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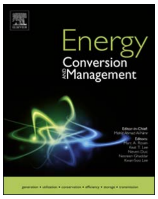

Performance investigation of a novel zeotropic organic Rankine cycle coupling liquid separation condensation and multi-pressure evaporation

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ABSTRACT

The decrease in fossil energy reserves and the increase in energy costs have resulted in a strong interest in power generation using renewable heat sources or waste heat. Organic Rankine cycle (ORC) is a promising heat-to-power conversion technology. Although the ORC using zeotropic mixture is superior to ORC using pure fluid in thermodynamic performance due to low irreversibility during the evaporation and condensation of zeotropic mixture, the improvement in thermodynamic performance is usually achieved at the cost of poor economic performance. The studies on improving the thermo-economic performance are limited. In the present study, a novel zeotropic ORC coupling liquid separation condensation and multi-pressure evaporation is proposed. Multi-pressure evaporation is presented to improve heat match between the heat source and working fluid. Liquid separation condensation is applied to control the composition of the mixtures that enter the evaporation processes. Thermodynamic analysis and optimization model of the novel ORC is developed. The superiority of the proposed novel ORC over the traditional simple zeotropic ORC and traditional multi-pressure evaporation zeotropic ORC is elaborated for different mixtures. The contribution of mixture composition adjustment and condensation enhancement through liquid-vapor separation on the cycle performance improvement is investigated. Sensitivity analysis of heat-sink inlet temperature, heat source inlet temperature, vapor quality, heat source specific heat capacity, and heat-sink temperature rise on the cycle performance are conducted. The case results show that net power output of the novel ORC is 13.05–26.18% higher than that of the simple zeotropic ORC. The contribution of mixture composition adjustment on improving the net power output can be up to 3.57% compared with traditional multi-pressure evaporation ORC for mixture R245fa–R365mfc. When the heat transfer enhancement through liquid separation is incorporated into the thermodynamic optimization, the net power output of the novel zeotropic ORC can be increased by 8.22% compared with the traditional multi-pressure evaporation ORC under the same economic constraint.

1. Introduction

Currently, the decrease in fossil energy reserves and increase in energy costs have resulted in a strong interest in power generation that utilizes renewable heat sources or waste heat. Organic Rankine cycle (ORC) is a promising heat-to-power conversion technology. Given the low-temperature nature of energy sources, the thermal efficiency of the ORC is relatively lower than that of traditional power generation technologies that use high-grade energy [1]. Therefore, research on improving the thermal efficiency and reducing the investment cost of the ORC is vital.

Significant efforts have been devoted to the performance improvement of ORC using pure fluid. The studies on fluid screening [2,3], cycle configuration improvement [4–6], component screening [7,8], and thermo-economic optimization [9] have been widely investigated. As demonstrated in previous published studies, the exergy destruction of the evaporator and condenser accounts for 70–90% of the total exergy destruction in ORC [10], and the capital investment of heat exchangers accounts for 40–90% of the total ORC investment cost [11,12]. These findings indicated that the heat transfer processes exert a key influence on the cycle performance of the ORC. However, the thermo-economic performance improvement is restricted due to the isothermal behavior of evaporation and condensation of pure fluid.

Fortunately, the ORC performance can be improved using zeotropic mixtures, which exhibit non-isothermal characteristics during the evaporation and condensation. The ORC that uses zeotropic mixture as working fluid has been regarded as a promising choice to reduce the irreversibility in the heat transfer process [13,14]. Abadi et al. [15]

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Nomenclature

m	mass flow rate (kg s^{-1})
Q	heat transfer flow rate (kW)
w	mole fraction (%)
W	power output/input (kW)
h	specific enthalpy (kJ kg^{-1})
E	exergy (kW)
IR	irreversible loss (kW)
T	temperature of fluid (K)
s	specific entropy [kJ/(kgK)$^{-1}$]
x	vapor quality
U	heat transfer coefficient [W/(m^2 K)]
A	heat transfer area (m^2)
c_p	specific heat at constant pressure of heat source/sink [kJ (kg K)$^{-1}$]

Greek letters

η	efficiency

Subscripts

H	heat source
C	heat sink
a	high-pressure evaporation
b	low-pressure evaporation
in/out	inlet/outlet
sec	the second law of thermodynamics
p	pump
exp	expander
wf	working fluid
v	vapor
L	liquid
X	pinch point

Acronyms

ORC	organic Rankine cycle
NPO	net power output
BZORC	basic zeotropic organic Rankine cycle
MZORC	multi-pressure evaporation zeotropic organic Rankine cycle
LMZORC	liquid–vapor separation condensation and multi-pressure evaporation zeotropic organic Rankine cycle
IGWT	intermediate geothermal water temperature
DLEI	percentage increase in CHTC
ME	multi-pressure evaporation
LSC	liquid–vapor separation condenser
LMTD	logarithmic mean temperature difference
PPTD	pinch-point temperature difference
CHTC	condensation heat transfer coefficient
HSTR	heat sink temperature rise

presented an experimental study of a 1 kW ORC using R245fa-R134a. The performance of the ORC using pure fluid and ORC using mixture was compared. The results indicated that the power generation of the proposed ORC using R245fa-R134a is higher than that of the ORC using R245fa. Sadeghi et al. [16] presented a multi-objective optimization of ORC using zeotropic mixtures. Their findings showed that the power generation of the ORC using zeotropic mixture is 27.76% higher than that of the ORC using pure fluid. Liu et al. [17] optimized an ORC using R600a/R601a. Their results showed that the power generation of ORC using R600a/R601a is 4–11% higher than that of ORC using R600a. Lecompte et al. [18] conducted a second law analysis of the ORCs using various mixtures. Their results showed that the second law efficiencies of the zeotropic ORCs are increased by 7.1–14.2% compared to the ORCs using pure working fluids. Dong et al. [19] conducted a thermodynamic and economic performance assessment of the ORCs using zeotropic mixture and pure fluid. Bao and Zhao [20] experimentally investigated the impact of key system parameters on composition shift of the ORC. Shu et al. [21] presented an application of mixtures based on hydrocarbons blending with refrigerant retardants for engine waste heat ORC. These previous studies showed that considerable net power output (NPO), thermal efficiency, or the second-law efficiency of the ORC using zeotropic mixture can be enhanced over the ORC using pure fluid.

Owing to the superiority of zeotropic fluid over pure fluid in heat matching between fluid and heat source/sink, considerable efforts have also been devoted to improve the thermodynamic performance of zeotropic ORC. Zhang et al. [22] proposed a regenerative organic Rankine cycle to recover the exhaust heat of a diesel engine. Their results showed that the power output and fuel economy of the diesel engine were improved by 10.54% and 9.55%, respectively. Tian et al. [23] investigated a dual-loop organic Rankine cycle using binary zeotropic mixture; they found that the dual-loop organic Rankine cycle using octamethylcyclotetrasiloxane/R123 (0.3/0.7) has the best thermodynamic performance among the candidate mixtures. Li et al. [5,6] analyzed an ORC with two evaporation stages in parallel and an ORC with two evaporation stages in series to improve the system performance; their findings showed that the irreversible loss of evaporation processes can be effectively reduced. Sadeghi et al. [16] presented an optimization of various ORC configurations using mixtures; the results showed that the NPO of the ORC with two-stage evaporation in series can be further increased compared with that of the basic zeotropic ORC with single-stage evaporation and the zeotropic ORC with two-stage evaporation in parallel. Shokati et al. [24] presented a double-pressure ORC and compared it with a basic ORC; they found that the NPO of the former was 15.22% higher than that of the latter.

As demonstrated in the previous studies, the multiple pressure evaporation ORC, regenerative ORC, and dual-loop ORC are superior to the ORC using pure fluid or the simple ORC using zeotropic fluid in terms of thermodynamic performance. However, the economic performance was not reasonably investigated. Liu et al. [25] pointed out that the condensation transfer area of zeotropic ORC significantly increased compared to pure fluid ORC. The improvement in power generation or second-law efficiency of an ORC using zeotropic mixtures is mainly attributed to the improvement on the heat matching between zeotropic fluid and heat source. However, the non-isothermal behavior of these mixtures during the condensation and evaporation processes may reduce the logarithmic mean temperature differences (LMTDs) of the heat exchangers under the constraint of the same minimum pinch-point temperature difference (PPTD). Consequently, more heat exchanger areas are required to offset the reduction in LMTD. In addition, the existence of mass transfer resistance during the phase transition of a zeotropic fluid may degrade the heat transfer performance, especially in-tube condensation [26,27]. The experimental and simulation studies showed that the heat transfer coefficients of zeotropic mixtures may be lower than those of the pure fluid during evaporation and condensation. Heberle and Brüggemann [28,29] investigated the thermo-economic analysis of the ORC using pure and mixture fluids; their findings showed that the condensation heat transfer coefficient and condensation area of zeotropic mixture are decreased by 18% and increased by 47%, respectively, compared to the corresponding pure fluids. These findings indicate that the improvement in NPO or the second-law efficiency is usually achieved at the cost of high-heat exchanger area and