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Potential of organic Rankine cycle using zeotropic mixtures as working fluids for waste heat recovery

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ABSTRACT

The performance of the ORC (organic Rankine cycle) systems using zeotropic mixtures as working fluids for recovering waste heat of flue gas from industrial boiler is examined on the basis of thermodynamics and thermo-economics under different operating conditions. In order to explore the potential of the mixtures as the working fluids in the ORC, the effects of various mixtures with different components and composition proportions on the system performance have been analyzed. The results show that the compositions of the mixtures have an important effect on the ORC system performance, which is associated with the temperature glide during the phase change of mixtures. From the point of thermodynamics, the performance of the ORC system is not always improved by employing the mixtures as the working fluids. The merit of the mixtures is related to the restrictive conditions of the ORC, different operating conditions results in different conclusions. At a fixed pinch point temperature difference, the small mean heat transfer temperature difference in heat exchangers will lead to a larger heat transfer area and the larger total cost of the ORC system. Compared with the ORC with pure working fluids, the ORC with the mixtures presents a poor economical performance.

1. Introduction

As a potential technique for power generation utilizing low grade waste heat, the ORC (organic Rankine cycle) system has received increasing attention over the past decades. Compared with the conventional steam cycle system, the use of the low boiling point organic fluids as working fluids in the ORC makes a better adaption to low temperature heat source than that of water. The ORC has a simple structure, the low cost and a good applicability for various kinds of heat resource, and also offers advantageous efficiency in decentralized lower-capacity power plants [1]. Up to now, there have been many studies carried out on various aspects of the ORC. The main challenges for pursuing a better performance are the particular cycle design, the selection of working fluids and the determination of key parameters.

Many investigations have been contributed to the selection of the working fluids in the ORC. The working fluid has a large impact on the ORC performance and is often studied for specific ORC applications in solar heat source [2], biomass [3] and geothermal energy [4], industrial waste heat recovery [5], or for different levels of heat source temperature [6–8]. According to the slope of saturation curve in T–s diagram, the working fluids can be classified into three categories, that is, dry, wet or isentropic fluid, which has a positive, negative or infinitely large slope [9], respectively. Hung et al. [10] suggested that the isentropic fluids are the best candidate for the ORC on account of the moisture content during the expansion process of wet fluids and the lower efficiency of dry fluids. Liu et al. [11] found that the presence of hydrogen bond in certain molecules may result in wet fluid such as water and ammonia, and is regarded as inappropriate for the ORC systems. Aljundi [12] showed that the ORC performance has certain relation with the critical temperature of working fluids. The working fluid that has a critical temperature of approaching to the heat source inlet temperature could produce a high efficiency for supercritical pressure ORC [13]. However, when the safety level and environmental impact are considered, the suitable working fluids should be different [14].

Previous studies on the working fluids of the ORC aimed mostly at pure working fluids. However, during phase change of the pure fluid, the constant temperature brings substantial deficiencies in

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Nomenclature

A	heat transfer area (m^2)
ALT	atmosphere life time (yr)
B_1, B_2	coefficients for cost evaluation
C	cost ($)
C_1, C_2, C_3	coefficients for cost evaluation
C_b	basic cost ($)
C_{bm}	bare module cost ($)
CEPCI	Chemical Engineering's Plant Cost Indices
COM_{pl}	cost of operation and maintenance ($)
CRF	capital recovery factor
E	exergy
EPC	electricity production cost ($/(kW h))
F_{bm}	bare module factor
F_m	material factor
F_p	pressure factor
GWP	global warming potential (yr)
h	specific enthalpy (kJ/kg)
i	interest rate
K	overall heat transfer coefficient (W/(m^2 K))
K_1, K_2, K_3	coefficients for cost evaluation
LT_{pl}	life time of the plant (years)
M	molecular weight (kg/kmol)
m	mass flow rate (kg/s)
P	pressure (MPa)
Pr	Prandtl number
Q	heat flow rate (kW)
Re	Reynolds number
T	temperature (°C)
t_{op}	operation time (h)
W	power output or input (kW)

Greek symbols

α	convective heat transfer coefficient (W/(m^2 K))
η	efficiency
λ	thermal conductivity (W/(m K))
μ	viscosity (kg/(m s))
ω	mass fraction

Subscripts

a	air
b	boiling point
c	condenser
cri	critical
e	evaporator
exp	expander
g	flue gas
i	inlet
is	isentropic
max	maximum
min	minimum
net	net
o	outlet
opt	optimal
p	pump
pp	pinch point
th	thermal
wf	working fluid

heat transfer process. The mixture presents a temperature glide during phase change process, which is benefit to reduce the mismatch of temperature profiles in evaporator and condenser. When the irreversibilities associated with pressure drop and mass transfer resistances are neglected, the mixtures create a potential to reduce the irreversibility of heat transfer [15–22], especially in the condenser [16]. Therefore, the performance of the ORC system may be improved by employing multi-component working fluids.

Angelino et al. [15] evaluated the merits of the organic mixtures in Rankine cycle. They demonstrated that the composition of the working fluids has important effect on the ORC performance, so it is necessary for the ORC system design to select suitable composition. Heberle et al. [16] investigated the performance of isobutane/isopentane and R227ea/R245fa in Rankine cycle system for geothermal applications. The results showed that zeotropic mixtures can produce higher second law efficiency than pure fluids because of a better thermal match in the evaporator and condenser. Chen et al. [17] introduced zeotropic mixture R134a/R32 (0.7/0.3) as the working fluid to an SRC (supercritical Rankine cycle). The comparison between the mixture-based SRC and the R134a-based ORC showed that the proposed cycle gives higher thermal efficiency and exergy efficiency than the R134a-based ORC. Nguyen et al. [18] introduced the main features of the ammonia–water mixture as the working fluid in Rankine cycle. The ammonia–water mixture provides a closer temperature curve of the working fluid and the heat source, a higher vapor pressure than water, and a variable mixture composition to fit the heat source better. Li et al. [19] compared the performance of the ORC with pure fluid R141b and that with mixture of R141b/RC318 as the working fluid. They found that the mixture-fluid ORC has lower thermal efficiency and lower exergy efficiency than the pure-fluid ORC. Wang and Zhao [20] presented an analysis of solar Rankine cycle for power generation at a fixed condensation bubble point temperature of 25 °C employing three typical mass fractions of R245fa/R152a as the working fluids. The zeotropic mixtures give lower Rankine cycle efficiency than pure working fluids in the proposed temperature condition. Meanwhile, a comparative experimental study on the pure fluid (R245fa) and the zeotropic mixtures (R245fa/R152a) in solar Rankine cycle system had also been presented in Ref. [21], and the result showed that in the experimental condition, the zeotropic mixture produces a higher thermal efficiency than pure fluid.

The evaluation criterion of system performance depends on system applications, configurations, or heat source conditions [23–26]. For the ORC system of recovering waste heat of flue gas from industrial boiler, how to generate more electric power as possible with a lower investment cost is the primary aspect to be considered. Therefore, the net power output and the EPC (electrical production cost) are two major concerned performance evaluation criteria. Meanwhile, researchers often integrate the working fluids selection with parametric optimization during the design of the ORC system [25–29]. Performance comparison based on the optimal parameters is more rational for the working fluid selection. The system performance is particularly sensitive to the evaporating temperature, which has always been paid much attention [19,25,26,30–32]. Therefore, in this work, the ORC performance with different working fluids is compared under the optimized evaporation temperature.

As mentioned in Refs. [16,17,21], the non-isothermal phase change of the multi-component mixtures has a potential of reducing the heat transfer irreversibility and improving system efficiency. In fact, different parametric conditions of the ORC would lead to different conclusions in performance analysis. For example,