Energy Conversion and Management 140 (2017) 324–333

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

The discussion of composition shift in organic Rankine cycle using zeotropic mixtures

Yaodong Zhou, Fengyuan Zhang, Lijun Yu [*]

Institute of Thermal Energy Engineering, School of Mechanical Engineering, Shanghai Jiao Tong University, Shanghai 200240, China

ARTICLE INFO

Article history:
Received 6 January 2017
Received in revised form 28 February 2017
Accepted 28 February 2017

Keywords:
Organic Rankine cycle
Zeotropic mixtures
Composition shift
Circulating composition

ABSTRACT

Zeotropic mixtures have been important candidates for working fluids in the organic Rankine cycle (ORC) because of the temperature glide characteristic. "Composition shift" is a widespread phenomenon for zeotropic mixtures' application in thermodynamic systems and certainly needs to be considered in ORC. In this paper, the evaporator, condenser, expander and pump models are respectively developed and then the circulating composition is calculated. Based on that, the forming reasons of "composition shift" are well illuminated. The influences of composition shift on the system net power output and heat transfer process are presented and analysed. The influence factors including pressure, two-phase zone area, total charge mass and velocity difference between liquid and vapor phase are also carefully discussed. Besides, the inner relation between temperature glide and composition shift is also revealed at last. The results showed that the optimal charge concentration of the low boiling point component in practice should be a bit lower than the optimal concentration without considering composition shift. Besides, the local composition shift characteristic will affect the heat transfer process by altering the temperature along the heat exchanger. Reducing the two-phase zone area, increasing the total charge mass, increasing the evaporation pressure and reducing the slip ratio can mitigate the effect of composition shift. The simulation also reveals that the magnitudes of temperature glide and composition shift show a good linear relation by just altering the charge composition.

1. Introduction

Along with the increasing demand for energy, it is urgent to find out an effective way to improve the energy utilization efficiency. Investigations reveal that about 50% [1] thermal energy is directly discharged to the atmosphere in the form of low temperature waste heat in traditional industries. The organic Rankine cycle (ORC) is considered as a promising technology to recover the low temperature waste heat. According to previous researches, working fluids show an important effect on the system performance. In recent years, zeotropic mixtures [2–8] have attracted relevant researchers' attention because of their unique advantages in recovering low temperature waste heat.

A zeotropic mixture (nonazeotropic mixture) is a mixture of substances that have different boiling points. And unlike the azeotropic mixtures, the dew point and bubble point curves do not touch each other over the entire composition range, which means that the temperature varies continuously during phase change at constant pressure. And this characteristic is usually called "temperature glide". The zeotropic mixtures can improve the cycle performance just because of the temperature glide characteristic during phase change, which will improve the temperature match with the heat source and heat sink, reducing the irreversible loss within heat transfer processes and therefore leads to a higher system performance. Abadi et al. [9] proposed and evaluated the performance of a zeotropic mixture of R245fa 60%/R134a 40% (molar concentration) in a small scale ORC experimentally. Results showed that with a heat source between 80 °C and 100 °C, the proposed zeotropic mixture increases the power output compared to an identical ORC with pure R245fa despite working at a lower pressure ratio. Wu et al. [10] studied the ORC system performance of zeotropic mixture R227ea/R245fa, Butane/R245fa and Rc318/R245fa. The results indicated that better thermal performance can be achieved when the temperature difference of cooling water is near the temperature glide of zeotropic mixture in the condenser. Feng et al. [11] selected zeotropic mixture R227ea/R245fa as working fluid and made the thermo-economic comparison between pure and mixture working fluid for ORCs. The exergy efficiency and levelized energy cost (LEC) are optimization objectives in their research. The results reveal that compared with pure

---

[*] Corresponding author.
E-mail address: ljyu@sjtu.edu.cn (L. Yu).

http://dx.doi.org/10.1016/j.enconman.2017.02.081

Nomenclature

Latin symbols

A	heat transfer area, m^2
C	local composition, 1
C_p	heat capacity at constant pressure, kJ/K
E	enhancement factor, 1
F_{er}	expander correction factor, 1
f	friction factor, 1
H	pump head, m
h	specific enthalpy, kJ/kg or heat transfer coefficient, W/(m^2 K)
K	mixture correction factor, 1
M	mass, kg
m	mass flow rate, kg/s
Nu	Nusselt number, 1
P	pressure, kPa
Pr	Prandtl number, 1
Q	heat rate, W
q	heat flux, kW/m^2
Re	Reynolds number, 1
S	slip ratio, 1 or suppression factor, 1
T	temperature, K
U	heat transfer coefficient, W/(m^2 K)
V	volume, m^3
v	specific volume, m^3/kg or velocity, m/s
W	work rate, W
X	vapor quality, 1
x	liquid mass fraction, 1
y	vapor phase fraction, 1
Z	composition

Greek letters

η	efficiency, 1
α	void fraction, 1
κ	adiabatic coefficient
δ	plate thickness, m
λ	thermal conductivity, W/(m K)
π	pressure ratio, 1
ρ	density, kg/m^3

Subscripts

1, 2, 3, etc.	state points of ORC system
a	actual
bd	bubble point and dew point
c or con	condensation or condenser
cir	circulating
e or eva	evaporation or evaporator
exp	expander
f	working fluid
ha	hot air
i	the ith component or built-in
id	ideal
j	the jth control volume
l	liquid phase
nb	nucleate boiling
r	reduced
sp	single-phase
th	thermal
tp	two-phase
v	vapor phase

working fluids, the mixture working fluids present better exergy efficiency but worse LEC except in a few situations.

Different from pure working fluids, one important characteristic "composition shift" needs to be considered when applying zeotropic mixtures to the ORCs. "Composition shift" [12] means that the circulation composition (the composition circulating in the pipes) is different from the charge composition (the composition charged in the tank initially), which is mainly caused by the phenomenon called "two phase hold-up". There are mainly two reasons for this phenomenon. First, in the two phase zone, the fluid compositions of the liquid and vapor phase are different because of different boiling points for each component. Besides, the flow velocity difference between liquid and vapor phase is also an important reason. Many researchers noticed this phenomenon and did some work on it. Youbi-Idrissi et al. [13] proposed a local simulation model of a water-to-water heat pump using R407c by adopting a modular approach. The numerical results showed that, compared to the nominal composition of R-407C (R-134a/R-125/R-32; 52/25/23%), the circulating composition in the machine is low in the less volatile component R-134a (−3%absolute variation) and rich in the most volatile component R-32 (+3% absolute). Xu et al. [14] proposed a local composition calculation model based on conservation equation derivation. And the result calculated with propane/i-butane binary mixture was verified by the experiment in the evaporator of a refrigerator. Chen et al. [15] also proposed a model for calculating the differential holdup in the heat exchangers' two-phase regions, and for predicting the circulation concentration. The analysis of the air-conditioning system shown in this paper demonstrated that the concentration shift was mainly caused by the differential holdup in the two-phase regions in the condenser and evaporator, and that the effect of the differential solubility of the crankcase oil was very small. But so far, most researches about the "composition shift" characteristic is based on the refrigeration system or heat pump. Few researchers considered this characteristic in the ORC system. Zhao et al. [16] discussed the influence of composition shift on organic Rankine cycle with zeotropic mixtures. The results show that composition shift significantly influence the performance of organic Rankine cycle with zeotropic mixtures, which will result in a lower output work of expander, a higher power consumption of pump, a lower net output work and lower thermal efficiency.

However, the research on the influence of composition shift on organic Rankine cycle with zeotropic mixtures is still not enough. In this paper, the forming reasons of composition shift are well illuminated. The influences of composition shift on the system net power output and heat transfer process are presented and analysed. The influence factors including pressure, two-phase zone area, total charge mass and velocity difference between liquid and vapor phase are also carefully discussed. Besides, the inner relation between temperature glide and composition shift is also revealed at last.

2. System description and thermodynamic model

2.1. System description

The schematic of the traditional subcritical ORC system is shown in Fig. 1. The working fluid in the liquid tank is first pumped to the evaporator. Then the working fluid in the evaporator is heated to the superheated vapor and flows to the expander to do work. The exhausted stream after the expander enters the condenser and is cooled down to the saturated liquid. At last, the cooled-down liquid will flow to the tank to complete the cycle.