Prediction of the roles of critical properties for pure and binary mixture working fluid in Rankine cycle performances

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Abstract

This presented work concerns the effect of critical properties for pure and binary mixture working fluid on the cycle performances. The results revealed that the relationship between critical temperature and thermal efficiency for pure fluid would depend on the initial operating conditions. Fluids with lower critical temperature would be preferred candidate under defined condensing pressure, while the result would reverse as the condensing temperature is constant. There existed the optimal reduced evaporating temperature range around which the corresponding fluids achieve the peak efficiency, and the maximum would shift right towards the larger ratio as the evaporating pressure increases. For the binary mixtures, the trend of critical pressure with the quality was basically opposite to that of evaporator irreversibility rate. Therefore, the critical properties could be considered as predictive index for selecting working fluids to achieve a preferred efficiency for pure fluids and reduce the evaporator irreversibility rate for mixture fluids.

Keywords: Working fluid; Critical temperature; Reduced temperature; Critical pressure; Rankine cycle

1. Introduction

Organic Rankine cycle (ORC) has been widely used to convert low grade heat into high grade power for waste heat recovery (WHR). Reviewing the investigations [1] reveals the selection of working fluid plays critical roles for achieving high thermal efficiency as well as optimum utilization of the available heat source. Many efforts [2-3] have been made on the choice of working fluids and the performance analysis of the ORC. However, the impacts of working fluid physical properties on ORC performances have not been identified clearly so far, although some researches were presented to discuss the issues. For instances, by theoretical deductions, Liu et al. [4] held that the thermal efficiency for various working fluids is a weak function of the critical temperature. On the contrary, the evaluation results by Aljundi [5] suggested that the higher critical point temperature the fluid has, the better the cycle thermal efficiency would be. These investigations were carried out under defined condensing temperature, which is the conventional assumption in low temperature WHR fields. However, for the high temperature WHR such as exhaust energy recovery from internal combustion engine, which has revived to be emphasized again
in recent years, fluids with high boiling temperature like water are determined to serve as the working medium, and operate under given condensing pressure for avoiding leakage in condenser [6].

Therefore, the above related researches seem not enough and applicable for the high temperature WHR, few related reports were conducted under provided condensing pressure. In this paper, attempts were made to estimate the relationships between the critical properties of working fluids and the performance of ORC with condensing pressure constant. Critical temperature, reduced evaporating temperature, and critical pressure were examined with thermal efficiency and evaporator irreversibility rate as the objective functions. The model information and its validation in detail could be found in [7].

2. Results and Discussion

In the following analysis, the influence of working fluid critical temperature on the cycle performance was verified under defined condensing pressure at 0.1 MPa. The working fluid temperature at the outlet of the evaporator was assumed 10 K higher than the saturated temperature to guarantee dry expansion in the expander. The pure fluids analyzed cover the most frequently used refrigerants for ORC.

![Figure 1](image_url)

Figure 1. Thermal efficiency of working fluids with different critical temperature.

It could be revealed from Figure 1 that fluids with lower critical temperature would yield higher efficiencies on the whole, although slight fluctuation occurs for individual ones at high pressure. This result is opponent to those in other reports [4-5] due to the different initial conditions. Therefore, it is better to select fluids with lower critical temperature to achieve better cycle performance when condensing pressure is defined, on the contrary, fluids with higher critical temperature is preferred for the case of constant condensing temperature.

The relationship between cycle efficiency and the reduced evaporating temperature, i.e. the ratio of evaporating and critical temperature, could be observed in Figure 2. The efficiency shows parabolic tendency as the reduced evaporating temperature increases, having the optimum ratio range around which the corresponding fluids achieve the peak performance. Moreover, the peak value would shift right towards the larger ratio as the evaporating pressure increases, as well as the performance would be enhanced.

Rankine cycle performance could be improved by use of mixture fluids with properly chosen components as the ORC medium [8]. Besides, researchers [9] suggested that the evaporator irreversibility rate account for the most proportion in the system total one. Therefore, this objective function for binary mixture fluids was examined to search for its relationship with some physical property such as the critical pressure of working substances.
Figure 2. Thermal efficiency of working fluids with different reduced evaporating temperature.

(a) Evaporating pressure = 1MPa
(b) Evaporating pressure = 2MPa

Figure 3. Evaporator irreversibility rate and critical pressure of binary mixtures as mass fraction.

(a) Mixture of propane and isobutane
(b) Mixture of propane and ethane
(c) Mixture of R32 and R125
(d) Mixture of R32 and R134a

It is interesting to find that the trend of critical pressure with the quality is basically opposite to that of evaporator irreversibility rate, particularly existing certain corresponding correlation between the peak value of the former and the least one of the latter, that is to say, when the critical pressure reaches its maximum at a certain mass fraction, the evaporator irreversibility rate will also drop down to its minimum.
3. Conclusions

This paper examined the relationships between the critical parameters of working fluids and the Rankine cycle performances under defined condensing pressure. Several conclusions were found as follows:

(1) The effect of critical temperature for pure fluids on the thermal efficiency would depend on the initial operating conditions. When the condensing pressure is constant, fluids with lower critical temperature would be beneficial for yielding higher efficiency, which is opposite to the case at given condensing temperature.

(2) There exists the optimal ratio range around which the corresponding fluids give rise to the peak efficiency. Moreover, the maximum value would shift right towards the larger ratio as the evaporating pressure increases, as well as yielding better performance.

(3) For the binary mixture fluids, the trend of critical pressure with the quality is basically opposite to that of evaporator irreversibility rate, particularly existing certain corresponding correlation between the peak value of the former and the least one of the latter.

Therefore, the critical properties could be considered as index for selecting working fluids to achieve a preferred efficiency for pure fluids and reduce the evaporator irreversibility rate for binary mixture ones.

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