeotropic mixtures is proposed. Zeotropic mixtures can improve the thermodynamic performance of ORC systems owing to their excellent temperature glide characteristics during evaporation and condensing processes. A case study with butane/pentane (R600/R601) and butane/isopentane (R600/R601a) is investigated, aiming to analyze the effect of seawater temperature increase on the cycle performance. In the temperature range investigated, the power profit first increases rapidly then decreases. For the mixture R600/R601 at a mole fraction of 0.9/0.1, the maximum power profit value of 29.3 kW occurred with the temperature rise of 26 K, and for the mixture R600/R601a at a mole fraction of 0.9/0.1, the maximum power profit value of 30.9 kW occurred with the temperature rise of 27 K. The results show that, it is necessary to consider the effects of seawater temperature increase in both the ORC and RO simultaneously to design the ORC-RO system.

1. Introduction

There are three dominant seawater desalination technologies, multi-effect distillation, multi-stage flash and reverse osmosis (RO). Of these, RO has gradually gained more popularity, mainly because of the recent progress in the membrane industry and development of high-efficiency energy recovery equipments [1].

In RO process, energy prices remain a drawback in terms of desalination economics [2]. To reduce the cost and environmental impacts associated with the use of fossil fuel sources, one possible solution is to adopt renewable sources [3]. Of the available renewable sources, the use of low-temperature thermal energy, including waste heat, geothermal heat and solar sources, for organic Rankine cycle (ORC) coupled with reverse osmosis desalination has received an increasing amount of interest.

Manolakos et al. [4] pioneered theoretical and experimental research in this field. They presented a system that the high pressure pump (HPP) of RO was directly driven by the expander of the ORC sub-system, and the results proved that their concept was technically feasible. Later, they proposed a cascade ORC cycle for RO desalination consisting of two cycles of different temperatures, and proved that the proposed two-stage ORC significantly improved the efficiency and reduced the cost of the previously-developed single-stage low-temperature ORC for RO desalination [5]. However, Delgado-Torres et al. [6] argued that the efficiency of a single ORC with R245fa was higher than that of a two-stage system within the same temperature conditions. Nafey et al. [7] made a detailed investigation of a combined ORC-RO desalination system with different types of solar collectors, based on energy, exergy, and economic analyses. Moreover, they also did a thermo-economic analysis of different energy recovery units and concluded that the pressure exchanger configuration was more economical than either stand alone or Pelton wheel turbine configurations

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Abbreviations: ORC, organic Rankine cycle; RO, reverse osmosis; HPP, high pressure pump; TDS, total dissolved solids; GWP, global warming potential; ODP, ozone depression potential; NDP, net driving pressure.

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Nomenclature

m	specific enthalpy (kJ/kg)
m	mass flow rate (kg/s)
p	pressure (MPa)
Q	heat transfer rate (kW)
s	specific entropy (kJ/(kg·K))h
W	power (kW)
x	mole fraction
A	membrane's permeability to water ($m^3/(m^2 \cdot s \cdot bar)$)
TCF	temperature correction factor
FF	membrane fouling factor
S_T	total membrane's effective surface area (m^2)
S_E	membrane area of each element (m^2)
N_E	number of membrane elements
P_{net}	net driving pressure (MPa)
Π	osmotic pressure in the concentrate flow (MPa)
P_f	feed pressure at the inlet of the vessel (MPa)
ΔP_{fs}	average pressure losses between the feed and concentrate flows (MPa)
ΔT_E	evaporator pinch temperature (K)
ΔT_C	condenser pinch temperature (K)

Greek symbols

η	efficiency

Subscripts

1–6	point corresponding to Fig. 2
exp.	expander
con	condenser
p	pump
eva	evaporator
th	thermal efficiency
net	net work output
pro	power profit
in	inlet
out	outlet
f	working fluid
h	heat source
sw	seawater
s	isentropic

[8]. Li et al. [9] proposed a supercritical organic Rankine cycle for a seawater reverse osmosis system with two types of heat sources. In addition,they also presented a co-generation system to produce electricity and freshwater using a solar supercritical ORC coupled with a desalination unit. This system can reduce the negative impact of intermittent solar energy without using thermal energy storage by converting solar energy to desalinated water [10].

In the design of the ORC cycle, one crucial issue is the selection of working fluids for the given temperature. Previous studies regarded more about pure working fluids; however, zeotropic mixtures have received significant attention recently, because of their excellent temperature glide characteristics during evaporation and condensation processes, which lead to a better temperature match with heat source/sink. This allows for the system irreversibility to be minimized and the cycle efficiency to be increased.

Angelino et al. [11] made a comparison of n-pentane and mixture n-butane/n-hexane for a low-temperature ORC system. Their results showed that the mixture yielded 6.8% more electricity than the pure working fluid. Wang et al. [12–13] made a theoretical and experimental analysis of a zeotropic mixture of R245fa/R152a. The results showed that the zeotropic mixture had higher collector and thermal efficiencies than the pure R245fa. Chen et al. [14] proposed a supercritical ORC system with zeotropic mixtures. The comparison of R134a/R32 (0.7/0.3) and R134a suggested that the cycle efficiency with R134a/R32 increased by 10–30%. Heberle [15] investigated the exergetic efficiency of a subcritical cycle with isobutene/isopentane and R227ea/R245fa. The case study indicated that exergetic efficiency increased by 4.3% to 15%. Chys et al. [16] presented a mixture selection method and optimized mixture concentrations to realize the maximum ORC thermal efficiency for the low-temperature heat source, which increased from 10.85% to 11.57% with zeotropic mixture of isopentane/cyclohexane. Liu et al. [17] presented a method to determine the optimal ORC condensation pressure using the zeotropic mixtures and investigated the effects of the condensation temperature glide of the zeotropic mixture on the ORC thermodynamic performance. Lecompte et al. [18] examined the cycle performance of a subcritical ORC with zeotropic mixtures, their study suggested that the second law efficiency with mixtures can be improved by 7.1% to 14.2% and the exergy loss of condenser can be reduced with 3% to 6%. Radulovic et al. [19] conducted a parametric optimization of a supercritical ORC with six mixtures. Their results indicated that the thermal and exergetic efficiencies of R143a/R124 were higher than those for R143a/RC318 in the range of the parameters investigated. Guo et al. [20] analyzed the effects of three types of working fluids, a mixture that matched the heat source, a mixture that matched the heat sink and a pure working fluid on the performance of ORC system. The result suggested that the mixture that matched the heat sink achieved the highest thermal efficiency. Zhao et al. [21] presented a thermodynamic model mainly including Jacob number and the ratio of evaporation and condensation temperatures, to forecast the thermal efficiency, work output and exergetic efficiency of the ORC cycle with zeotropic working fluids. Mavrou et al. [22] investigated the performance of working fluid mixtures including conventional working fluids and mixtures designed by the method proposed by Papadopoulos [23]. The result suggested that the mixture of neopentane/2-Fluoromethoxy-2-methylpropane (70%/30%) exhibited the best performance.

It can be observed that the Rankine cycle performance with zeotropic mixtures have been investigated in terms of the thermal efficiency, the exergetic efficiency and net work output as a function of different process parameters, such as the mixture type, mixture composition, temperature of the heat source, etc. However, unlike the sole ORC system, the coolant in the ORC-RO system is seawater, and its temperature rise also directly affects the RO performance. Consequently, both the temperature match of the seawater with the mixtures and the effect of the seawater temperature rise on the RO performance should be considered simultaneously for the design of the ORC-RO system. However, there have been no reports on this subject till now. Therefore, the cycle performance of an ORC-RO system with zeotropic working fluids will be analyzed in the current study, with emphasis on the effects of the seawater temperature rise.

2. Cycle

2.1. System description

The ORC-RO system analyzed in this study is shown in Fig. 1, which is composed of an ORC engine and a desalination unit. A heat source of low-temperature geothermal water and heat sink of raw water are used as the external inputs for the proposed system.

A basic Rankine cycle is adopted, including a feed pump, an evaporator, an expander, and a condenser. The working fluid undergoes the following processes: pressurized by the pump, the working fluid is heated by the heat source and vaporized in the evaporator, and the generated high pressure vapor expands through the expander and generates power for the RO system, then, the low pressure vapor at the outlet of the expander is cooled by the feed seawater in the condenser, and pumped back to the evaporator, completing the cycle.

In the desalination sub-system, feed seawater is used to condense the working fluid, which consequently preheats the seawater. The shaft