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Research Paper

Analysis of the quantitative correlation between the heat source temperature and the critical temperature of the optimal pure working fluid for subcritical organic Rankine cycles

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HIGHLIGHTS

- A quantitative correlation is provided for subcritical ORC working fluid selection.
- The quantitative correlation relates the T_{hs}, T_{p_eva} and the working fluid T_c.
- The correlation is verified with simulation results.
- The correlation provides guidelines for future study and engineering application.

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ABSTRACT

Organic Rankine cycles can use various working fluids. Different heat sources and working conditions lead to very different optimal working fluids. This paper presents a new quantitative criterion for selecting the optimal working fluid for open type heat sources with temperatures from 150 to 350 °C. The heat source recovery exergetic efficiency is used as the evaluation indicator. Over 30 working fluids with critical temperature from 71.87 to 357.65 °C are under evaluation. The working fluid critical temperature's influence on the heat source utilization, cycle efficiency and exergetic loss in the evaporator and condenser is analyzed to show that the critical temperature is the key parameter for selecting the optimal working fluid. The critical temperature of the optimal working fluid is determined by the heat source temperature, the pinch point temperature difference and the condensation temperature. When the cooling fluid outlet temperature is between 30 and 60 °C, which covers the most common natural cooling condition and the requirement of combined heat and power system, the correlation between the critical temperature of the optimal working fluid and the heat source temperature with different pinch point temperature difference is given. This correlation provides concise guidance for the optimal pure working fluids selection and mixture design.

1. Introduction

There have been many studies on working fluid selection for organic Rankine cycles (ORC). Most research focused on obtaining the best working fluids depending on a specific heat source under different working conditions. In these research, cycle efficiencies, work output, volume flow rate, mass flow rate, pressure ratio, toxicity, flammability, ozone depletion potential (ODP), global warming potential (GWP) and even some economic indicators such as heat exchanger and turbine size can be used as working fluid screen indicators [1–4]. Different heat sources, different working conditions and different performance indicators result in quite different optimal working fluids [5]. Thus, it is hard to provide unified conclusion on the optimal working fluid screening for ORC.

From the point of view of thermodynamics, the cycle performance is strictly linked to the thermodynamic properties of the working fluid such as the heat capacity C_p, the latent heat of vaporization ΔH, the degree of dryness ξ, the boiling temperature T_b and the critical temperature T_c of the fluid [6–9]. Among all these properties, the critical temperature T_c shows the most direct relationship with the cycle performance. Because how the working fluid evaporation process matches with the heat source in the subcritical ORC is limited by T_c. Thus, the previous literature showed that the working fluids recommended to the high temperature heat source were usually high T_c working fluids such as cyclohexane, siloxanes and toluene [10–12] while to the low temperature heat

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source were usually low T_c working fluids such as R134a, R123 and R245fa [2,13–15]. Studies of ORC working fluid screening considering T_c are reviewed below in detail.

Aljundi [16] used fixed evaporation and condensation temperatures and found that T_c was positively correlated with the thermal and exergetic efficiencies. However, this is the result of an isolated ORC and did not take the heat source temperature, pinch point temperature difference or the optimal working conditions into consideration. He et al. [17] analyzed 22 working fluids for 150 °C heat sources and found that the working fluid provided more work output when T_c was close to heat source temperature and recommended R114, R245fa, R123, R601a, n-pentane, R141b and R113 as suitable working fluids. Liu et al. [18] analyzed 28 working fluids for 85 °C–150 °C heat sources and found the relationship among the optimal evaporating temperature, the heat source temperature, the working fluids T_c and the pinch temperature difference in the evaporator. Gao et al. [19] studied 24 working fluids with T_c from 66.17 to 214.21 °C for a 320 °C heat source and concluded that the optimal evaporation temperature was 0.98–0.99T_c and that high T_c working fluids were much better than low T_c working fluids. Mago [20] considered 230–650 °C heat sources with R245fa, R123, R142b, isobutane, R113 and R141b as the working fluids to show that T_c closer to the heat source temperature gave higher exergetic efficiencies. These four studies focused on the low or high temperature heat source only and the chosen working fluid T_c were either too high [17,18] or too low [19,20] relating to the heat source temperatures, so the results only reveal part of the relationship between the heat source temperature and the working fluid T_c and the chosen fluids may not be the optimal working fluids for the given heat source. Wang et al. [21] identified the optimal working fluids with T_c from 72.73 to 204.5 °C for different heat source temperatures from 70 to 230 °C and recommended low T_c, low specific liquid heat and high vaporization latent working fluid for ORC. However, neither the working fluid T_c nor the source temperature is broad enough and the conclusion contraries to [19]. Xu et al. [22] analyzed how T_c influenced on the cycle efficiency and work output for the closed type heat sources (source with outlet temperature limitation) with different heat source inlet and outlet temperatures, so the analysis did not show how T_c influenced on the heat source utilization. However, how T_c influences on the heat source utilization is very important for the open type heat sources (source without outlet temperature limitation).

The studies above only considered a specific heat source temperature, a fixed pinch point temperature difference with limited working fluids and cannot show the overall relationship between the heat source temperature and the working fluid T_c or generalize to other working conditions. And no quantitative correlations are provided.

This study simulated with open type heat source temperatures from 150 to 350 °C and working fluid T_c from 71 to 344 °C which are broad enough to conclude a general relationship between the heat source temperature and the working fluid T_c. The influence of T_c on the heat source utilization, cycle efficiency and the exergetic losses in the evaporator and condenser is analyzed. A quantitative correlation between the heat source temperature and the optimal working fluid T_c is developed based on a theoretical analysis and simulation results. This correlation provides concise guidance for the optimal pure working fluid selection and mixture design.

2. Model description of subcritical ORC

2.1. Simple subcritical ORC description

The ORC is a simple four-component system as shown in Fig. 1. The working fluid is pumped to the evaporator to be vaporized by the heat source and then expands in the turbine to generate work.

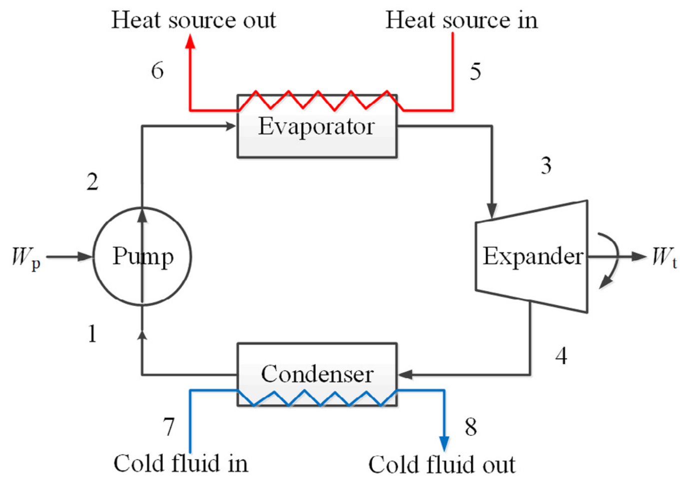

Fig. 1. Schematic process scheme of the ORC configuration.

The vapor out of the turbine goes into the condenser to totally condense to liquid. Then the working fluid goes to the pump and begins a new circulation. Evaporation pressure is controlled to be lower than 0.9P_c or saturated pressure of ($T_5 - T_{p\_eva}$) to guarantee a subcritical cycle as shown in Fig. 2. The state point number in Fig. 2 corresponds to that in Fig. 1.

2.2. Subcritical ORC model

2.2.1. Model assumption

No pressure drop.

The cycle is run at steady state.

The heat exchanger is a counter flow layout.

The state point number in Sections 2.2.2 and 2.2.3 corresponds to that in Fig. 2.

2.2.2. First law of thermodynamic analysis

The cycle efficiency is calculated by:

$$\eta = \frac{w_t - w_{pp}}{q_{eva}} \tag{1}$$

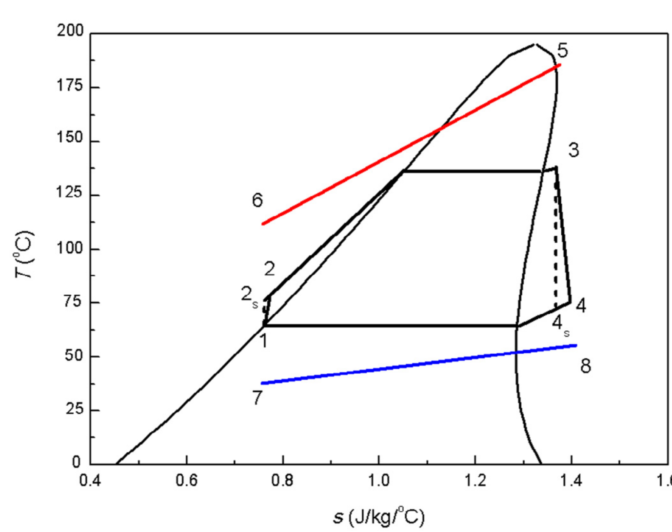

Fig. 2. Subcritical ORC in a T-s diagram (1. pump inlet; 2. evaporator inlet; 3. turbine inlet; 4. condenser inlet; 5. heat source inlet; 6. heat source outlet; 7. cold fluid inlet; 8. cold fluid outlet).