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Analysis of organic Rankine cycles using zeotropic mixtures as working fluids under different restrictive conditions

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ABSTRACT

Organic Rankine cycle has been regarded as a reasonable technology to utilize low-temperature geothermal sources. This paper analyzes the internal relation about zeotropic mixture selection under different restrictive conditions. R601a/R600 and R245fa/R600a are selected as typical examples of symmetrical and asymmetric zeotropic mixtures. The fixed condenser bubble temperature, the fixed cooling water temperature rise and the fixed cooling water flow rate are considered as restrictive conditions. Both the basic and the regenerative organic Rankine cycle system are considered as research subjects. The fixed cooling water flow rate is suggested to select the appropriate zeotropic mixture. The results indicate that the performance corves with the fixed condenser bubble temperature of 25 °C are significant in zeotropic mixture selection, and these corves reflect the full potential of zeotropic mixtures to improve the net power. The temperature glide decreases the net power with the fixed condenser bubble temperature. However, the opposite phenomenon is found when the fixed cooling water temperature rise or the fixed cooling water flow rate is applied. The application of intermediate heat exchangers may lead to the larger, the smaller or the same net power with different temperature glides and restrictive conditions. However, the cycle efficiency is increased all the time.

1. Introduction

The emission and pollution have drawn great public attention due to the enormous consumption of fossil energy. In order to rid the excessive dependence on fossil energy, people try to search the novel technologies to utilize alternative energy such as geothermal resources. In recent decades, organic Rankine cycle (ORC) systems have received considerable attention to utilize low-temperature geothermal sources.

Organic fluids such as refrigerants or hydrocarbons have lower evaporating temperature than water. Thus ORC systems, which use organic fluids as working fluids, are potential to utilize low-temperature heat sources. Thermodynamic properties of organic fluids and working conditions of ORC systems have significant impacts on the performance of ORC systems. Therefore, the working fluid selection and the parameter optimization are overarching concerns for researchers. The application of pure working fluids were proposed and researched firstly. Chen et al. [1] presented a review of ORC and supercritical ORC systems for low-temperature heat sources. Selection criteria of potential working fluids were proposed and 35 pure working fluids for the two cycles were analyzed to research the influence of fluid properties on system performance. Imran et al. [2] conducted the thermo-economic optimization of basic ORC and regenerative ORC systems using Non-dominated Sorting Genetic Algorithm-II. Five pure working fluids were studied and the optimization results indicated that R245fa was the best choice under considered conditions. The performance of ORC using pure working fluids has been studied extensively, and the selection of pure working fluids has been relatively mature [3].

The application of zeotropic mixtures is put forward in ORC systems afterwards. The feature of zeotropic mixtures is the temperature glide, which means that condensing temperature and evaporating temperature may vary in condensation and evaporation processes. The temperature glide may result in a better temperature match between working fluids and heat source (heat sink). Therefore ORC systems using zeotropic mixtures are highlighted by some articles. Radulovic and Castaneda [4] conducted a parameter optimization of a supercritical ORC using six zeotropic mixtures. A comparative analysis between the zeotropic mixtures and pure R-143a revealed that the cycle efficiency could be

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Nomenclature

C	specific heat capacity (kJ/kg °C)
h	enthalpy (kJ/kg)
m	mass flow rate (kg/s)
P	pressure (kPa)
Q	heat transfer rate (kW)
T	temperature (°C)
W	power (kW)
Greek letters	
η	efficiency
ω	mass fraction
Subscripts	
1, 2, 3, 4, 5, 6, 7, 8, 41, 12, 78	state point in systems
con	condense
cw	cooling water
cycle	cycle
dew	dew point
eva	evaporator
gw	geothermal water
h	high
l	low
m	middle point
net	net
pin	pinch point
pum	pump
tur	turbine
wf	working fluid
Superscript	
s	isentropic

increased by 15% at the same operational conditions. Chys et al. [5] selected 11 zeotropic mixtures to examine the feasibility of zeotropic mixtures in a basic ORC and a ORC with an intermediate heat exchanger (IHX). The net power at optimal thermal power recuperation could be improved by 20% for the heat source at 150 °C. A potential increase of 6% and 16% in cycle efficiency was found for heat sources at 250 °C and 150 °C. Heberle et al. [6] studied a subcritical ORC system using isobutane/isopentane and R227ea/R245fa as working fluids for low-temperature geothermal resources. The results indicated that the raise of second law efficiency was up to 15% compared with pure working fluids for heat source temperatures below 120 °C. Then they conducted a thermo-economic evaluation and the results showed that the efficiency increase caused by zeotropic mixtures could overcompensate the additional economic requirements in binary power plants [7]. Lecompte et al. [8] conducted the second law efficiency analysis of ORC system with seven zeotropic working fluids. They indicated that the second law efficiency of mixture presented 7.1–14.2% higher than that of the pure working fluids. Shu et al. [9] analyzed the exergy loss and thermal efficiency of ORC systems using mixtures of two retardants and three pure hydrocarbons. They indicated that zeotropic mixtures presented better thermodynamic performance than the pure working fluids.

However, the opposite conclusions have been found by many scholars and they point out zeotropic mixtures are not always profitable. Feng et al. [10] indicated that the mixtures would not lead to the better thermodynamic and economic performance than pure working fluids all the time. Angelino and Di Paliano [11] demonstrated that the temperature glide would alleviate the temperature mismatch between cold side and hot side in the two-phase heat transfer region. And ORC systems with zeotropic mixtures presented the lower efficiency than ORC systems with pure working fluids. Li et al. [12] analyzed the influence of IHX on ORC systems and found that the ORC system with R141b/RC318 have the lower efficiency than that with pure R141b. Kheiri et al. [13] carried out a thermo-economic optimization of a subcritical ORC system using *n*-pentane, R245fa, and their mixtures as working fluids. The results indicated that ORC using *n*-pentane had advantages over the ORC using mixtures in the exergy efficiency and the levelized cost of electricity. Li and Dai [3] also researched the application of zeotropic mixtures in a basic ORC system and a ORC system with an IHX as the work of Chys et al. [5]. However the results showed that ORC systems using isobutane/isopentane and R245fa/R123 had the lower net power output, thermal efficiency and exergy efficiency. Meanwhile, the work of Wu et al. [14] demonstrated that mixtures presented the worse economic performance.

As mentioned above, it is controversial whether zeotropic mixtures should be applied in ORC systems on the views of both thermodynamics and economics. The thermodynamic performance of ORC using zeotropic mixture seems to be the more fundamental and urgent problem to be solved. Some significant research, which is extremely significant to explain this phenomenon, is presented as below. Li et al. [15] indicated it was the different restrictive conditions such as the fixed dew point temperature, the fixed bubble point temperature, or the pressure in condenser that leaded to different results when pure working fluids and their zeotropic mixtures were compared. Three restrictive conditions were considered in the simulation, but regenerative ORC systems were not included in their work. Liu et al. [16] owed it to the competition of the cooling water temperature increment and the condensation temperature glide. If cooling water temperature increment was less than the maximum condensation temperature glide, two optimal working fluid mole fractions could be found to maximize the cycle efficiency, exergy efficiency and net power output. Otherwise, only one optimal working fluid mole fraction could be found. Both the basic ORC and regenerative ORC were studied by them. However, only one restrictive condition (the fixed cooling water temperature rise) was considered in the paper. Therefore, it is meaningful to further study the zeotropic mixture selection in ORC systems under different restrictive conditions.

There are several articles that have been published involving the influence of restrictive conditions on the application of zeotropic mixtures, but few of them try to find the internal relation of the results under different restrictive conditions. More importantly, the previous literature only put forward the controversy, no uniform restrictive condition or appropriate method is proposed to solve the controversy. In this paper, the fixed condenser bubble temperature, the fixed cooling water temperature rise and the fixed cooling water flow rate are considered as three restrictive conditions throughout all the simulation. The authors try to explore the internal relation about zeotropic mixture selection under different restrictive conditions on the view of thermodynamics. The content basically consists of three parts. In the first part, the basic ORC systems using R601a/R600 and R245fa/R600a are studied to explore their trends under different restrictive conditions. In the second part, the comparative study of the basic ORC