Applied Thermal Engineering 94 (2016) 754–762

Contents lists available at ScienceDirect

Applied Thermal Engineering

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

Research Paper

Optimization of mixed working fluids for a novel trigeneration system based on organic Rankine cycle installed with heat pumps

Zishen Li [a], Weiyi Li [a,*], Borui Xu [b]

[a] Key Laboratory of Efficient Utilization of Low and Medium Grade Energy, MOE, Tianjin University, No.92 Weijin Road, Tianjin 300072, China
[b] China Aviation Planning and Construction Development Co,. LTD, Beijing 100120, China

HIGHLIGHTS

- Investigation of a novel CCHP–ORC system built-in heat pumps.
- Ejector coefficient and evaporation temperature are considered for dual variables.
- To find an optimized zeotropic mixture and component concentration to the system.
- Thermodynamic, systematic and economic assessment methodology for mixtures selected.

ARTICLE INFO

Article history:
Received 25 June 2015
Accepted 28 October 2015
Available online 11 November 2015

Keywords:
CCHP–ORC system
Heat pumps
Zeotropic mixtures
Evaluation index
Component concentration
Ejector coefficient

ABSTRACT

A novel combined cooling, heating and powerorganic Rankine cycle (CCHP–ORC) system installed with heat pumps is presented in this paper. The CCHP–ORC system using zeotropic mixtures is first discussed, and this work is focused on selecting optimal zeotropic mixtures and determining the component concentration that gives a better performance. A system model under an idealized operating condition was built. The heat source is geothermal water whose temperature is 95 °C, and the mass flow is 40 t/h. The heat transfer fluid is heated to 45 °C for heating with the ambient temperature of –5 °C, and the refrigerating fluid is cooled to 0 °C with the ambient temperature of 35 °C. In this paper, 20 zeotropic mixtures were analyzed. The evaluation index net output power, heating capacity, refrigerating capacity, coefficient of performance (COP), economic thermal efficiency and exergy efficiency were calculated with the changing evaporation temperature under the condition of ejector coefficient 0.2. The ejector coefficient and evaporation temperature had been analyzed as independent variables. The results showed that R141b/R134a, R141b/R152a and R123/152a have a higher COP and exergy efficiency than others. By analyzing the component concentration of the optimized three kinds of zeotropic mixtures, it can be inferred that a mixture of dry and wet working fluids is more suitable for the system. The system gives rise to higher energy output if zeotropic mixtures are made of a higher proportion of wet working fluid and a lower proportion of dry working fluid.

1. Introduction

Over the past quarter-century, because of the increasingly serious problem such as shortage of global energy, climate variation and environmental pollution, energy and environment have gradually attracted people's attention. Energy saving and renewable energy have now been promoted in many parts of the world via various measures, like incentives and legislations. The world energy demand is expected to increase by around 40% between 2006 and 2030 [1]. To improve energy utilization efficiency, increasing the use of renewable energy and developing new and clean energy have become an important solution to solve the problem of global energy shortage and environmental pollution.

CCHP systems may be promising to increase utilization efficiency of energy. The main characteristic of this technology is that the production of energy is dispersedly close to the consumption of energy, and based on the principle of energy cascade utilization, it is beneficial to meet the demand of user's energy consumption. Most of the studies on CHP (combined heating and power) or CCHP over the past few decades have shown that they have enormous advantages in comparison with the traditional way of energy consumption [2–4].

The overall thermal efficiency of a conventional power plant that produces electricity and heat separately reaches about 60% [5]. On the other hand, the efficiency of a power plant where the waste heat from the prime mover is utilized could reach up to 80% [5,6].

* Corresponding author. Tel.: +86 36 0213 5402.
E-mail address: liwy@tju.edu.cn (W. Li).

http://dx.doi.org/10.1016/j.applthermaleng.2015.10.145
1359-4311/

Table 1
Some cycle parameters of selected mixtures.

Components	Component concentration %	Critical temperature °C	Critical pressure MPa	Initial temperature (H-T-E) °C	Pressure (H-T-E) MPa	Initial temperature (L-T-E) °C	Pressure (L-T-E) MPa
R245ca/R141b	50:50	190.4	4.05	84.26	0.53	−10.16	0.018
R245ca/R123	50:50	178.75	4.13	84.83	0.66	−10.01	0.024
R245ca/R142b	50:50	153.1	4.01	78.89	1.01	−21.74	0.040
R245ca/R236ea	50:50	157.96	3.78	82.35	0.85	−13.88	0.031
R141b/R123	50:50	195.39	4.03	84.78	0.52	−10.13	0.019
R141b/R142b	50:50	170.49	4.40	72.81	0.80	−25.04	0.032
R141b/R236ea	50:50	176.06	3.79	79.05	0.62	−14.74	0.023
R123/R142b	50:50	155.58	4.00	76.70	0.97	−22.141	0.041
R123/R236ea	50:50	161.42	3.51	80.85	0.75	−13.90	0.028
R142b/R236ea	50:50	137.98	3.75	84.27	1.35	−12.40	0.071
R245ca/R152a	70:30	145.97	4.29	68.56	1.07	−33.57	0.037
R245ca/R134a	50:50	132.77	4.19	61.70	1.15	−34.12	0.045
R141b/R152a	80:20	176.40	4.67	57.49	0.67	−39.88	0.025
R141b/R134a	70:30	174.61	4.93	54.15	0.70	−40.67	0.026
R123/R152a	85:15	163.25	4.10	64.06	0.76	−35.60	0.028
R123/R134a	70:30	155.82	4.40	60.22	0.87	−37.03	0.032
R142b/R152a	95:5	135.15	4.10	84.18	1.59	−10.96	0.10
R142b/R134a	85:15	131.47	4.12	82.83	1.68	−12.25	0.11
R236ea/R152a	65:35	124.88	4.02	80.05	1.74	−18.19	0.088
R236ea/R134a	55:45	188.29	3.88	78.72	1.85	−20.45	0.091

Note: Terminal temperature of low temperature evaporation is −10 °C.
"H-T-E" means high temperature evaporation, "L-T-E" means low temperature evaporation.

Trigeneration plants appear to be more efficient because of utilizing the waste heat from prime movers.

Huang et al. studied a biomass fuelled trigeneration system integrated with organic Rankine cycle, and the results showed that for a wide range of commercial buildings, biomass trigeneration offers an economical solution of providing power, heating and cooling which is more environment friendly than conventional methods [7]. Al-Sulaiman et al. also got similar conclusions through the experiment research of CCHP–ORC system driven by biomass [8].

Ahmadi et al. proposed a new multi-generation system based on an ORC system; besides the CCHP structure, it also included a proton exchange membrane electrolyzer to produce hydrogen. A parametric study was performed to investigate the effects of several important design parameters on the energy and exergy efficiencies of the system [9].

Khaliq conducted a performance analysis of an industrial waste heat-based trigeneration system. They analyzed the system from the aspect of exergy to calculate the source of irreversibility [10]. Al-Sulaiman made an energy and exergy analysis of a novel trigeneration system using parabolic trough solar collectors for combined cooling, heating, and power production [11]. Cardona also carried out a research on the CCHP or/and CHP system from the perspective of energy management and environmental benefits, and the results indicated that polygeneration was considered to have a large potential for residential and commercial buildings district network [12].

ORC refers to the traditional Rankine cycle using organic substance. The ORC has become a hot research topic in the field of utilizing low grade thermal energy in recent years [13–16]. Zhao investigated an ORC system using zeotropic mixtures, and the results showed that the generator temperature, condenser temperature and evaporator temperature have a strong effect on the cycle performance [17,18]. Researchers also studied the ORC system with zeotropic mixtures from the perspective of first law thermal efficiency [19], exergy [20] and composition shift [21]. It was demonstrated that the use of zeotropic mixtures leads to an efficiency increase compared to the ORC system using pure fluids.

Hong replaced the heat pump compressor with an ejector and combined heat pumps with ORC to increase energy utilization efficiency [22]. In another study, Hong has completed a variety of heat pumps and ORC cogeneration system, and by the optimization of working fluids, finding that R600 has highest comprehensive evaluation [23]. Guo et al. proposed a novel cogeneration system driven by low-temperature geothermal sources. It consists of a low-temperature geothermally-powered ORC subsystem, an intermediate heat exchanger and a commercial R134a-based heat pump subsystem, with main purpose of identifying appropriate fluids for a better performance [24]. The thermodynamic properties are obtained by the software REFPROP 8.0 [25], which was developed by the National Institute of Standards and Technology of the United States. Refer to previous studies on working fluids of ORC system [26–29], selecting typical dry and wet working fluids to mix. The properties of zeotropic mixtures are listed in Table 1.

In this paper, a novel CCHP–ORC system built-in heat pumps is put forward. It consists of an ORC subsystem using zeotropic mixtures and a heat pump subsystem. The system is simple and more efficient compared to general trigeneration systems.

This work is focused on identifying an optimized zeotropic mixture for the CCHP–ORC system and understanding the effects on component concentration to the system. Firstly, we make a research about the dual variables ejector coefficient and evaporation temperature. And then, on the condition of the fixed ejector coefficient, we select some optimized pure working fluids which give a better performance in pure substance system, make a series of combinations of two together and then select the best zeotropic mixture. Thirdly, we determine the best component concentration according to the system requirements. Finally, through the changing evaporation temperature, performance indicators using different working fluids with different component concentrations are compared so as to select the most suitable one. Meanwhile, besides the CCHP, the system is also able to achieve only CCP or CHP by adjusting the four-way valve.

2. Structure and model

2.1. System description

The schematic of the CCHP–ORC system using zeotropic mixtures is shown in Fig. 1. In the system, condensing process in pure working fluids is transformed as partial condensation–gas–liquid