Thermodynamic performance comparison between single-pressure and dual-pressure evaporation organic Rankine cycles for heat sources with outlet temperature limit

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Abstract. Organic Rankine cycle (ORC) is a widely used technology to generate power from renewable energy and waste heat. Dual-pressure evaporation cycle holds immense potential to be used in ORC systems because it can remarkably increase the heat-work conversion efficiency and improve the adaptability of ORC to heat sources with various characteristics. This study compared the thermodynamic performance of single-pressure and dual-pressure evaporation ORCs for heat sources with outlet temperature limit, based on five organic fluids. Effects of the heat source outlet temperature limit on the characteristics of dual-pressure evaporation ORC system were also discussed. Results show that the dual-pressure evaporation cycle can substantially increase the net power output by increasing system efficiency, and is beneficial to reduce the charge volume of organic fluid in the system, compared to the single-pressure evaporation cycle. The increments in net power output of dual-pressure evaporation cycle over the single-pressure evaporation cycle can be 4.9%, 8.3%, 10.8%, 12.8%, and 14.0% at most for R227ea, R1234ze(E), R600a, R245fa, and R601a, respectively. While, compared to heat sources without outlet temperature limit, the increment in net power output of dual-pressure evaporation cycle is remarkably lower for heat sources with outlet temperature limit.

1. Introduction
Organic Rankine cycle (ORC) is a promising technology to generate power from the renewable energy and waste heat [1, 2]. The fundamental study and engineering application of ORC technology has been continuously growing in recent years [3]. The improvement of cycle type is always a hot study issue in the ORC field, because it significantly affects the overall performance of ORC system [4]. To achieve a high heat-work conversion efficiency is the primary goal for the improvement of cycle type. Moreover, a large design freedom degree of cycle structure is also crucial for ORC system to match the remarkably different heat release characteristics of various heat sources [5]. Dual-pressure evaporation cycle has two evaporation processes with different pressures and an isobaric condensation process [6]. For the dual-pressure evaporation cycle, the evaporation pressure, superheat degree, and mass flow rate of working fluid in each evaporation process can be optimized to achieve the preferable temperature match effect between heat source fluid and working fluid, and thereby substantially reducing the exergy loss in the cycle heat absorption process and also improving the adaptability of ORC to heat sources with various characteristics, compared to the conventional single-pressure evaporation cycle [6]. The superiority in thermodynamic performance of dual-pressure
evaporation cycle has been proven by several studies [6] [7] [8]. Our previous work [6] compared the thermodynamic performance between single-pressure and dual-pressure evaporation ORCs based on nine pure fluids for heat sources without outlet temperature limit, and a quantitative criterion was provided to assess the optimal cycle type (single-pressure or dual-pressure) for the ORC system. For lots of heat sources, the outlet temperature cannot be cooled to a low value due to the limit of several external factors (e.g., the scale formation for geothermal water, and dew point corrosion for industrial flue) [5]. For these heat sources with outlet temperature limit, the advantages of dual-pressure evaporation cycle in increasing the system heat absorption capacity (reducing the heat source outlet temperature) will be significantly weakened and even disappearing, compared to heat sources without outlet temperature limit. Thus, the superiority in thermodynamic performance of dual-pressure evaporation cycle over conventional single-pressure evaporation cycle should be further analyzed for heat sources with outlet temperature limit. Moreover, for the dual-pressure evaporation cycle, the selections of optimal cycle parameters, and variations in the thermodynamic performance superiority with increasing heat source temperature will be substantially different for heat sources with and without outlet temperature limit. These are also important issues to be further studied. This study focuses on the single-pressure and dual-pressure evaporation ORC systems driven by heat sources with outlet temperature limit. The heat source temperature was selected as 100-200°C, and five common pure fluids were selected as the working fluids, to guarantee the studied heat source temperature range and working fluid are broad enough. The thermodynamic performance of single-pressure and dual-pressure evaporation ORC systems was compared, and effects of heat source temperature and working fluid thermophysical properties on the thermodynamic performance superiority of dual-pressure evaporation cycle were revealed. Effects of the heat source outlet temperature limit on the characteristics of dual-pressure evaporation ORC system were also discussed.

2. Methodology

2.1. ORC system and working fluids

The system of dual-pressure evaporation ORC and its T-s diagram are shown in Figure 1. The descriptions of thermodynamic processes for single-pressure and dual-pressure evaporation ORCs can refer to our previous work [6]. R227ea, R1234ze(E), R600a, R245fa, and R601a were selected as working fluids due to their preferable thermodynamic performance in the ORC system [6], and their critical temperatures are 101.75°C, 109.36°C, 134.66°C, 154.01°C, and 187.20°C, respectively [9].

![Figure 1](image1.png)

**Figure 1.** Schematics of dual-pressure evaporation ORC system: (a). ORC system; (b). Thermodynamic processes

2.2. System model

The inlet temperature of heat source fluid (hot water) is 100-200°C, and its outlet temperature should be not lower than 70°C. The mass flow rate of hot water is 1 kg·s⁻¹, and its pressures are 0.5 MPa, 1.2 MPa, and 1.6 MPa for the inlet temperatures of 100-150°C, 151-180°C, and 181-200°C, respectively. The efficiencies of turbine and feed pump are 0.8 and 0.75, respectively. The cooling water inlet temperature is 20°C, and its temperature rise in the working fluid condensation process is 5°C. The
pressure head of cooling system is 10 m. The ORC systems are assumed as in the steady state, and heat dissipation and pressure drop of fluids are negligible in heat exchangers and pipes. In this study, the evaporation pressures and evaporator outlet temperatures of single-pressure and dual-pressure evaporation ORC systems were optimized to achieve the largest net power output. The net power output of an ORC system is equal to the power output of turbines deducts the power consumed by the working fluid feed pumps and cooling system ($W_{\text{net}} = W_T - W_p - W_{\text{cool}}$). The selectable ranges of optimized cycle parameters can refer to our previous work [6], including the detailed system model equations, optimized processes and model validation. Thermophysical properties of fluids are from REFPROP 9.1 [9].

3. Results and discussion
The comparison results of optimized cycle parameters and system thermodynamic performance between single-pressure and dual-pressure evaporation ORCs are similar for five selected working fluids; thus, R245fa is selected as an example to introduce the details of comparison.

3.1. Comparisons for optimized cycle parameters
Figure 2 shows the comparisons for optimized evaporation pressures between single-pressure and dual-pressure evaporation ORCs using R245fa. With increasing heat source inlet temperature, the optimized evaporation pressure of single-pressure evaporation cycle ($p_{\text{e\_single\_opt}}$) initially increases for the heat source inlet temperature below 190°C, and then it remains at the upper limit ($0.9p_c$). For the dual-pressure evaporation cycle, with increasing heat source inlet temperature, the optimized evaporation pressure in the high-pressure stage ($p_{\text{e\_HP\_opt}}$) initially increases for the heat source inlet temperature below 170°C and then it remains at the upper limit ($0.9p_c$). The optimized evaporation pressure in low-pressure stage ($p_{\text{e\_LP\_opt}}$) increases with increasing heat source inlet temperature. The $p_{\text{e\_HP\_opt}}$ will be higher than $p_{\text{e\_single\_opt}}$ unless the $p_{\text{e\_HP\_opt}}$ and $p_{\text{e\_single\_opt}}$ remain at the upper limits. The $p_{\text{e\_LP\_opt}}$ is lower than $p_{\text{e\_single\_opt}}$ and the decrement increases with increasing heat source inlet temperature; while, the $p_{\text{e\_LP\_opt}}$ is nearly equal to $p_{\text{e\_single\_opt}}$ when the heat source inlet temperature is lower than approximately 170°C.

![Figure 2. Comparisons for optimized evaporation pressures between single-pressure and dual-pressure evaporation ORCs.](image1)

![Figure 3. Comparisons for optimized evaporator outlet temperatures between single-pressure and dual-pressure evaporation ORCs.](image2)
heat source inlet temperatures not exceeding 180°C and 170°C, respectively. For the single-pressure and dual-pressure evaporation ORCs, the comparison results of optimized evaporator outlet temperatures are similar to those of optimized evaporation pressures; while, the optimized evaporator outlet temperature in the high-pressure stage is slightly higher than that in the single-pressure evaporation cycle when the heat source inlet temperature exceeds 190°C.

Figure 4 presents the mass flow rates of R245fa in single-pressure and dual-pressure evaporation ORCs. In the single-pressure evaporation cycle, the mass flow rate of R245fa initially increases nearly linearly with increasing heat source inlet temperature, and then it remains nearly constant for the heat source inlet temperature of 180-200°C. In the dual-pressure evaporation cycle, the total mass flow rate of R245fa increases with a low increment as the heat source inlet temperature increases. Therein, with increasing heat source inlet temperature, the mass flow rate of R245fa in the low-pressure stage initially increases for \( T_{\text{w,in}} < 170^\circ \text{C} \) and then decreases with a low decrement. While, the mass flow rate of R245fa in the high-pressure stage initially increases nearly linearly for \( T_{\text{w,in}} < 170^\circ \text{C} \), and then increases with a low increment, with increasing heat source inlet temperature. The mass flow rate of R245fa in the high-pressure stage is significantly higher than that in the low-pressure stage, and the increment generally increases with increasing heat source inlet temperature. Therefore, the effect of high-pressure stage on the system net power output becomes more remarkable with increasing heat source inlet temperature; while, the effect of low-pressure stage on the system net power output becomes weaker due to its lower mass flow rate of R245fa. Furthermore, the working fluid mass flow rate in the dual-pressure evaporation cycle is lower than that in the single-pressure evaporation cycle, which indicates that the dual-pressure evaporation cycle is beneficial to reduce the charge volume of organic fluid in the ORC system.

Figure 4. Mass flow rates of R245fa in single-pressure and dual-pressure evaporation ORC systems.

Figure 5. Comparisons for maximized net power outputs between single-pressure and dual-pressure evaporation ORC systems.

3.2. Comparisons for system thermodynamic performance

For the single-pressure and dual-pressure evaporation ORCs driven by heat sources of various inlet temperatures, the heat source outlet temperatures are always equal to the lower limit (70°C) at the optimized operating conditions. Thus, the heat absorption capacities of two ORC systems are equal, and comparisons of their maximized net power outputs depend on the system efficiency.

Figure 5 presents the comparisons for maximized net power outputs between single-pressure and dual-pressure evaporation ORC systems using R245fa. The maximized net power output of dual-pressure evaporation cycle is larger than that of single-pressure evaporation cycle when the heat source inlet temperature is below approximately 190°C, and the increment initially increases for heat source inlet temperature below 130°C and then decreases with increasing heat source inlet temperature. Compared to single-pressure evaporation cycle, the largest increment in maximized net power output of dual-pressure evaporation cycle is 12.8% which occurs at the heat source inlet temperature of 130°C. When the heat source inlet temperature exceeds 190°C, the maximized net power output of dual-pressure evaporation cycle is slightly lower than that of single-pressure evaporation cycle due to the upper limit
of evaporation pressure in the high-pressure stage \((p_{e,HP,\text{opt}})\) cannot increase, Figure 2). In summary, with the limits of heat source outlet temperature and pinch point temperature difference in the heat absorption process \((\Delta T_{\text{HAP,pp}})\), the dual-pressure evaporation cycle can obtain a higher system efficiency due to its larger design freedom degree in the cycle heat absorption process, and thereby increases the system net power output, compared to the single-pressure evaporation cycle.

Given the evaporation pressure(s) and evaporator outlet temperature(s), the heat source outlet temperature will decrease theoretically with increasing heat source inlet temperature for single-pressure and dual-pressure evaporation ORCs. For the working fluid with a low critical temperature, the high heat source inlet temperature will be not applicable because the heat source outlet temperature is always lower than 70°C for the whole selectable ranges of evaporation pressure(s) and evaporator outlet temperature(s). Results show that R227ea and R1234ze(E) can be used for heat sources of 100-120°C and 100-140°C, respectively. R600a, R245fa, and R601a can be used for heat sources of 100-200°C. Figure 6 presents the increments in maximized net power output of dual-pressure evaporation cycle over the single-pressure evaporation cycle \(\left(\frac{W_{\text{net_dual}} - W_{\text{net_single}}}{W_{\text{net_single}}}\right)\) for various working fluids. For R1234ze(E), R600a, R245fa, and R601a, the \(\left(\frac{W_{\text{net_dual}} - W_{\text{net_single}}}{W_{\text{net_single}}}\right)\) initially increases and then decreases with increasing heat source inlet temperature. While, for R227ea, the \(\left(\frac{W_{\text{net_dual}} - W_{\text{net_single}}}{W_{\text{net_single}}}\right)\) decreases with increasing heat source inlet temperature due to its narrow applicable heat source inlet temperature range. For R227ea, R1234ze(E), R600a, R245fa, and R601a, the \(\left(\frac{W_{\text{net_dual}} - W_{\text{net_single}}}{W_{\text{net_single}}}\right)\) can be 4.9%, 8.3%, 10.8%, 12.8%, and 14.0% at most, respectively; and the suitable heat source inlet temperature ranges of dual-pressure evaporation cycle (obtaining a larger net power output) are 100-120°C, 100-140°C, 100-160°C, 100-180°C, and 100-200°C, respectively. Thus, the critical temperature of working fluid is higher, the applicable heat source inlet temperature range is wider, and the suitable heat source inlet temperature range of dual-pressure evaporation cycle is also larger.

![Figure 6](image1.png)

**Figure 6.** Increments in maximized net power output of dual-pressure evaporation cycle over the single-pressure evaporation cycle for various working fluids.

![Figure 7](image2.png)

**Figure 7.** Comparisons for increments in maximized net power output of dual-pressure evaporation cycle for heat sources with and without outlet temperature limit.

### 3.3. Effects of the heat source outlet temperature limit

In this study, the operating condition will be ignored if the heat source outlet temperature below 70°C. For the single-pressure evaporation cycle, the heat source outlet temperature decreases as the evaporation pressure decreases; thus, the heat source outlet temperature may be lower than 70°C when the evaporation pressure is low. Given the heat source inlet temperature and evaporation pressure, the heat source outlet temperature may be lower than 70°C for a low evaporator outlet temperature; thus, the operating condition will be ignored. The similar situations also exist for the dual-pressure evaporation cycle.
evaporation cycle. Therefore, the applicable operating conditions of single-pressure and dual-pressure evaporation ORCs will be significantly shrunken due to the limit of heat source outlet temperature. For heat sources with and without outlet temperature limit, the comparisons for increments in maximized net power output of dual-pressure evaporation cycle \((W_{\text{net_dual}} - W_{\text{net_single}})/W_{\text{net_single}}\) are presented in Figure 7. The suitable heat source inlet temperature ranges of dual-pressure evaporation cycle are nearly equal for heat sources with and without outlet temperature limit. While, the \((W_{\text{net_dual}} - W_{\text{net_single}})/W_{\text{net_single}}\) for heat sources with outlet temperature limit is remarkably lower than that for heat sources without outlet temperature limit. In addition, for heat sources without outlet temperature limit, the dual-pressure evaporation cycle dramatically increases the system net power output by reducing heat source outlet temperature (increasing system heat absorption capacity), as described in our previous work [6]. While, for heat sources with outlet temperature limit, the dual-pressure evaporation cycle significantly increases the system net power output by increasing system efficiency due to its higher evaporation pressure in the high-pressure stage compared with that in the single-pressure evaporation cycle. Moreover, compared to the single-pressure evaporation cycle, the dual-pressure evaporation cycle significantly increases the working fluid mass flow rate for heat sources without outlet temperature limit; while, it will reduce the working fluid mass flow rate for heat sources with outlet temperature limit.

4. Conclusions
The thermodynamic performance between single-pressure and dual-pressure evaporation ORCs was compared for heat sources with outlet temperature limit, based on five organic fluids. Effects of the heat source outlet temperature limit on the characteristics of dual-pressure evaporation ORC system were also discussed. Main conclusions are below:
For heat sources with outlet temperature limit, the dual-pressure evaporation cycle can significantly increase the net power output by increasing system efficiency, and is also beneficial to reduce the charge volume of organic fluid in the system, compared to the single-pressure evaporation cycle.
The \((W_{\text{net_dual}} - W_{\text{net_single}})/W_{\text{net_single}}\) can be 4.9%, 8.3%, 10.8%, 12.8%, and 14.0% at most for R227ea, R1234ze(E), R600a, R245fa, and R601a, respectively. While, compared to heat sources without outlet temperature limit, the increment in net power output of dual-pressure evaporation cycle is remarkably lower for heat sources with outlet temperature limit.

5. References
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