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A supercritical Rankine cycle using zeotropic mixture working fluids for the conversion of low-grade heat into power

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ABSTRACT

A supercritical Rankine cycle using zeotropic mixture working fluids for the conversion of low-grade heat into power is proposed and analyzed in this paper. Unlike a conventional organic Rankine cycle, a supercritical Rankine cycle does not go through the two-phase region during the heating process. By adopting zeotropic mixtures as the working fluids, the condensation process also happens non-isothermally. Both of these features create a potential for reducing the irreversibilities and improving the system efficiency. A comparative study between an organic Rankine cycle and the proposed supercritical Rankine cycle shows that the proposed cycle can achieve thermal efficiencies of 10.8–13.4% with the cycle high temperature of 393 K–473 K as compared to 9.7–10.1% for the organic Rankine cycle, which is an improvement of 10–30% over the organic Rankine cycle. When including the heating and condensation processes in the system, the system exergy efficiency is 38.6% for the proposed supercritical Rankine cycle as compared to 24.1% for the organic Rankine cycle.

1. Introduction

Low-grade heat such as geothermal, waste heat, and heat from low to mid temperature solar collectors, accounts for 50% or more of the total heat generated worldwide [1]. Due to the fact that conventional steam Rankine cycle does not allow efficient energy conversion at low temperatures [1–5], organic Rankine cycle (ORC) has been extensively studied for the conversion of low-grade heat into power for its simplicity and relatively high efficiency [1–15]. However, an important limitation of the ORC with a pure working fluid is the isothermal boiling, which creates a bad thermal match between the working fluid and the heat source due to the pinch point, leading to large irreversibilities. Use of mixtures [16–23] and supercritical fluids [24–26] can reduce this problem.

Supercritical Rankine cycles (SRC) have been studied to improve the performance of the energy conversion at low temperatures [26–29]. In contrast to a conventional ORC, the working fluid of an SRC is heated directly from liquid state into supercritical state, bypassing the two-phase region, which allows it to have a better thermal match with the heat source, resulting in less exergy destruction [28]. Furthermore, in a conventional ORC, the boiling system requires specialized equipment to separate the vapor phase from the liquid phase, while a supercritical system simplifies that.

The choice of working fluids is of key importance for the performance of an SRC. Carbon dioxide has been studied as the working fluid of SRCs by a number of investigators [25,30,31]. Zhang et al. [32,33] conducted research on a CO_2-based SRC, and reported the power generation efficiency of the cycle to be 8.0%–11.4%, depending on the working condition. Chen et al. [29] did a comparative study between a CO_2-based SRC and an R123-based ORC, finding that under the same thermodynamic mean heat rejection temperature, the CO_2-based SRC gives a slightly higher power output than the R123-based ORC. However, the CO_2-based SRC operates under pressures as high as 16 MPa, while condensing the carbon dioxide is also a challenge due to its low condensation temperature. Beside carbon dioxide, fluids such as hydrocarbons [32] and refrigerants R134a, R227ea, R236fa and R245fa have also been studied as the working fluids in SRCs, and the results showed that the thermal efficiency could improve by 10%–20%, compared to the same working fluids used in ORCs [4,28,33–35].

A review of the literature shows that all of the research on SRCs has been limited to pure fluids. While SRC using a pure working fluid does overcome the pinch point limitations of ORCs during the heating process, the condensation process is still isothermal. Our research introduces the novel concept of using zeotropic mixtures as the working fluids in an SRC, which results in much lower exergy destruction during both boiling and condensation, and, therefore,

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higher efficiencies. This study compares the performance of a conventional ORC with a zeotropic mixture-based SRC under the same temperature limits, which shows the advantages of the zeotropic mixture-based SRC.

2. Zeotropic mixture-based supercritical Rankine cycle

2.1. Cycle configuration and processes

Fig. 1 shows the basic configuration and a T-s diagram of the proposed SRC. The working fluid is pumped above its critical pressure, and then heated from the liquid to the supercritical state directly; the supercritical fluid expands in the turbine, generating power; the exhaust fluid from the turbine is condensed, thus completing the cycle. The proposed SRC using zeotropic mixtures as the working fluids has two important features: in the heating process (process $2 \rightarrow 3$ in Fig. 1(b)), the working fluid is heated directly to a supercritical state from the liquid phase; and in the condensation process (process $4 \rightarrow 1$ in Fig. 1(b)), the working fluid is condensed isobarically but non-isothermally. Both of these features results in temperature glides which allow us to reduce irrversibilities of the heat transfer processes during the heating and condensation.

2.2. Zeotropic mixtures as the working fluids

Zeotropic mixtures of refrigerants are the potential candidates for the proposed SRC due to their thermophysical properties and stability. Over 50 refrigerants were considered, however, some of them were rejected due to environmental concerns [36]. Beside the environmental concerns, some refrigerants are not suitable because of their thermophysical properties, such as a low critical temperature, which would be a challenge for the condensation process [37]. In consideration of their environmental impacts and thermophysical properties, 22 refrigerants, listed in Table 1, are screened as the potential candidates for designing the zeotropic mixtures. In order to take advantage of non-isothermal condensation, only those mixtures that can create thermal glides greater than 3 K during the condensation process are considered.

3. Comparative study of an organic Rankine cycle and the proposed supercritical Rankine cycle

In order to investigate the performance of the proposed SRC with zeotropic mixture working fluids, it was compared with an ORC over the same temperature range. A zeotropic mixture of R134a and R32 (0.7/0.3, mass fraction) is used as the working fluid of the SRC, while pure R134a is considered as the working fluid of the ORC. A zeotropic mixture of 0.7R134a and 0.3R32 is considered safe and environmentally friendly and has been used in refrigeration systems [36], while pure R134a is often used as the working fluid of ORCs [1,9,38] and refrigeration cycles.

A T-s diagram of an ORC using R134a as the working fluid is shown in Fig. 2, while an SRC using the zeotropic mixture of 0.7R134a/0.3R32 is shown in Fig. 3. The thermal efficiencies and the net work output of the thermodynamic cycles, the exergy efficiencies of the condensing processes, and the exergy efficiencies of the heating processes are analyzed in this section for both cycles with the cycle high temperature in the range of 393 K–473 K. Properties of the working fluids for this simulation are obtained by process simulation software ChemCAD® and NIST database.

3.1. Thermal efficiencies and net work outputs of the cycles

The thermal efficiencies and the net work outputs of the two cycles are investigated for the turbine inlet temperature of 393 K–473 K and average condensing temperature of 309.5 K. The pump and turbine efficiencies are set both at 85% for both cycles.

The cycle high pressure of the 134a-based ORC is set to be 3.3 MPa (critical pressure 4.06 MPa), and that of the zeotropic mixture-based SRC is 7 MPa (critical pressure 5.13 MPa) in the simulation. The low pressures of the cycles are determined by the average condensation temperature of 309.5 K.

The computed thermal efficiencies of the ORC and the SRC are shown in Fig. 4(a). Over the investigated cycle high temperature range (393 K–473 K), the thermal efficiency of the ORC using pure R134a is 9.70–10.13%, while that of the SRC using the zeotropic mixture is 10.77–13.35%, showing 10–30% increase over the R134a-based ORC. Fig. 4(a) also shows that the thermal efficiency of the R134a-based ORC has no significant increase as the cycle high temperature is increased from 393 K to 473 K.

The above simulations were based on constant cycle high pressures. Computations were also made with changing cycle high pressures in order to optimize the cycle thermal efficiencies. Assuming the minimum vapor quality at the turbine exit is 90%, the optimized thermal efficiency of the SRC is shown with a dotted line in Fig. 4(a). Comparing it with the efficiency of the SRC working at 7 MPa (continuous line in Fig. 4(a)), it is seen that there is a significant improvement at higher cycle temperatures. Fig. 4(b) shows the cycle high pressure of the SRC for optimized thermal efficiency. It is observed that in order to get the optimized thermal efficiency of 15.08% at 473 K, the pressure of the cycle is as high as 33 MPa. A high pressure like that could be a concern in real practice. The analysis of optimized thermal efficiency is only to show that there is a potential

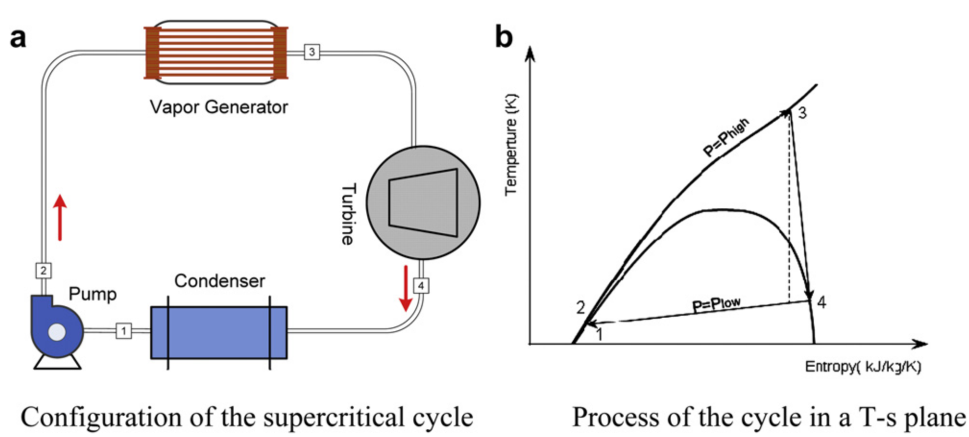

Fig. 1. Configuration and processes of a zeotropic mixture supercritical Rankine cycle.