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Research Paper

Thermal and economic performance analysis of zeotropic mixtures for Organic Rankine Cycles

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HIGHLIGHTS

- Zeotropic mixtures R227ea/R245fa, Butane/R245fa and RC318/R245fa are researched.
- The mixture ORC is compared with the common ORC.
- The influence of temperature glide in ORC is studied.
- The first and second law efficiency for mixture ORC are both calculated.
- The net power output per unit UA based on counter flow is analyzed.

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ABSTRACT

In order to reveal the performance of mixture in Organic Rankine Cycle (ORC), this paper presents the performance of ORC using hot air as heat resource. The zeotropic mixture fluids studied are R227ea/R245fa, Butane/R245fa and RC318/R245fa. The first law efficiency, the second law efficiency, exergy loss distributions and net power output of zeotropic mixture fluids are calculated and compared with corresponding pure fluids. By using the counter flow heat exchangers, the system's economic performance is analyzed based on the net power output per unit UA. The result indicates 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; cycle efficiency, exergy efficiency and net power output increase compared to corresponding pure fluid cycles, but the net power output per unit UA decreases; in other words, the economic performance of this system becomes worse in some degree.

1. Introduction

Along with the increasing traditional energy consumption as well as the larger electricity demand of human daily consumption, it is urgent to find out an effective way to improve the energy efficiency. About 50% [1] thermal energy is directly discharged in the form of low temperature waste heat in traditional industries such as oil, steel and cement industry. Therefore, collection and utilization of low temperature waste heat is of great significance.

In recent years, Organic Rankine Cycles have attracted relevant researchers' attention because of its unique advantages in recovering low-grade thermal energy. Selecting the appropriate organic working medium exerts an important impact on the entire cycle efficiency. Nguyen et al. [2] researched the impact of six kinds of pure refrigerants, including R718, R717, R290, iso-pentane, benzene and n-heptane on system performance with industrial waste gas as heat source, here, the temperature of the heat source varied between 100 and 250 °C. The result suggests, in the case of constant temperature heat source, the system has the highest thermal efficiency when using benzene as working fluid. Saleh et al. [3] have studied the cycle performance of 31 kinds of pure refrigerants driven by a heat source whose temperature was below 100 °C. The results show that with the increase of critical pressure of pure refrigerant, thermal efficiency varies between 0.36% and 13%. Gu et al. [4] have calculated the performance of the system using R21, R123 and R245fa as fluid for heat source below 100 °C respectively. It is found that R245fa is an ideal working fluid in ORC when considering the factors of cycle performance and environmental characteristics. He [5] has discussed system performance when using R1270, R125, R134a, R290, R116 and R23 as working medium with low temperature industrial waste heat and sea water as heat sources. The results indicate that when using R134a, R290 and R1270 as working medium, the system has a better entropic efficiency and net output power. Wang et al. [6] have done a comparative analysis about physico-chemical properties and thermal properties of R11, R141b, R113, R123, R236ea, R245fa, R245ca and R600 with automobile exhaust as heat source. They reached a conclusion that R11, R141b, R600, R123 and R113 have higher cycle efficiency than other

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refrigerants, but R245fa and R245ca are the best if taking safety and environmental features into consideration.

The emergence of mixture not only broaden the scope of available alternative refrigerants, but also effectively reduced the irreversible loss of the working medium and improved the cycle performance because of temperature glide during the phase transition, which will increase the temperature match between cold and hot fluids. With these advantages, the mixture has attracted great attention in the study of Organic Rankine Cycle [7–16]. Wang et al. [12] have comparatively analyzed the cycle performance of pure fluid R245fa and mixture R245fa/R152a through experiment, and found that the cycle efficiency and the output power of mixture is increased obviously compared to pure fluid. Garg et al. [17] have researched cycle performance of Isopentane, R245fa and their mixture Isopentane/R245fa of 0.7/0.3 when system expansion ratio changing between 3 and 12. What they revealed is that thermal efficiency of their mixture reaches a maximum value of 13%. Heberle et al. [18] have investigated the impacts of mixing fraction, temperature of heat source and the temperature difference between the inlet and outlet of cool water on the system's second law efficiency separately with working fluid isobutene/isopentane and R227ea/R245fa when using the low grade geothermal energy as heat source. They concluded that the efficiency of mixture is improved about 15% compared to corresponding pure fluid for the heat source whose temperature is below 120 °C. Lecompte et al. [19] have researched the second law efficiency of ORC system when using mixture R245fa/pentane, R245fa/R365mfc, isopentane/isohexane, isopentane/cyclohexane, isopentane/isohexane, isobutene/isopentane and pentane/hexane as working fluids. They estimated that the performance of the system is best when the temperature match between cold and hot fluids in the condenser is optimum and the increase of the second law efficiency is between 7.1% and 14.2% compared to pure fluid. Li et al. [20] have calculated and analyzed the economy of the mixture ORC when three typical flow patterns (fair current, countercurrent and cross-flow) were used in heat exchangers separately. The result shows the annual cost of system first decreases and then increases, and a minimum value appears in the process with the increasing of the NTU, in addition, the cost of system using countercurrent heat exchanger is minimal.

In this paper, zeotropic mixtures of R227ea/R245fa, Butane/R245fa and RC318/R245fa are selected as working fluids of Organic Rankine Cycle with hot air as heat source. Sections 2 and 3 present the system description and working fluids selection, respectively; the main content of Section 4 is system assumptions and parameters; in Section 5, the first law efficiency, the second law efficiency, exergy loss distributions of main parts of ORC and net power output are calculated; in addition, the net power output per unit UA is also discussed to analyze the economic performance of the system; Section 6 is the conclusion for this paper.

2. System description

The schematic of ORC system provided in this paper is shown in Fig. 1. Mixed working medium in the evaporator is heated to saturated vapor, and then flows into the expander to do work. After the process of doing work, the steam exhausted from the expander enters the condenser and is cooled down to saturated liquid. Liquid working medium flows into the liquid storage tank. Then the pump extracts liquid working medium from the tank and pumps it into the evaporator to complete a working cycle.

Fig. 2 shows the mixtures' changes of state in a T-S diagram. As shown in Fig. 2, during the process of the phase changes (see below processes 6-1 and 3-4), there is a significant temperature glide, which is helpful to reduce the irreversible loss of heat transfer in the evaporator and condenser through improving the temperature match between cold and hot fluids, and this is one of the key factors that improve the performance of ORC using zeotropic mixture.

In the process of simulation, this paper chooses 120 °C hot air as the heat source; other assumptive conditions of ORC system are shown in Table 1.

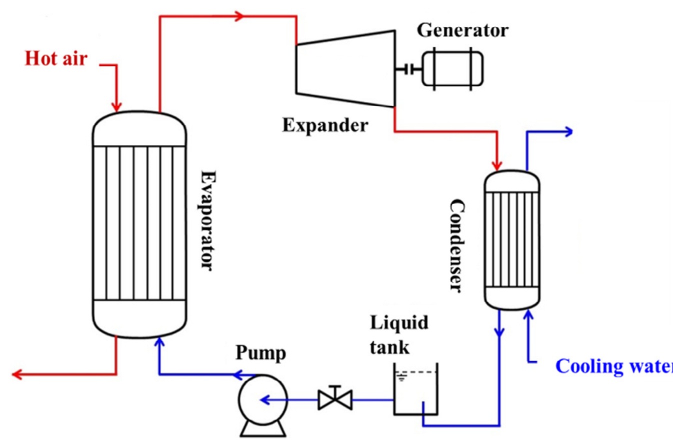

Fig. 1. The schematic of ORC.

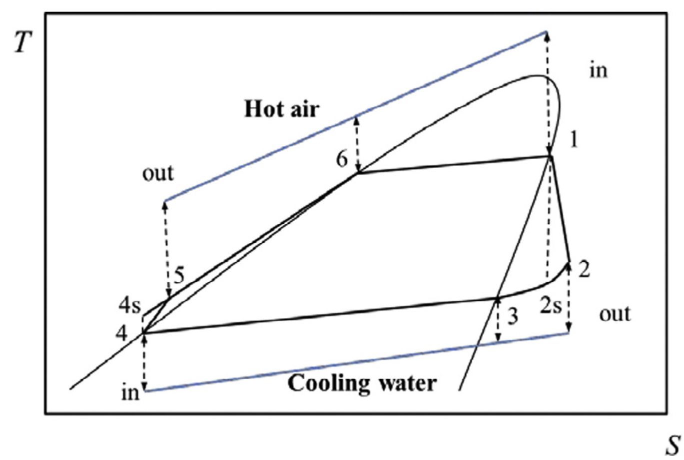

Fig. 2. The T-S diagram of mixture ORC.

Table 1
Other assumptive operating conditions for mixture ORC.

Parameter	Value
Environment temperature	25 °C
Flow rate of hot air	4000 m^3/h
Pressure of hot air	0.1 MPa
Bubble point temperature of evaporation	80 °C
Evaporator pinch temperature	5 °C
Condenser pinch temperature	5 °C
Inlet temperature of cooling water	25 °C
Outlet temperature of cooling water in phase change process	30 °C
Pressure of cooling water	0.1 MPa
Isentropic efficiency of pump	0.8
Isentropic efficiency of expander	0.8

3. Working fluid selection

Principles for selecting zeotropic mixtures and pure fluids are consistent. Choosing suitable mixtures not only needs considering the thermal properties of the components separately, but also