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Critical temperature criterion for selection of working fluids for subcritical pressure Organic Rankine cycles

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ABSTRACT

A method was proposed to couple the heat source with ORCs (Organic Rankine Cycles). The integrated-average temperature difference, ΔT_{ave}, quantifies the thermal match in the evaporator. ΔT_{ave} decreases with increase in critical temperatures (T_c). The fluid with T_c approaching $T_{gas,in}$ (flue gas inlet temperature) can have $\Delta T_{ave} \rightarrow 0.5 \times (T_{gas,out} - T_5)$, which is called the optimal temperature difference, at which the thermal efficiency is maximum. The ORC performance with fluids of $T_c > T_{gas,in}$ has less deviation from the optimal condition. Thermal efficiencies are well correlated with critical temperatures. The ORC thermal efficiencies are randomly distributed against other fluid physical properties except T_c. Thus, the critical temperature can be the sole criterion for the fluid selection, as far as the thermal efficiency is concerned. The organic fluids with T_c in the range of ($T_{gas,in} - 20$–30 K, $T_{gas,in} + 100$ K) are recommended. Specific fluids are recommended for heat source temperature in the range of (100–300 °C) by screening 57 fluids. More fluids are available for ORCs with low heat source temperatures. Limited fluids are available for high temperature heat source applications. Due to the expanded fluids in region II, some fluids such as R245fa can be used over a wide heat source temperature range.

1. Introduction

Various criteria have been proposed for the selection of working fluids for ORCs (Organic Rankine Cycles) [1–4]. Chen et al. [1] commented the selection criteria for ORCs. Thirty-five working fluids were screened. The physical properties, stability, environmental impacts, safety, compatibility, availability and cost are the important considerations. Qiu [3] optimized eight mostly applied working fluids and gave a preferable ranking by means of spinal point method: HFE7000, HFE7100, PF5050, R123, n-pentane, R245fa, R134a and isobutene. He developed a methodology for the selection of organic fluids without practical computation data for ORCs. Stijepovic et al. [4] explored the relationships between the fluid physical properties and ORC thermodynamic and economic performance criteria, analytically.

Alternatively, the thermodynamic performance of ORCs was computed with various working fluids to select the "best" fluid. The available studies dealt with the thermodynamic cycle alone without coupling the heat source [5–10]. Wang et al. [6] investigated the effect of molecular structures and entropies on the ORC thermal efficiencies. The ORC considered was a subcritical pressure cycle with an evaporation temperature of 90 °C and a condensation temperature of 35 °C. They noted that the working fluids with low molecular entropies could generate high thermal efficiencies. Rayegan and Tao [7] identified the most suitable fluids to operate a solar ORC. The authors calculated the cycle thermal efficiency with flexible evaporation temperatures. They found that higher critical temperatures of organic fluids allowed higher evaporation temperature to reach higher thermal efficiencies. The above conclusion was correct for specific evaporation temperatures such as 130 °C and 85 °C. Kosmadakis et al. [8] selected the "best" fluid for an ORC included in a two-stage combined system for RO desalination application. The thermal efficiency of R245fa was acceptable and its use was not restricted by any international regulations, even though the thermal efficiency was not the highest. Mikielewicz and Mikielewicz [9] proposed a thermodynamic criterion for fluid selection: $Ja(T_1) = C_pT_1/h_{fg}(T_1)$ for subcritical pressure ORC and $Ja(T_1,T_2) = C_pT_1/\Delta H(T_2)$ for supercritical pressure ORCs, where $C_pT_1/h_{fg}(T_1)$ and $C_pT_1/\Delta H(T_2)$ were the Jakob number, representing the sensible heat relative to latent heat in the evaporator, T_1 and T_2

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were the fluid temperatures at the turbine inlet and outlet, respectively. Kuo et al. [10] investigated the effect of working fluids on ORC performance with an ORC power output in the capacity of 50 kW. A dimensionless "figure of merit" combining the Jakob number, evaporating temperature and condensing temperature was proposed as far as the thermal efficiency was concerned. The thermal efficiency was decreased with increase in the figure of merit. The proposed "figure of merit" was not only applicable to the eighteen working fluids but also was consistent with some existing references.

Some researchers considered the thermodynamic cycle coupling with the heat source [11–25]. When the heat source was solar energy, waste heat or geothermal water, it was usually treated as isothermal [11–16]. The heat source temperature was the evaporator outlet vapor temperature plus a specific temperature difference. Mago et al. [11,12] recovered low grade heat to generate power using dry organic fluids. The heat source temperature was uniform in the evaporator with its temperature equal to the turbine inlet temperature plus the pinch point temperature difference. It was concluded that ORC achieved higher thermal efficiency with higher boiling temperature of the organic fluid. Facão and Oliveira [13] assumed the isothermal heat source temperature to be 10 °C higher than the turbine inlet temperature. Papadopoulos et al. [14] applied the CAMD (computer aided molecular design) to select fluids for ORCs. The heat source was the saturation steam with its temperature of 90 °C. The maximum temperature of the organic fluid was 80 °C. The optimum designs were searched to identify organic fluids that exhibited optimum ORC economic, operating, safety and environmental performances. Hung [15] assumed the heat source temperature of 600 K which was 15 K high than the turbine inlet temperature. Aljundi [16] analyzed the effect of dry fluids on the ORC. The heat source temperature was 5 K higher than the turbine inlet temperature. It was found that the thermal efficiencies were increased with the critical temperatures of the organic fluids monotonously.

The non-isothermal heat sources were paid attention recently. Chen et al. [17] proposed a new design method to fully couple the ORC with the heat source by specifying the inlet and outlet temperatures of the heat carrier fluid. Other researchers dealt with the coupling which was different from Chen et al. [17]. They determined the cycle first. The outlet temperature of the heat source was finally decided by the cycle, the inlet temperature of the heat source and the pinch point temperature difference. Tchanche et al. [18] investigated the low temperature solar ORC. Hot water at the maximum temperature of 90 °C served as the heat source and the pinch point temperature was 6 K. R134a followed by R152a, R600, R600a and R290 were suitable fluids. Guo et al. [19] proposed a low temperature geothermally-powered ORC integrating with an intermediate heat exchanger and a heat pump. The geothermal water temperature was 90 °C and the pinch temperature difference was 3 °C. The selection criteria of working fluids included the net power output per unit mass flow rate of the geothermal water, the total heat transfer area relative to net power output and the electricity production cost. The relationship between the boiling temperature of working fluid and the system performance indicators was discussed. Wang et al. [20] investigated the effect of the boiling temperature of working fluids on the ORC performance. They investigated the multi-objective optimization model for ORCs. The heat source temperature had a range of 100–220 °C and the pinch point temperature difference had a range of 5–30 °C. Results showed that boiling temperature of working fluids greatly affected the optimal evaporating pressure to affect the cycle performance. R123 was the "best" fluid for the temperature range of 100–180 °C and R141b was the optimal fluid with the temperature higher than 180 °C. The influence of critical temperatures of working fluids on the cycle performance has been paid attention recently [21–25]. Liu et al. [21] specified the inlet temperature of waste heat and the pinch point temperature difference. The thermal efficiency of R123 with lower critical temperature was lower than that of toluene with higher critical temperature. He et al. [22] proposed a theoretical formula to calculate the optimal evaporation temperature of subcritical ORC. The waste heat source temperature and the pinch temperature difference were fixed to be 423.15 K and 5 K, respectively. They found that the larger net power output was produced when the critical temperature of working fluid approached the waste heat source temperature. Saleh et al. [23] proposed a thermodynamic screening of 31 working fluids for ORCs. They analyzed the ORC cycle alone (isolated cycle) and the cycle matching with the heat source. For the isolated cycle operating between 100 and 30 °C, they found a trend that the thermal efficiency increased with increasing the critical temperature. For the ORC coupling with the heat source, they set the initial heat carrier temperature of 120 °C and the pinch point temperature difference of 10 °C. They found that fluids with lower critical temperatures were favorable because they yielded a more uniform increase of the T–H curve during heating. Lai et al. [24] investigated both isolated ORCs and those coupling with the heat source. The similar trend that the thermal efficiency increased with working fluid critical temperatures was also observed for isolated ORCs. For ORCs coupling with the heat source, the heat source temperature was selected as 280 °C and 350 °C. The influence of critical temperatures on thermal efficiencies was not as obvious as that for isolated ORCs. Heberle and Brüggemann [25] combined heat and power generation for geothermal resources at a temperature level below 450 K. They compared series and parallel circuits of an ORC and an additional heat generation. In series circuit the outlet temperature of geothermal water in the ORC evaporator was restricted by the heat generation demand, while in parallel circuit such restriction was not used. The outlet temperature of geothermal water influenced the thermal match between the geothermal water and the organic fluid. The most efficient concept was a series circuit with an organic fluid having higher critical temperature like isopentane. For parallel circuits and for power generation, fluids like R227ea with lower critical temperatures were preferred.

The above literature review showed that when the evaporation temperature was not fixed for either an isolated ORC or an ORC coupling with an isothermal heat source, the thermal efficiency was increased with the critical temperatures of the organic fluids [7,16,23,24]. We note that the heat received from the heat source is equal to $Q_a = mC_p(T_{in} - T_{out})$, where m is the mass flow rate, C_p is the specific heat, and T_{in} and T_{out} are the inlet and outlet temperatures of the heat carrier fluid. The isothermal heat source is difficult to be fulfilled because the mass flow rate should be infinity to receive a specific heat from the heat source. Therefore, the thermal match between the heat carrier fluid (non-isothermal heat source) and the organic fluid in the evaporator is important for the ORC design, operation and performance evaluation. How the critical temperatures of organic fluids influence the thermal match between the heat carrier fluid and the organic fluid has not been understood for a non-isothermal heat source.

Furthermore, the available literature used the pinch point temperature difference in the evaporator to analyze the ORC performance. Physically, the pinch point temperature difference is a local parameter occurring somewhere in the evaporator. Thus, it cannot quantify the thermal match between the heat source and the organic fluid in the evaporator, quantitatively. The objective of this paper was to thoroughly investigate the effect of critical temperatures on the ORC performance. This paper had the following contributions: