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Thermodynamic performance comparison of Organic Rankine Cycle between zeotropic mixtures and pure fluids under open heat source

Wen Su[a], Yunho Hwang[b], Shuai Deng[a], Li Zhao[a,*], Dongpeng Zhao[a]

[a] Key Laboratory of Efficient Utilization of Low and Medium Grade Energy (Tianjin University), MOE, Tianjin 300072, China
[b] Center for Environmental Energy Engineering, University of Maryland, College Park, MD 20742, USA

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ABSTRACT

Zeotropic mixtures have been widely investigated for the development of Organic Rankine Cycle (ORC) as an alternative option for pure fluids. However, few zeotropic mixtures have been applied to the ORC in practical engineering. Therefore, a nature question is that whether zeotropic mixture has better thermodynamic performance of ORC than pure fluid. In this contribution, a comprehensive performance comparison between zeotropic mixtures and pure fluids is conducted via cycle simulation for the basic ORC and recuperative ORC driven by open heat source. In the simulation, a certain range of mass flow rate of cooling water is considered as the condition of heat sink, and mixtures R600a/R601a, R600a/R227ea are employed. Performances of these mixtures are optimized and compared with those of their constituents from the points of first and second laws. It can be concluded that zeotropic mixture may have lower cycle performance than pure fluid. For the optimal mixture R600a/R601a (0.1/0.9, mass fraction) with the highest net power of basic ORC, the cycle efficiency 8.18% is lower than that of R601a 8.24%. Although zeotropic mixture generally has lower temperature differences in the evaporator and condenser, the exergy losses of these heat exchangers are not certain to be reduced. In the basic ORC, the exergy efficiency 34.61% of optimal R600a/R227ea (0.2/0.8, mass fraction) is lower than that of R227ea 35.68%. Furthermore, the introduction of internal heat exchanger (IHE) can enhance the output work and cycle efficiency. The exergy loss in the evaporator and condenser can be reduced by IHE. The mixture with a larger temperature glide can generally recover more heat in the IHE.

1. Introduction

In the past two decades, Organic Rankine Cycle (ORC) has become a field of intensive research and development as a promising technology for conversion of low-grade heat into electricity, due to the fact that the ORC has a simple structure, a low cost and a good utilization of various kinds of heat sources such as geothermal energy, solar energy and waste heat [1]. In order to utilize these heat sources efficiently, organic substance instead of water is applied as the working fluid of ORC. Therefore, for different applications, how to screen the environmentally friendly and efficient working fluids from a large number of organic substances has become a core research of ORC. In published literatures, many different models have been proposed to find the best working fluids based on the operating conditions [2–4]. Furthermore, zeotropic mixtures have been proposed as alternative working fluids of ORC to pure fluids, just like the application of mixtures in refrigeration systems and heat pumps [5,6]. Compared with the pure fluids, zeotropic mixtures have the characteristic of temperature glide during the phase change process, thus alleviating the mismatch of temperature profiles in the evaporator and condenser [7]. However, to the best of authors' knowledge, few mixtures have been employed in practical engineering of ORC, while pure fluids have been widely used in various ORC applications. In the available literatures, only 6 experiments of small-scale ORC have been conducted to investigate the performance of mixtures [8–13]. Thus, compared with the pure fluids, whether the thermodynamic performance of ORC can be improved by the introduction of zeotropic mixtures is an open question.

Cycle simulations have been employed to compare the thermodynamic performances of zeotropic mixtures and pure fluids. Table 1 presents the summary of existing researches on the performance comparison between zeotropic mixtures and pure fluids. The used mixtures and required assumptions for cycle simulations are summarized too.

* Corresponding author.
E-mail address: jons@tju.edu.cn (L. Zhao).

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Nomenclature

Symbols

C	heat capacity, kJ/(kg·K)
h	enthalpy, kJ/kg
HTF	heat transfer fluid
I	irreversibility rate, kW
IHE	internal heat exchanger
m	mass flow rate, kg/s
ORC	Organic Rankine Cycle
P	pressure, MPa
Q	heat flow, kW
s	entropy, kJ/(kg·K)
T	temperature, K
W	work, kW

Greeks

η	efficiency
Δ	difference

Subscripts

0	Environmental state
1,…7	thermodynamic state points (Fig. 1, Fig. 2)
a	lower boundary in Fig. 4
air	cooling air
b	bubble temperature or upper boundary in Fig. 4
c	condenser
Cal	calculated value
con	condensation
e	evaporator
evap	evaporation
ex	exergy
exp	expander
f	working fluid
glide	temperature glide
h	heat source
i	inlet
IHE	internal heat exchanger
Lf	liquid working fluid
lower	lower boundary in Figs. 5 and 6
m	mean temperature
max	maximum
net	net output
o	outlet
p	pressure or pinch point
pump	pump
re	recovery
sub	subcooling temperature
sup	superheating temperature
th	thermodynamic
upper	upper boundary in Figs. 5 and 6
Vf	vapor working fluid
w	cooling water

Due to the different assumptions for the condensation process, the contradictory conclusions are obtained for the comparison. For instance, Chys et al. [14] found that the use of suitable zeotropic mixtures as working fluids has a positive effect on the ORC performance, when keeping the inlet and outlet temperatures of cooling water fixed. In the geothermal ORC, Liu et al. [15] optimized the cooling water temperature rise as well as the evaporation and condensation pressures of R600a/R601a for various mole fractions to maximize the net power output. Based on the optimization results, they concluded that the ORC with mixture generates 4–11% more power than with pure R600a. As for the exergy loss, Lecompte et al. [16] conducted exergy analysis of ORC system with four zeotropic mixtures. They concluded that the second law efficiency of mixture is higher than that of pure working fluid under the fixed temperatures of cooling water. However, for the basic ORC and ORC with internal heat exchanger (IHE), researchers such as Wang and Zhao [17], and Li et al. [18] found that the cycle efficiency of zeotropic mixture is lower than that of pure fluid at the fixed bubble temperature of condensation process. Furthermore, Li et al. [19] investigated the performance of basic ORC using zeotropic mixtures and pure fluids under different operating conditions such as the fixed dew temperature, the fixed bubble temperature, or the same pressure in the condenser. They found that the thermodynamic performance of ORC is not always improved by employing mixtures as working fluids.

In summary, the above researches show that the merit of mixtures is related to the restrictive conditions of the ORC. Different conditions can lead to contradictory results, when comparing thermodynamic performances of pure fluids and zeotropic mixtures. However, in most of the simulations, the used restrictions, such as the fixed temperature of working fluid and the fixed mass flow rate of cooling water, are not very consistent with the practical conditions of ORC, so that the thermodynamic performance of pure fluids and mixtures can't be compared reasonably for the screening of working fluids in the design and construction of ORC. Furthermore, the pinch points of evaporator and condenser are usually assumed to occur at the bubble and dew temperatures of working fluids respectively. In the cycle optimization, the evaporation temperature is optimized to get the maximal output power of ORC, while the condensation temperature is generally determined from the given conditions. As for the employed mixtures such as R245fa/R227ea and R245fa/R600a, due to the lack of corresponding equation parameters in commercial software either REFPROP [25] or COOLPROP [26], their thermodynamic properties can't be calculated out accurately by these software, so that the drawn conclusions of performance comparison are questionable.

In order to address the above issues, new cycle simulation models are developed to conduct a comprehensive comparison of thermodynamic performance between zeotropic mixtures and pure fluids for two frequently employed cycle structures, namely basic ORC and recuperative ORC. Geothermal water is employed as an open heat source. Cooling water is used to condense the working fluid. In order to achieve a better temperature match in the condenser, the temperature rise of water may be almost zero for a large flow rate or very large for a small flow rate. Therefore, in this work, a certain range of mass flow rate of cooling water is considered. The positions of pinch point in heat exchangers are determined using the bisection method. The evaporation and condensation temperatures are optimized simultaneously to get the