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Research paper

Parametric optimization and performance analysis of zeotropic mixtures for an organic Rankine cycle driven by low-medium temperature geothermal fluids

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HIGHLIGHTS

- Mixtures of HFCs/HCs and HFOs/HCs are investigated as working fluids.
- Performance of R245fa/R600a (0.9/0.1) is considered more preferable.
- Maximum net power output corresponds to an optimal mixture ratio.
- An optimal evaporating temperature exists.

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ABSTRACT

The selection of working fluids is one of the important approaches to optimize the performance of an organic Rankine cycle (ORC). In order to select appropriate working fluids, zeotropic mixtures were investigated in this paper by theoretical analysis and detailed numerical simulation. Since the flame retardancy of fluoride can overcome the strong flammability of HCs, the mixtures of HFCs and HFOs with HCs were particularly investigated. The influences of 10 groups of mixtures on the performance of ORC were analyzed. The results show that the maximum net power output of the ORC using each mixture corresponds to an optimal mixture ratio that gives a highest temperature glide. In addition, an optimal evaporating temperature exists. It was found that R245fa/R600a (0.9/0.1) was the most preferable mixture among the working fluids within the scope of this research.

1. Introduction

Due to the dual crises of energy and environment, humans began to explore environmentally friendly energy. The low-medium temperature geothermal resources have caused widely attention and been applied in some countries. Organic Rankine cycle (ORC) is one of the effective ways to use the low-medium temperature energy to generate electricity or recover waste heat [1]. In order to optimize the performance of power cycles, improve the utilization of resources and increase the output ratio, experts have analyzed ORC from different angles [2,3], for example, systemic optimization design of structures, equipment improvement, parameter optimization under different working conditions, and working fluids selection to increase power cycle efficiency.

Many studies on working fluids have been carried out. Saleh et al. [4] studied 31 pure substances with the operating temperatures below 100 °C, including alkane, fluorine alkane, ether and desflurane etc. The results showed that n-butane had the highest thermal efficiency. Chys et al. [5] analyzed the selection method of mixed components and studied binary and ternary mixtures; they found that the addition of a third component to a binary mixture had only a small effect. Heberle et al. [6] carried out a detailed simulation and analysis on isobutane/isopentane and R227ea/R245fa. They found the system efficiency could reach 15% by using a mixture as working fluid with the heat source temperature below 120 °C. Borsukiewicz et al. [7] investigated a low temperature organic Rankine cycle and found that the power output of the ORC using propane/ethane was higher than that

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Nomenclature

a	mass fraction
c_p	specific heat (kJ/kg °C)
h	specific enthalpy (kJ/kg)
I	irreversibility rate (kW)
M	molar mass (g/kmol)
m	mass flow rate (kg/s)
P	net power (kW)
p	pressure (bar)
Q	heat absorption (kJ)
s	specific entropy (kJ/(kg °C))
T	temperature (°C)
Δt	temperature difference at the pinch point (°C)
W	work (kJ)

Greek symbols

η	efficiency (%)

Superscript

-	average

Subscripts

b	boiling point
c	condenser
cri	critical
E	motor
e	evaporator
ex	exergy
f	fluid
H	heat source
in	inlet
J	mechanical
Lin	inlet of cooling water
Lout	outlet of cooling water
max	maximum
min	minimum
out	outlet
pu	pump
pp	pinch point
r	resource
t	expander
th	thermal
0	environment
1, 2, 2s, 3, 4, 4s, 5	state points

Acronyms

ASHRAE-SL	ASHRAE security level
GWP	global warming potential
ODP	ozone deletion potential
ORC	organic Rankine cycle
IHE	internal heat exchanger

using pure propane. Angelino and Paliano [8] compared n-pentane with the mixture of n-butane and n-hexane (50%/50%) as a working fluid in a power cycle where liquid geothermal resource was used as heat source for electricity generation. The results showed that the mixture yielded 6.8% more electricity than n-pentane and 25% less air were used with potential benefits in both cooler frontal area and fan power consumption. Lakew et al. [9] stated that when a heat source with temperature ranging from 80 to 160 °C, using R227ea resulted in a maximum power output; when heat source temperature ranged from 160 to 200 °C, using R245fa could obtain a maximum power. Gawlik and Hassani [10] demonstrated that levelized equipment costs could be reduced by using mixtures instead of using pure fluids in geothermal binary plants. Borsukiewicz-Gozdur and Nowak [7] studied Rankine cycles with heat source temperature of 80–115 °C using natural and synthetic working fluids, as well as mixtures. They found that highest values of power obtained have been for the natural working fluid-propylene and single-component synthetic fluid R227ea; highest values of efficiency obtained have been for the natural working fluid-propylene and single-component synthetic fluid R245fa.

Hydrofluorocarbons (HFCs) is currently widely used as working fluids such as R134a and R245fa. Their performances are suitable and the ozone depleting potential (ODP) is zero. However, they have relatively high global warming potential (GWP), which has certain unfavorable effects on the environment. Hydrocarbons (HCs) are friendly to environment as natural working substances. Recently, many scholars found the power generation performances of R601a, R600a and some other alkane fluids are also very good [11–15]. But their applications are limited because of flammability.

In this study, R227ea, R134a, R245fa, R1234yf and R1234ze were mixed with R600a and R601a, respectively. The performances of mixtures were investigated through numerical simulation of an ORC system.

2. Description

2.1. System structure

The modeling is set up based on the basic power generation system, which is composed of three circuits: ORC, geothermal water and cooling circuits. The structure of the system is shown in Fig. 1. The ORC consists of the following main components: evaporator, expander, condenser, and fluid pump.

The *T-s* diagram of the ORC is shown in Fig. 2. The whole cycle can be divided into four processes: 1–2: the saturated vapor process in the expander where the power is generated (1–2 stands for the actual process and 1–2s is the ideal isentropic process); 2–3:

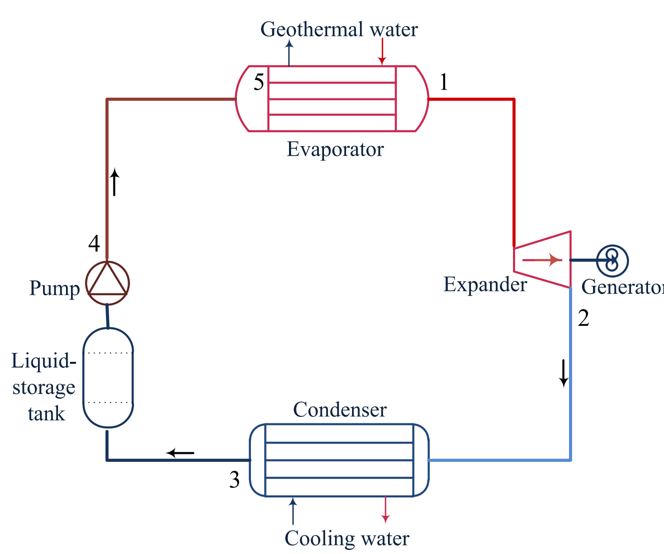

Fig. 1. Structure of the system.