Conventional and advanced exergy analyses of an organic Rankine cycle by using the thermodynamic cycle approach

Yi Wang1,2 | Guoliang Qin1 | Yong Zhang2 | Shuhua Yang2 | Changsheng Liu2 | Cheng Jia1 | Qin Cui1

Abstract
In this study, a basic organic Rankine cycle (ORC) is introduced in an air separation process for waste heat recovery. Conventional and advanced exergy analyses are adopted to investigate the thermodynamic properties of components in the ORC. A comprehensive thermodynamic model is constructed to improve the advanced exergy analysis in the ORC, thereby encompassing real, theoretical, unavoidable, and hybrid cycles. Nine organic working fluids are introduced to investigate the influence on the ORC performance. (1) The conventional exergy analysis reveals the following: (a) The expander constantly demonstrates the maximum exergy efficiency except when R227ea is used. (b) The evaporator constantly exhibits the maximum exergy destruction regardless of the working fluid used. (c) The maximum product exergy is obtained when R114 is used. (d) Key components must focus on the condenser and evaporator to improve the ORC performance. (2) The advanced exergy analysis reveals that the expander demonstrates maximum potential for improvement because its endogenous avoidable exergy destruction accounts for approximately 90% of its real exergy destruction for all working fluids. The expander must be improved to achieve the optimal ORC performance. The advanced exergy analysis can distinguish the source of exergy destruction and the magnitude for possible improvement via the proposed thermodynamic model in this study. The comprehensive thermodynamic model can promote the investigation of the advanced exergy analysis in the ORC. Applying conventional and advanced exergy analyses to investigate the thermodynamic performance of a system or its components is highly recommended.

KEYWORDS
advanced exergy analysis, multiple working fluids, organic Rankine cycle, performance improvement
1 | INTRODUCTION

Exergy, a quantity that can appropriately evaluate the quality or usefulness of energy in accordance with the basic concept of the second law of thermodynamics, can be categorized into physical, kinetic, potential, and chemical exergies. Exergy represents the maximum useful work. The exergy destruction and efficiency of a system or components within the system can be calculated using the conventional exergy analysis method.

Exergy destruction can be due to many factors, including chemical reactions, heat transfer under a finite temperature difference, mixing of substances with different compositions or states, and unlimited expansion and friction. The exergy destruction of a system or components inevitably occurs due to physical and economic constraints under a certain given state of technical development, whereas the remaining exergy destruction can be avoided. The avoidable exergy destruction is indistinguishable from the unavoidable exergy destruction when the conventional exergy analysis method is applied. Additionally, the conventional exergy analysis method fails to identify the specific source of exergy destruction, such as whether the exergy destruction is generated by the thermodynamic inefficiency of a certain component or indirectly induced by other components in the system. Therefore, an “advanced exergy analysis method” is proposed to investigate such detailed information.

Many researchers explored organic Rankine cycles (ORCs) by using the conventional exergy analysis. Jiang et al. performed a thermodynamic study on the overall performance of a small-scale pumpless ORC system and compared the output work and the exergy efficiency at different hot water temperatures. Navongxay and Chaiyat calculated the enhancement efficiency of ORC coupling with an absorption system and evaluated enhancement effects from energy efficiency, exergy efficiency, and cost. Sun et al. compared the efficiency of single-stage, two-stage parallel, and two-stage cascade ORCs. Sun et al. investigated the net output power, cooling capacity, and exergy efficiency of ORCs combined with absorption and ejector refrigeration cycles. Alsagri et al. proposed an ORC combined with a subcooled compressed air energy storage system to enhance electricity efficiency. These studies changed the configuration in ORC and examined thermodynamic performance but ignored working fluids.

Other researchers explored ORCs with various working fluids. Lin et al. selected multiple pure working fluids and zeotropic mixtures to investigate their effect on the ORC performance. Uusitalo et al. explored the critical temperature of different organic fluids at subcritical ORC. Wang et al. presented the carbon footprint model of ORC by using zeotropic mixture in life cycle perspective and selected R134a/R290, R134a/R600, R134a/R600a, R245fa/R600a, R245fa/R290, R227ea/R600a, and R227ea/R290 as working fluids. Seyedkavossi et al. applied the conventional exergy analysis to calculate the thermodynamic performance of a two-step parallel ORC for waste heat recovery in an internal combustion engine. Researchers used R123, R134a, and water as working fluids and showed that R123 demonstrates the best performance by comparing the net output and exergy efficiency when different working fluids are utilized. Yang et al. adopted ORC to obtain the waste heat produced by the heat pump assisted reactive dividing wall column. Five working fluids are selected, and an improved multi-objective genetic algorithm is used to optimize the ORC system. Feng et al. constructed four thermodynamic models on the basis of different evaporating bubble or condensing dew point temperatures of mixed liquid to examine the thermo-economic comparison of pure and mixed working fluids and the exergy efficiency and homogenization energy cost of the ORC. Yuan et al. analyzed the Fischer-Tropsch syngas production by using the advanced exergy analysis and optimal schema with dual-pressure ORC system, which is designed for further energy recovery based on the theoretical exergy analysis. Three organic working fluid are used for comparing the energy saving of ORCs. Yuan et al. addressed the components with remarkable energy-saving potential in a superstructure triple-column extractive distillation via avoidable exergy analysis and proposed a superstructure triple-column extractive distillation with four-parallel evaporator ORC system by using four working fluids. However, studies on the advanced exergy analysis of the ORC performance with multiple working fluids are limited.

Ambriz–Díaz et al. adopted the advanced exergy analysis on a polygeneration plant with an ORC, an absorption chiller, and a dehydrator as components but failed to perform the advanced analysis on the ORC in detail. Nami et al. conducted conventional and advanced exergy analyses on geothermal-driven dual-fluid ORC. Khosravi et al. discussed the ORC from the perspectives of conventional exergy, advanced exergy, and exergoeconomic analyses. However, both studies failed to construct thermodynamic cycle diagrams during the advanced exergy analysis of ORC.

Chen et al. showed a T–S diagram of ORC at real and unavoidable cycles but neglected hybrid cycles related to endogenous/exogenous exergy destructions. Dai et al. discussed avoidable/unavoidable and endogenous/exogenous exergy destructions, but only real, ideal, and unavoidable cycles are shown in the T–S diagram. Galindo et al. indicated hybrid cycles but still displayed a T–S diagram only containing real, ideal, and unavoidable cycles.
The process of building hybrid cycles has been rarely discussed, requiring further investigations.

The neglected, incomplete, or misleading information on how to use the advanced exergy analysis in the ORC inhibits the promotion of the advanced exergy analysis method in the ORC. Therefore, a comprehensive thermodynamic model is constructed, thereby encompassing real, theoretical, unavoidable, and hybrid cycles. The creation of all thermodynamic cycles of the model applied to the advanced analysis method is described in the following section. Moreover, the thermodynamic analysis of the ORC performance under various organic working fluids is conducted using conventional and advanced exergy analyses for the first time in this study.

The rest of this paper is organized as follows. The ORC system conditions, basic assumptions, and the selection of working fluids are introduced in Section 2. Nine organic working fluids are introduced to analyze the influence of the working medium property on the component performance. Conventional and advanced exergy analyses, which encompass construction processes of all thermodynamic cycles, are described in Section 3. The performance of each component and the overall ORC system when nine working fluids are used are discussed thoroughly in Section 4. Lastly, the main conclusions are summarized in Section 5.

2 | SYSTEM DESCRIPTION

2.1 | General description of an ORC

A simplified schematic of a basic ORC is shown in Figure 1. The four major sections in a basic ORC are evaporator, expander, condenser, and pump. The organic working fluid obtains energy from the waste heat source through the evaporator and then becomes saturated steam at high temperature and pressure. The basic ORC diagram is shown in Figure 2. The heat absorption process in the evaporator is divided into two stages, namely preheat process (line 4-5) and evaporation stage (line 5-1). The saturated organic working fluid in the expander drives the generator for power output denoted in line 1-2. The organic working fluid in the hypersaturated stage flows into the condenser after expansion, cools from the hypersaturated steam to the saturated steam at low temperature and pressure (line 2-2j), and is turned into saturated liquid by cooling water (line 2j-3). The organic working fluid is then pressurized by a pump from low pressure to high pressure (line 3-4) and flows into the evaporator.

The ORC is combined with an air separation unit to recover the heat of the air at the outlet of the compressor in this study. A multi-stage compression with interstage cooling is usually used when compressing air in the air separation unit to reduce the power consumption of the compressor. The temperature and pressure of air increase after being compressed by the compressor. The temperature of air at the compressor outlet is about 393 K. The air is cooled in the heat exchanger for further compression. The ORC is introduced to replace the heat exchanger and recover the low-grade heat energy of the air at the outlet of the compressor. The air flows into the evaporator at 373.15 K with a mass flow of 30.52 kg/s, and the cooling water flows into the condenser at 293.15 K and discharges at 303.15 K. The air temperature at the outlet of the evaporator is assumed to be 333.15 K. The mass flow of the cooling water varies with the cooling capacity of the condenser in the ORC.

The environmental temperature and pressure are 293.15 K and 101.325 kPa, respectively. The NIST software is used to calculate all thermodynamic properties of all media in the ORC, as shown in Tables 1-4.
TABLE 1  Thermodynamic data for air and water

| Stream | Medium | T (K)  | p (kPa) | h (kJ/kg) | s (kJ/[kg K]) | e (kJ/kg) |
|--------|--------|--------|---------|-----------|---------------|-----------|
| 6      | Air    | 373.15 | 300     | 373.82    | 6.77          | 100.68    |
| 8      | Air    | 333.15 | 300     | 318.19    | 6.61          | 92.32     |
| 0      | Air    | 293.15 | 101.33  | 293.41    | 6.84          | 0.00      |
| 9      | Water  | 293.15 | 300     | 84.19     | 0.30          | 0.20      |
| 11     | Water  | 303.15 | 300     | 126.00    | 0.44          | 0.90      |
| 0      | Water  | 293.15 | 101.33  | 84.01     | 0.30          | 0.00      |

TABLE 2  Thermodynamic data for real cycles

| Working fluid | Stream | T(K)  | p(kPa) | h(kJ/kg) | s(kJ/[kg K]) | e(kJ/kg) | \( \dot{m}_{wf}(kg/s) \) |
|---------------|--------|--------|--------|-----------|---------------|-----------|-------------------------|
| Butane        | 1R     | 335.38 | 673.76 | 673.24    | 2.46          | 76.73     | 3.18                    |
|               | 2R     | 316.14 | 327.79 | 650.19    | 2.48          | 47.72     |                         |
|               | 2JR    | 308.09 | 327.79 | 635.08    | 2.43          | 46.80     |                         |
|               | 3R     | 308.09 | 327.79 | 284.06    | 1.29          | 29.78     |                         |
|               | 4R     | 308.28 | 673.76 | 284.74    | 1.29          | 30.40     |                         |
|               | 5R     | 335.38 | 673.76 | 354.90    | 1.51          | 36.64     |                         |
|               | 0      | 293.15 | 101.33 | 618.92    | 2.53          | 0.00      |                         |
| Isobutane     | 1R     | 336.50 | 938.34 | 637.69    | 2.34          | 88.23     | 3.49                    |
|               | 2R     | 316.23 | 461.87 | 616.54    | 2.37          | 60.79     |                         |
|               | 2JR    | 307.92 | 461.87 | 600.90    | 2.32          | 59.84     |                         |
|               | 3R     | 307.92 | 461.87 | 283.10    | 1.28          | 44.60     |                         |
|               | 4R     | 308.20 | 938.34 | 284.01    | 1.28          | 45.48     |                         |
|               | 5R     | 336.50 | 938.34 | 357.77    | 1.51          | 52.17     |                         |
|               | 0      | 293.15 | 101.33 | 589.62    | 2.48          | 0.00      |                         |
| R114          | 1R     | 336.50 | 630.05 | 374.83    | 1.54          | 25.61     | 8.81                    |
|               | 2R     | 318.73 | 291.29 | 366.29    | 1.55          | 14.93     |                         |
|               | 2JR    | 308.04 | 291.29 | 358.40    | 1.52          | 14.42     |                         |
|               | 3R     | 308.04 | 291.29 | 234.29    | 1.12          | 8.42      |                         |
|               | 4R     | 308.22 | 630.05 | 234.54    | 1.12          | 8.66      |                         |
|               | 5R     | 336.50 | 630.05 | 263.80    | 1.21          | 11.30     |                         |
|               | 0      | 293.15 | 101.33 | 350.65    | 1.54          | 0.00      |                         |
| R123          | 1R     | 334.12 | 293.92 | 417.97    | 1.67          | 21.92     | 6.77                    |
|               | 2R     | 314.60 | 130.39 | 407.16    | 1.68          | 8.79      |                         |
|               | 2JR    | 308.12 | 130.39 | 402.52    | 1.66          | 8.52      |                         |
|               | 3R     | 308.12 | 130.39 | 235.38    | 1.12          | 0.40      |                         |
|               | 4R     | 308.19 | 293.92 | 235.50    | 1.12          | 0.51      |                         |
|               | 5R     | 334.12 | 293.92 | 262.70    | 1.21          | 2.88      |                         |
|               | 0      | 293.15 | 101.33 | 220.06    | 1.07          | 0.00      |                         |
| R227ea        | 1R     | 342.47 | 1464.41| 364.47    | 1.51          | 35.09     | 9.99                    |
|               | 2R     | 319.59 | 602.66 | 357.18    | 1.52          | 24.33     |                         |
|               | 2JR    | 307.68 | 602.66 | 346.08    | 1.48          | 23.61     |                         |
|               | 3R     | 307.68 | 602.66 | 240.10    | 1.14          | 18.61     |                         |
|               | 4R     | 308.26 | 1464.41| 240.77    | 1.14          | 19.25     |                         |
|               | 5R     | 342.47 | 1464.41| 285.02    | 1.27          | 23.65     |                         |
|               | 0      | 293.15 | 101.33 | 342.26    | 1.55          | 0.00      |                         |

(Continues)
The following are assumed for all thermodynamic cycles:

1. The ORC process is in the steady state.
2. Pressure losses in the pipelines and equipment as well as the heat loss from the ORC to the environment are neglected.
3. The states of the organic working fluid at the outlet of the evaporator and condenser are saturated steam and liquid, respectively.
4. The isentropic efficiencies of the expander and pump are constant.

### Organic medium

Various organic working fluids are used to eliminate the influence of the medium property on the thermodynamic performance of components in the ORC. The working fluid of the ORC must meet the following requirements:26,27

1. The working fluid demonstrates excellent flow, heat transfer, and thermal performance, such as standard boiling point, critical temperature, and critical pressure, which should be within a reasonable range.
2. The working fluid exhibits certain safety performance, such as nontoxicity or low toxicity, noncorrosion or low corrosion, and nonflammable and nonexplosive properties.
3. The working fluid shows environmentally friendly properties, including nondestructive characteristics to the ozone layer and minimal effect on the greenhouse effect, that is, low potential for ozone depletion and global warming.
4. The working fluid is reasonably priced and easy to buy and obtain.
| Working fluid | Stream | $T$(K) | $p$(kPa) | $h$(kJ/kg) | $s$(kJ/[kg K]) | $e$(kJ/kg) | $\dot{m}_{wf}$(kg/s) |
|--------------|--------|--------|-----------|-------------|----------------|-------------|-------------------|
| Butane       | 1T     | 343.26 | 811.13    | 683.92      | 2.46           | 84.69       | 3.00              |
|              | 2T     | 309.95 | 282.65    | 640.62      | 2.46           | 41.40       |                   |
|              | 2jT    | 303.06 | 282.65    | 627.93      | 2.42           | 40.84       |                   |
|              | 3T     | 303.06 | 282.65    | 271.54      | 1.25           | 29.19       |                   |
|              | 4T     | 303.30 | 811.13    | 272.47      | 1.25           | 30.12       |                   |
|              | 5T     | 343.26 | 811.13    | 376.37      | 1.57           | 39.79       |                   |
|              | 0      | 293.15 | 101.33    | 618.92      | 2.53           | 0.00        |                   |
| Isobutane    | 1T     | 344.69 | 1124.44   | 647.60      | 2.35           | 95.60       | 3.29              |
|              | 2T     | 309.94 | 403.58    | 607.13      | 2.35           | 55.12       |                   |
|              | 2jT    | 303.05 | 403.58    | 594.44      | 2.31           | 54.57       |                   |
|              | 3T     | 303.05 | 403.58    | 270.99      | 1.24           | 44.01       |                   |
|              | 4T     | 303.44 | 1124.44   | 272.33      | 1.24           | 45.33       |                   |
|              | 5T     | 344.69 | 1124.44   | 380.50      | 1.58           | 55.66       |                   |
|              | 0      | 293.15 | 101.33    | 589.62      | 2.48           | 0.00        |                   |
| R114         | 1T     | 344.68 | 766.88    | 379.26      | 1.54           | 28.56       | 8.25              |
|              | 2T     | 313.90 | 249.03    | 363.33      | 1.54           | 12.64       |                   |
|              | 2jT    | 302.89 | 249.03    | 355.31      | 1.52           | 12.24       |                   |
|              | 3T     | 302.89 | 249.03    | 229.11      | 1.10           | 8.18        |                   |
|              | 4T     | 303.13 | 766.88    | 229.47      | 1.10           | 8.54        |                   |
|              | 5T     | 344.68 | 766.88    | 272.61      | 1.23           | 12.62       |                   |
|              | 0      | 293.15 | 101.33    | 350.65      | 1.54           | 0.00        |                   |
| R123         | 1T     | 341.58 | 361.59    | 422.30      | 1.67           | 25.47       | 6.43              |
|              | 2T     | 307.54 | 109.07    | 402.64      | 1.67           | 5.81        |                   |
|              | 2jT    | 303.02 | 109.07    | 399.45      | 1.66           | 5.69        |                   |
|              | 3T     | 303.02 | 109.07    | 230.12      | 1.10           | 0.17        |                   |
|              | 4T     | 303.11 | 361.59    | 230.30      | 1.10           | 0.34        |                   |
|              | 5T     | 341.58 | 361.59    | 270.73      | 1.23           | 3.98        |                   |
|              | 0      | 293.15 | 101.33    | 220.06      | 1.07           | 0.00        |                   |
| R227ea       | 1T     | 352.56 | 1834.58   | 368.09      | 1.51           | 37.75       | 9.28              |
|              | 2T     | 313.07 | 521.14    | 352.53      | 1.51           | 22.20       |                   |
|              | 2jT    | 302.68 | 521.14    | 343.07      | 1.48           | 21.74       |                   |
|              | 3T     | 302.68 | 521.14    | 234.07      | 1.12           | 18.31       |                   |
|              | 4T     | 303.46 | 1834.58   | 235.03      | 1.12           | 19.27       |                   |
|              | 5T     | 352.56 | 1834.58   | 299.55      | 1.31           | 26.20       |                   |
|              | 0      | 293.15 | 101.33    | 342.26      | 1.55           | 0.00        |                   |
| R236ea       | 1T     | 345.37 | 828.88    | 419.23      | 1.67           | 33.17       | 6.79              |
|              | 2T     | 313.83 | 243.39    | 399.89      | 1.67           | 13.82       |                   |
|              | 2jT    | 303.03 | 243.39    | 389.95      | 1.63           | 13.33       |                   |
|              | 3T     | 303.03 | 243.39    | 236.98      | 1.13           | 8.34        |                   |
|              | 4T     | 303.26 | 828.88    | 237.40      | 1.13           | 8.76        |                   |
|              | 5T     | 345.37 | 828.88    | 292.90      | 1.30           | 14.07       |                   |
|              | 0      | 293.15 | 101.33    | 384.55      | 1.66           | 0.00        |                   |

(Continues)
Organic working fluids can be sorted into dry, isentropic, and wet fluids in accordance with the slope of their saturated steam curves, as shown in Figure 3. The $\frac{dT}{dS}$ values of the saturated steam curve of dry, isentropic, and wet fluids are higher than 0, close to infinite and less than 0, respectively (Figure 3).

The wet fluid from the expander is clearly in the two-phase state region, where droplets existing within are harmful for expander blades. The working fluid state at the expander outlet is steam without droplet formation when the dry fluid or isentropic fluid flows. Therefore, the working fluids selected in this study are dry or isentropic fluids, namely R227ea, R236fa, R236ea, R245ca, R245fa, R123, R114, isobutene, and butane.

### TABLE 3 (Continued)

| Working fluid | Stream | $T$(K) | $p$(kPa) | $h$(kJ/kg) | $s$(kJ/[kg K]) | $e$(kJ/kg) | $\dot{m}_{wf}$(kg/s) |
|---------------|--------|--------|----------|-----------|---------------|-----------|-------------------|
| R236fa        | 1T     | 347.04 | 1081.81  | 407.53    | 1.63          | 36.28     | 7.27              |
|               | 2T     | 312.74 | 318.13   | 388.94    | 1.63          | 17.69     |                   |
|               | 2J     | 302.87 | 318.13   | 380.04    | 1.60          | 17.27     |                   |
|               | 3T     | 302.87 | 318.13   | 236.92    | 1.13          | 12.68     |                   |
|               | 4T     | 303.22 | 1081.81  | 237.49    | 1.13          | 13.24     |                   |
|               | 5T     | 347.04 | 1081.81  | 296.49    | 1.31          | 19.04     |                   |
|               | 0      | 293.15 | 101.33   | 376.19    | 1.65          | 0.00      |                   |
| R245ca        | 1T     | 342.78 | 431.39   | 468.88    | 1.82          | 30.76     | 5.38              |
|               | 2T     | 311.00 | 121.08   | 445.16    | 1.82          | 7.04      |                   |
|               | 2J     | 303.02 | 121.08   | 437.55    | 1.79          | 6.69      |                   |
|               | 3T     | 303.02 | 121.08   | 239.17    | 1.14          | 0.23      |                   |
|               | 4T     | 303.11 | 431.39   | 239.39    | 1.14          | 0.46      |                   |
|               | 5T     | 342.78 | 431.39   | 294.59    | 1.31          | 5.52      |                   |
|               | 0      | 293.15 | 101.33   | 226.01    | 1.09          | 0.00      |                   |
| R245fa        | 1T     | 343.51 | 615.47   | 455.24    | 1.77          | 32.56     | 5.72              |
|               | 2T     | 309.46 | 176.71   | 432.59    | 1.77          | 9.91      |                   |
|               | 2J     | 302.98 | 176.71   | 426.31    | 1.75          | 9.64      |                   |
|               | 3T     | 302.98 | 176.71   | 238.88    | 1.13          | 3.56      |                   |
|               | 4T     | 303.14 | 615.47   | 239.21    | 1.13          | 3.89      |                   |
|               | 5T     | 343.51 | 615.47   | 295.11    | 1.31          | 9.09      |                   |
|               | 0      | 293.15 | 101.33   | 420.02    | 1.76          | 0.00      |                   |

3 | ANALYSIS METHODS

3.1 | Conventional exergy analysis

Chemical change processes are excluded from this study. Hence, chemical exergy is ignored. Kinetic and potential exergies are also ignored. Only physical exergy is discussed. The conventional exergy analysis method constructs an exergy equilibrium equation for the entire system or a specific component in the system. An exergy equilibrium equation for the $k$-th component in the system is established as follows:

$$\dot{E}_{F,k} = \dot{E}_{P,k} + \dot{E}_{D,k},$$

(1)

where $\dot{E}_{F,k}$ is the fuel exergy, which is the exergy input into the $k$-th component; $\dot{E}_{P,k}$ is the product exergy, which is the exergy obtained from the $k$-th component, and $\dot{E}_{D,k}$ is the exergy destruction of the $k$-th component. The exergy destruction of the $k$-th component is also referred to as the availability destruction or the lost work. The exergy destruction of the $k$-th component is the basic for advanced exergy analysis.

An exergy equilibrium equation for the system is established as follows:

$$\dot{E}_{F,\text{tot}} = \dot{E}_{P,\text{tot}} + \dot{E}_{D,\text{tot}},$$

(2)

where $\dot{E}_{F,\text{tot}}$, $\dot{E}_{P,\text{tot}}$, and $\dot{E}_{D,\text{tot}}$ represent the fuel exergy, product exergy, and exergy destruction of the overall system, respectively. The exergy balance of a system is proposed to investigate the performance of the system by calculating the value of product exergy and exergy destruction when the fuel exergy is constant.
| Working fluid | Stream | \( T \) (K) | \( p \) (kPa) | \( h \) (kJ/kg) | \( s \) (kJ/[kg K]) | \( e \) (kJ/kg) | \( \dot{m}_{wf} \) (kg/s) |
|--------------|--------|------------|-------------|-------------|-------------|-------------|----------------|
| Butane       | 1UN    | 342.53     | 797.60      | 682.94      | 2.46        | 83.96       | 3.02           |
|              | 2UN    | 311.71     | 285.46      | 643.76      | 2.47        | 41.96       |                |
|              | 2JUN   | 303.39     | 285.46      | 628.40      | 2.42        | 41.24       |                |
|              | 3UN    | 303.39     | 285.46      | 272.36      | 1.25        | 29.22       |                |
|              | 4UN    | 303.62     | 797.60      | 273.26      | 1.25        | 30.13       |                |
|              | 5UN    | 342.53     | 797.60      | 374.36      | 1.56        | 39.48       |                |
|              | 0      | 293.15     | 101.33      | 618.92      | 2.53        | 0.00        |                |
| Isobutane    | 1UN    | 343.95     | 1106.59     | 646.72      | 2.35        | 94.95       | 3.30           |
|              | 2UN    | 311.72     | 406.43      | 610.30      | 2.36        | 55.57       |                |
|              | 2JUN   | 303.30     | 406.43      | 594.77      | 2.31        | 54.85       |                |
|              | 3UN    | 303.30     | 406.43      | 271.61      | 1.25        | 44.03       |                |
|              | 4UN    | 303.68     | 1106.59     | 272.91      | 1.25        | 45.32       |                |
|              | 5UN    | 343.95     | 1106.59     | 378.41      | 1.57        | 55.32       |                |
|              | 0      | 293.15     | 101.33      | 589.62      | 2.48        | 0.00        |                |
| R114         | 1UN    | 343.88     | 752.61      | 378.83      | 1.54        | 28.28       | 8.30           |
|              | 2UN    | 315.58     | 253.15      | 364.51      | 1.55        | 12.93       |                |
|              | 2JUN   | 303.42     | 253.15      | 355.63      | 1.52        | 12.47       |                |
|              | 3UN    | 303.42     | 253.15      | 229.64      | 1.10        | 8.20        |                |
|              | 4UN    | 303.65     | 752.61      | 229.99      | 1.10        | 8.55        |                |
|              | 5UN    | 343.88     | 752.61      | 271.74      | 1.23        | 12.48       |                |
|              | 0      | 293.15     | 101.33      | 350.65      | 1.54        | 0.00        |                |
| R123         | 1UN    | 340.83     | 354.30      | 421.87      | 1.67        | 25.12       | 6.47           |
|              | 2UN    | 309.62     | 111.39      | 404.06      | 1.68        | 6.20        |                |
|              | 2JUN   | 303.61     | 111.39      | 399.80      | 1.66        | 6.02        |                |
|              | 3UN    | 303.61     | 111.39      | 230.73      | 1.11        | 0.19        |                |
|              | 4UN    | 303.70     | 354.30      | 230.90      | 1.11        | 0.36        |                |
|              | 5UN    | 340.83     | 354.30      | 269.91      | 1.23        | 3.86        |                |
|              | 0      | 293.15     | 101.33      | 220.06      | 1.07        | 0.00        |                |
| R227ea       | 1UN    | 351.44     | 1790.26     | 367.76      | 1.51        | 37.48       | 9.38           |
|              | 2UN    | 315.51     | 534.53      | 354.53      | 1.51        | 22.65       |                |
|              | 2JUN   | 303.54     | 534.53      | 343.59      | 1.48        | 22.07       |                |
|              | 3UN    | 303.54     | 534.53      | 235.10      | 1.12        | 18.36       |                |
|              | 4UN    | 304.33     | 1790.26     | 236.06      | 1.12        | 19.27       |                |
|              | 5UN    | 351.44     | 1790.26     | 297.89      | 1.31        | 23.89       |                |
|              | 0      | 293.15     | 101.33      | 342.26      | 1.55        | 0.00        |                |
| R236ea       | 1UN    | 344.59     | 812.84      | 418.73      | 1.66        | 32.84       | 6.83           |
|              | 2UN    | 315.46     | 246.68      | 401.33      | 1.67        | 14.12       |                |
|              | 2JUN   | 303.43     | 246.68      | 390.24      | 1.63        | 13.53       |                |
|              | 3UN    | 303.43     | 246.68      | 237.49      | 1.13        | 8.36        |                |
|              | 4UN    | 303.66     | 812.84      | 237.89      | 1.13        | 8.76        |                |
|              | 5UN    | 344.59     | 812.84      | 291.82      | 1.30        | 13.90       |                |
|              | 0      | 293.15     | 101.33      | 384.55      | 1.66        | 0.00        |                |
The exergy efficiency of the $k$-th component is calculated as follows:\(^2\):

$$
\varepsilon_k = \frac{\dot{E}_{F,k}}{\dot{E}_{F,k}}. \tag{3}
$$

The exergy destruction rate of the $k$-th component is expressed as follows:\(^1\):

$$
y_k = \frac{\dot{E}_{D,k}}{\dot{E}_{F,k}}, \tag{4}
$$

$$
y_k^* = \frac{\dot{E}_{D,k}}{\dot{E}_{D,\text{tot}}} \tag{5}
$$

$\varepsilon_k$, $y_k$, and $y_k^*$ are used to assess the thermodynamic performance of the $k$-th component. The ORC in this study contains four parts. The exergy calculation of each part is presented in Table 5.

### 3.2 Advanced exergy analysis

An advantage of the advanced exergy analysis method is that the exergy destruction can be divided in accordance with the first- and second-level splitting methods.

The first-level splitting can distinguish the avoidable part from the unavoidable part as follows:\(^2\):

$$
\dot{E}_{D,k} = \dot{E}_{D,k}^{AV} + \dot{E}_{D,k}^{UN}. \tag{6}
$$


This splitting method is derived from a thermoeconomics perspective. According to the basic laws of thermoeconomics, the exergy destruction rate is inversely proportional to the investment cost. The exergy destruction rate of the component decreases when the investment cost of the component increases. Therefore, the fuel exergy input to ORCs is constantly at 208.88 kW despite the difference in constructed cycles. The real cycle, denoted as 1R-2R-3R-4R-5R in Figure 5, are as follows:

\[ W_{PM} = (E_k - E_{1}) \]

The advanced exergy analysis method has led to many calculation approaches, such as thermodynamic cycle, process, and engineering approaches. Among them, the thermodynamic cycle approach is the most widely used method. The process of thermodynamic cycles constructed in this work is explicitly stated because of its remarkable difference from those stated in previous studies.23-25

The process parameters of the heat source air in the evaporator of all cycles are the same in this study. Therefore, the fuel exergy input to ORCs is constantly at 208.88 kW despite the difference in constructed cycles.

### Real cycle

A real cycle, denoted as 1R-2R-3R-4R-5R in Figure 5, must be constructed first for the ORC to divide the exergy destruction of each component into different parts. The assumptions of operation conditions for the real cycle are as follows:\[ \eta_{EX}^R = 0.85, \eta_{PM}^R = 0.8, \Delta T_{EV}^K = 5 K, \text{ and } \Delta T_{CD}^R = 5 K. \] The real exergy destruction of each component is obtained by calculating the real cycle. The results collected during this process are used as basic data in this study. Other subsequent cycles are constructed to divide the exergy destruction obtained in the real cycle.

### Theoretical cycle

A theoretical cycle must be constructed for the first- and second-level splitting methods when using the thermodynamic cycle approach. Each component must follow certain basic assumptions that meet the following conditions: #TABLE 5 Exergy calculation for components of the ORC

| Component | \( \dot{E}_{p,k} \) | \( \dot{E}_{p,k} \) | \( \dot{E}_{D,k} \) |
|-----------|-----------------|-----------------|-----------------|
| EV        | \( E_k - E_1 - E_2 \) | \( (E_k - E_1) - (E_1 - E_2) \) | \( (E_k - E_1) - (E_1 - E_2) \) |
| EX        | \( E_k - E_1 - E_2 \) | \( (E_k - E_1) - (E_1 - E_2) \) | \( (E_k - E_1) - (E_1 - E_2) \) |
| CD        | \( E_k - E_1 \) | \( (E_k - E_1) - (E_1 - E_2) \) | \( (E_k - E_1) - (E_1 - E_2) \) |
| PM        | \( E_k - E_1 \) | \( (E_k - E_1) - (E_1 - E_2) \) | \( (E_k - E_1) - (E_1 - E_2) \) |
The exergy destruction of components is equal to zero ($\dot{E}_{D,\delta} = 0$) or the minimum ($\dot{E}_{D,\delta} = \text{min}$).

The expansion process of the expander is assumed to be isentropic ($\eta_{EX} = 1, \dot{E}_{D,EX} = 0$) when constructing the theoretical cycle. Similarly, the compression process of the pump is assumed to be isentropic ($\eta_{PM} = 1, \dot{E}_{D,PM} = 0$). The minimum temperature difference between two fluids in the evaporator and condenser is assumed to be zero ($\Delta T_{min} = 0$). At this time, the exergy destruction in the evaporator and condenser is minimal. The theoretical cycle denoted as 1T-2T-3T-4T-5T in Figure 5 is based on these assumptions. The thermodynamic data of theoretical ORCs are presented in Table 3.

### 3.3.3 Unavoidable cycle

An unavoidable cycle must be constructed to divide the exergy destruction into unavoidable and avoidable parts. Accordingly, unavoidable temperature differences between two fluids in the evaporator and condenser due to irreversibility are assumed to be $\Delta T_{UN}^{EV} = 0.5$ K and $\Delta T_{UN}^{CD} = 0.5$ K, respectively. Isentropic efficiencies in the expander and pump are $\eta_{EX}^{UN} = 0.95$ and $\eta_{PM}^{UN} = 0.95$, respectively, due to irreversibility. These values indicate the optimal performance of the equipment regardless the amount of investment. Given technical limitations, the minimum temperature difference between two fluids is assumed to be 0.5 K in the evaporator and condenser even if the optimal material and manufacturing method are adopted. The same consideration is given to the expander and pump, and the isotropic efficiencies of these two devices are assumed to be 0.95 due to technical limitations. The thermodynamic cycle formed on the basis of these
assumptions is denoted as 1UN-2UN-3UN-4UN-5UN in Figure 5. The thermodynamic data of unavoidable ORCs are presented in Table 4. The exergy destruction value of the \( k \)-th component evaluated by this cycle is its unavoidable exergy destruction. The avoidable exergy destruction value of the \( k \)-th component can be calculated with this value along with the exergy destruction value evaluated by real cycles.

3.3.4 Hybrid cycles with endogenous exergy destruction

Hybrid cycles must be constructed to distinguish the endogenous exergy destruction from the exogenous exergy destruction. Accordingly, only the \( k \)-th component is assumed to be operating in the real state, and other components are running in the ideal state. A corresponding hybrid cycle must be built for each component when multiple components exist in the system as follows (Figure 6).

1. Cycle for the evaporator: 1R-2H**-3T-4H*-5R

Only the evaporator is assumed to be operating in a real state, and other components are running in an ideal state in the cycle. For the evaporator running in a real state, the state of the organic working fluid at the outlet of the evaporator is 1R. Then, the organic working fluid expands isentropically in the expander as line 1R-2H**. The point 2H** is located on line 2T-2jT. The thermodynamic state of the organic working fluid in the condenser is line 2H**-2jT-3T in Figure 6 because the working fluid is cooled from the hypersaturated steam to the saturated steam to the saturated liquid when the condenser is running in an ideal state. The organic working fluid is compressed isentropically in the pump. The state of the working fluid at the pump outlet is the same as that of the evaporator inlet. The reverse extension line of line 4R-5R is drawn and intersects with line 3T-4T at 4H* by considering the evaporator operating in a real state. Now, the hybrid cycle for the evaporator running in a real state is built as 1R-2H**-3T-4H*-5R.

2. Cycle for the expander: 1T-2H-3T-4T-5T

The expander is operating in the real state, whereas other components are running in an ideal state in this hybrid cycle. The organic working fluid at the outlet of the evaporator is at 1T for the evaporator running in an ideal state. The organic working fluid expands with the real isentropic efficiency when the expander is working in a real state. The reverse extension line of line 2T-2jT is drawn and intersects with the expansion line at 2H to obtain the state point of the expander outlet. The organic working fluid flows into the condenser under an ideal state. The state line in the condenser is shown as 2H-2jT-3T. Then, the working fluid goes to the pump and is compressed isentropically. The progress of isentropic compression is described as 3T-4T. The working fluid then flows into the evaporator under an ideal state and exchanges the heat from 4T-5T-1T. As a result, the hybrid cycle for the expander running in a real state is shown as 1T-2H-3T-4T-5T in Figure 6.

3. Cycle for the condenser: 1T-2H*-3R-4H**-5T

When only the condenser is working in a real state, the evaporator, expander, and pump are all operating in an ideal state. The working fluid out of the evaporator is at 1T when the evaporator is running in the ideal state. Then, the working fluid expands isentropically in the expander. Given that the condenser is running in a real state, the organic working fluid cannot expand from 1T to 2T in the expander. The reverse extension line of line 2R-2jR is drawn and intersects with line 1T-2T at 2H* to find the state of working fluid at the expander outlet. Sometimes, the reverse extension line of line 2R-2jR is not needed because the intersection of lines 1T-2T and 2R-2jR may be located on line 2R-2jR. The location of 2H* is affected by the property of the organic working medium. The organic working fluid is cooled from the hypersaturated steam to the saturated steam to the saturated liquid by cooling water in the condenser as line 2H*-2jR-3R. The thermodynamic process of the organic working fluid is isentropic compression in the pump. The state of the working fluid at the pump outlet is the same as that at the evaporation inlet. The intersection of the isentropic compression line and line 4T-5T is denoted as 4H**. The hybrid cycle for
the condenser operating under a real state is shown as 1T-2H*-3R-4H**-5T.

4. Cycle for the pump: 1T-2T-3T-4H-5T

The cycle for only the pump under a real state is relatively easy when the evaporator, expander, and condenser are running ideally. The thermodynamic process of the organic working fluid in the expander and condenser is limited along lines 1T-2T and 2T-2jT-3T. The state of the working fluid at the pump outlet is needed to build the cycle. The compression line with the real isentropic efficiency is drawn and intersects with line 4T-5T at 4H. The hybrid cycle for only the pump running in a real state is shown as 1T-2T-3T-4H-5T.

The symbol * only represents that the number of some state points appears repeatedly in different hybrid cycles and has no physical meaning.

3.3.5 | Hybrid cycles with endogenous unavoidable exergy destruction

The method for calculating the endogenous exergy destruction in Section 3.3.4 is adopted to distinguish the endogenous avoidable exergy destruction from other exergy destructions further. The operating condition data of cycles with the unavoidable exergy destruction are used to construct hybrid cycles. The calculated exergy destruction is $\dot{E}_{D,k}^{UN,EN}$. Values of $\dot{E}_{D,k}^{UN,EX}$, $\dot{E}_{D,k}^{AV,EN}$, and $\dot{E}_{D,k}^{AV,EX}$ can be calculated in accordance with the method used in Morosuk and Tsatsaronis.3

4 | RESULTS AND DISCUSSION

Methods discussed in Sections 3.1 and 3.2 and various cycles constructed in Section 3.3 can be divided into conventional and advanced exergy analyses.

The real cycle 1R-2R-3R-4R-5R based on the assumption of real conditions is the basic cycle of this study. Data, such as the exergy destruction and efficiency calculated by the real cycle, are the foundation of the conventional exergy analysis.

The theoretical cycle is another basic cycle of this work. The calculation results of real and theoretical cycles are listed in Table 6. Values of the product exergy and the exergy destruction of the pump are small. Focusing on other components is more beneficial than concentrating on the pump. Therefore, data on the exergy analysis of the pump are excluded in subsequent discussions. Discussions are focused on the evaporator, expander and condenser.

4.1 | Conventional evaluation

The thermodynamic performance of the ORC and its components can be analyzed from the aspects of the product exergy, exergy destruction, and exergy efficiency in the conventional exergy analysis.

1. The fuel exergy of the ORC input from the air into the evaporator is independent of organic working fluids. However, the real product exergy of the ORC with multiple working fluids varies even if each equipment is assumed to demonstrate the same performance for different working fluids. The high value of the product exergy indicates the improved performance of the working fluid. Product exergy values are calculated to obtain the performance difference of working fluids. R114 demonstrates the best performance followed by R236fa, R236ea, isobutene, R245ca, R123, and butane, whereas R227ea and R245fa exhibits the worst performance. The difference between the highest and the lowest product exergy values is 2.44 kW.

2. The conventional exergy analysis examines the thermodynamic performance of a component by comparing the exergy efficiency of each component by using the following sorting schemes:

- Expander > evaporator > condenser for butane, isobutane, R114, R123, R236ea, R236fa, R245ca, and R245fa.
- Evaporator > expander > condenser for R227ea.

The exergy efficiencies of components for all working fluids are as follows: 67.84%-82.34% for the expander, 69.37%-75.75% for the evaporator, and 33.86%-34.38% for the condenser. Therefore, the condenser exergy efficiency is the lowest. The improvement of the condenser should be prioritized because the condenser exergy efficiency is remarkably lower than those of other components for all working fluids based on the conventional exergy analysis.

3. The value of the evaporator exergy destruction is constantly the maximum for all working fluids from 50.66 kW for R227ea to 63.97 kW for R123. Hence, focusing on the performance improvement of the evaporator is also necessary.

4.2 | Advanced evaluation

4.2.1 | First-level splitting into unavoidable and avoidable parts

The avoidable exergy destruction $\dot{E}_{D,k}^{AV}$ represents the reduced exergy destruction evaluated in the extreme assumption without economic cost because the corresponding unavoidable exergy destruction of the $k$-th
| Working fluid | Component | Real cycle | Theoretical cycle |
|--------------|-----------|------------|------------------|
|              | $\dot{E}_{PA}$ (kW) | $\dot{E}_{PA}$ (kW) | $\dot{E}_{PA}^r$ (kW) | $\varepsilon_4$ (%) | $\lambda_4$ (%) | $\lambda_4^r$ (%) |
| butane       | EV        | 208.88     | 147.33           | 61.55              | 70.53                | 29.47              | 52.02              | 45.04              |
|              | EX        | 92.26      | 73.29            | 18.96              | 79.44                | 20.56              | 16.03              | 0                  |
|              | CD        | 57.04      | 19.44            | 37.61              | 34.08                | 65.92              | 31.78              | 36.63              |
|              | PM        | 2.17       | 1.97             | 0.20               | 90.86                | 9.14               | 0.17               | 0                  |
|              | System    | 208.88     | 73.29            | 118.31             | 35.09                | 56.64              | 100.00             | 81.67              |
| Isobutane    | EV        | 208.88     | 149.30           | 59.57              | 71.48                | 28.52              | 50.17              | 43.39              |
|              | EX        | 95.84      | 73.85            | 21.99              | 77.06                | 22.94              | 18.52              | 0                  |
|              | CD        | 56.56      | 19.45            | 37.11              | 34.38                | 65.62              | 31.25              | 36.58              |
|              | PM        | 3.18       | 3.09             | 0.08               | 97.46                | 2.54               | 0.07               | 0                  |
|              | System    | 208.88     | 73.85            | 116.59             | 35.96                | 55.82              | 100.00             | 80.46              |
| R114         | EV        | 208.88     | 149.25           | 59.62              | 71.45                | 28.55              | 51.14              | 43.74              |
|              | EX        | 94.04      | 75.12            | 18.92              | 79.88                | 20.12              | 16.22              | 0                  |
|              | CD        | 57.32      | 19.41            | 37.91              | 33.86                | 66.14              | 32.51              | 36.72              |
|              | PM        | 2.24       | 2.10             | 0.14               | 93.67                | 6.33               | 0.12               | 0                  |
|              | System    | 208.88     | 75.12            | 116.59             | 35.96                | 55.82              | 100.00             | 80.46              |
| R123         | EV        | 208.88     | 144.90           | 63.97              | 69.37                | 30.63              | 54.63              | 47.20              |
|              | EX        | 88.86      | 73.17            | 15.69              | 82.34                | 17.66              | 13.40              | 0                  |
|              | CD        | 56.81      | 19.42            | 37.40              | 34.18                | 65.82              | 31.94              | 36.28              |
|              | PM        | 0.81       | 0.77             | 0.04               | 95.13                | 4.87               | 0.03               | 0                  |
|              | System    | 208.88     | 73.17            | 117.10             | 35.03                | 56.06              | 100.00             | 83.48              |
| R227ea       | EV        | 208.88     | 158.22           | 50.66              | 75.75                | 24.25              | 41.14              | 37.28              |
|              | EX        | 107.41     | 72.87            | 34.54              | 67.84                | 32.16              | 28.05              | 0                  |
|              | CD        | 57.20      | 19.52            | 37.68              | 34.13                | 65.87              | 30.60              | 17.69              |
|              | PM        | 6.66       | 6.39             | 0.26               | 96.04                | 3.96               | 0.21               | 0                  |
|              | System    | 208.88     | 72.87            | 123.14             | 34.89                | 58.95              | 100.00             | 54.97              |
| R236ea       | EV        | 208.88     | 150.21           | 58.67              | 71.91                | 28.09              | 50.11              | 43.01              |
|              | EX        | 94.86      | 74.47            | 20.39              | 78.51                | 21.49              | 17.41              | 0                  |
|              | CD        | 57.35      | 19.42            | 37.93              | 33.86                | 66.14              | 32.39              | 37.20              |
|              | PM        | 2.11       | 2.00             | 0.10               | 95.05                | 4.95               | 0.09               | 0                  |
|              | System    | 208.88     | 74.47            | 117.09             | 35.65                | 56.06              | 100.00             | 80.21              |
| R236fa       | EV        | 208.88     | 152.22           | 56.65              | 72.88                | 27.12              | 48.13              | 41.48              |
|              | EX        | 98.02      | 74.78            | 23.24              | 76.29                | 23.71              | 19.74              | 0                  |
|              | CD        | 57.13      | 19.43            | 37.70              | 34.01                | 65.99              | 32.03              | 36.42              |
|              | PM        | 3.04       | 2.93             | 0.11               | 96.38                | 3.62               | 0.09               | 0                  |
|              | System    | 208.88     | 74.78            | 117.71             | 35.80                | 56.35              | 100.00             | 77.9               |
| R245ca       | EV        | 208.88     | 146.64           | 62.23              | 70.21                | 29.79              | 53.37              | 45.75              |
|              | EX        | 90.46      | 73.77            | 16.69              | 81.55                | 18.45              | 14.31              | 0                  |
|              | CD        | 57.03      | 19.41            | 37.62              | 34.04                | 65.96              | 32.26              | 36.61              |
|              | PM        | 0.91       | 0.84             | 0.07               | 92.79                | 7.21               | 0.06               | 0                  |
|              | System    | 208.88     | 73.77            | 116.61             | 35.32                | 55.83              | 100.00             | 82.36              |

(Continues)
component $\dot{E}_{D,k}$ is a value calculated in the same extreme case. Data of unavoidable and avoidable exergy destructions are shown in Figure 7.

The $\dot{E}_{AV}^{D,k}/\dot{E}_{D,k}$ value indicates the improved performance of the $k$-th component. The expander demonstrates the highest improvement potential followed by the condenser and the evaporator. This ordering is independent of all working fluid properties.

The analysis of the $\dot{E}_{AV}^{D,k}/\dot{E}_{D,k}$ value of each component obtains the following results: 23.86% (R123)-24.77% (R227ea) for the evaporator, 54.98% (butane)-56.32% (R227ea) for the expander, and 42.82% (R227ea)-47.6% (butane, isobutene) for the condenser. Hence, the improvement potential of each component in the ORC is basically independent of working fluid properties. The avoidable exergy destruction of the expander, which accounts for more than 50%, indicates that the expander is the focus of improvement that should be prioritized. The maximum exergy destruction can be reduced by 56.32% when the working fluid is R227ea through methods, such as optimizing the design, manufacturing, and material selection of the expander.

$\dot{E}_{AV}^{D,k}/\dot{E}_{D,k}$ changes from 35.05% (R123) to 38.99% (R227ea) in the overall system. Working fluid properties limit the improved extent of the overall ORC.

The comparison related to the avoidable exergy destruction of each component with various working fluids obtains the following results: 12.55 kW (R227ea)-15.26 kW (R123) for the evaporator, 8.51 kW (R123)-19.45 kW (R227ea) for the expander, and 16.14 kW (R227ea)-17.9 kW (butane) for the condenser. Only the avoidable exergy destruction of the expander varies in a wide range when various working fluids are introduced, whereas those of the condenser and evaporator demonstrates a slight change. Working fluid properties exert minimal influence on the thermodynamic inefficiencies of the evaporator and condenser.

4.2.2 | First-level splitting into endogenous and exogenous parts

The endogenous exergy destruction of the $k$-th component is obtained under the assumption that only the $k$-th component operates in a real state, whereas remaining components operate in an ideal state. The exogenous exergy destruction of the $k$-th component is generated by other components in the ORC or the irrationality of the ORC to the $k$-th component.

Figure 8 shows that the values of the exogenous exergy destruction of the evaporator and expander are negative regardless of the working fluid used. The negative exogenous exergy destruction indicates that the performance of the evaporator and expander can be improved and that the performance of other components deteriorate.

Endogenous and exogenous exergy destruction of the condenser are positive, and the endogenous exergy destruction demonstrates a higher proportion than the exogenous exergy destruction. This finding indicates that
other components in the ORC exert minimal influence on the condenser. Improvement on the condenser itself can reduce the condenser exergy destruction.

### 4.2.3 Second-level splitting

Endogenous and exogenous unavoidable exergy destructions are negligible because optimization or improvement fails to reduce them. Discussion is focused on endogenous and exogenous avoidable exergy destructions because they can be prevented.

The endogenous avoidable exergy destruction of the \( k \)-th component is an avoidable part that occurs due to the irreversibility of the \( k \)-th component and can be reduced using technical approaches. The endogenous avoidable exergy destruction of all components accounts for approximately half of the entire ORC exergy destruction from 45.26% (R123) to 55.52% (R227ea). Values of the proportion vary considerably for different working fluid properties. The summation of the endogenous avoidable exergy destruction in the entire ORC for R227ea is 68.36 kW, which is the maximum among all working fluids.

The data of all working fluids in Figure 9 show that the positive exogenous avoidable exergy destruction of the condenser indicates that the thermodynamic performance of the condenser is directly affected by the evaporator, expander, and pump in the ORC. The exogenous avoidable exergy destruction of the condenser can be reduced by enhancing the performance of the evaporator, expander, and pump. The negative exogenous avoidable exergy destructions of the evaporator and expander indicate that improving the performance of the condenser and pump increases the exergy destructions of the evaporator and expander. The expander is the focus for improvement because its endogenous avoidable exergy destruction takes approximately 90% of its real exergy destruction for all working fluids.

### 4.3 Comparison of conventional and advanced exergy analyses

The conventional exergy analysis assesses the thermodynamic performance of the system or each component by calculating the exergy destruction and efficiency. For example, the exergy efficiency of the condenser is constantly low regardless of the working fluid used. Therefore, the condenser is the device that needs the most improvement because it demonstrates the worst thermodynamic performance from the perspective of the conventional exergy analysis. The advanced exergy analysis shows that the avoidable exergy destruction of the condenser is less than half of its real exergy destruction. Most of the...
avoidable exergy destruction of the condenser are endogenous. Consequences from the advanced exergy analysis offer explicit information that cannot be gained from the conventional exergy analysis.

The highest exergy efficiency of the expander in the conventional exergy analysis indicates that the improvement on the expander is the least effective among the components. However, the endogenous avoidable exergy destruction of the expander accounts for approximately 90% of its real exergy destruction for all working fluids. This finding reveals the high improvement potential of the expander from the viewpoint of the advanced exergy analysis.

This discussion shows that the results obtained by the conventional exergy analysis are often inconsistent with those by the advanced exergy analysis. The advanced exergy analysis can determine the source of the exergy destruction and the magnitude for possible improvement.

5 | CONCLUSION

A comprehensive thermodynamic model, including the real, theoretical, unavoidable, and hybrid cycles, is constructed to improve the thermodynamic cycle approach of the advanced exergy analysis method in the ORC. Nine organic working fluids are introduced to investigate the thermodynamic performance in the basic ORC by using conventional and advanced exergy analyses. The following conclusions can be drawn from the comparison of exergy analysis results.

1. The conventional exergy analysis shows that the exergy efficiency of the condenser is lowest and that the exergy destruction of evaporator is highest regardless of the working fluid used. The condenser and evaporator are key components for performance improvement. The maximum product exergy is obtained when R114 is used.

2. The advanced exergy analysis split the exergy destruction to different parts to examine the source of the exergy destruction and the magnitude for possible improvement thoroughly. The value of $E^A_{D,EX}$ is approximately 90% of its real exergy destruction for all working fluids in this study. The component that demonstrates the maximum improvement potential is the expander. In addition, values of $E^A_{D,EX}$ and $E^A_{D,EX}$ vary considerably when different working fluids are introduced. The thermodynamic performance of the ORC depends on working fluids.

The construction process of all thermodynamic cycles applied in the advanced exergy analysis is described in detail to provide an instruction of the advanced exergy analysis in the ORC. The proposed comprehensive thermodynamic model encompassing these cycles improves the application of the advanced exergy analysis in the ORC to obtain specific information about the performance improvement of equipment in the ORC through the advanced exergy analysis. This comprehensive thermodynamic model can promote the investigation of the advanced exergy analysis in the ORC.

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NOMENCLATURE

| Symbol | Description |
|--------|-------------|
| $E$ | Exergy (kW) |
| $e$ | Specific exergy (kJ/kg) |
| $H$ | Enthalpy (kW) |
| $h$ | Specific enthalpy (kJ/kg) |
| $m$ | Mass flow rate (kg/s) |
| ORC | Organic Rankine cycle |
| $p$ | Pressure (kPa) |
| $Q$ | Heat rate (kW) |
| $S$ | Entropy (kW/K) |
| $s$ | Specific entropy (kJ/[kg K]) |
| $T$ | Temperature (K) |
| $W$ | Power (kW) |
| $y$ | Exergy destruction ratio (dimensionless) |

GREEK SYMBOLS

| Symbol | Description |
|--------|-------------|
| $\Delta$ | Difference |
| $\varepsilon$ | Exergy efficiency (dimensionless) |
| $\eta$ | Isentropic efficiency (dimensionless) |

SUPERSRIPTS

| Symbol | Description |
|--------|-------------|
| $AV$ | Avoidable |
| $EN$ | Endogenous |
| $EX$ | Exogenous |
| $UN$ | Unavoidable |
| $j$ | Junction |
| $R$ | Real cycle |
| $T$ | Theoretical cycle |

SUBSCRIPTS

| Symbol | Description |
|--------|-------------|
| $D$ | Destruction |
| $F$ | Fuel |
| $P$ | Product |
| $k$ | $k$-th component |
| $EX$ | Expander |
| $PM$ | Pump |
| $EV$ | Evaporator |
| $CD$ | Condenser |
| $wf$ | Working fluid |
| $tot$ | Overall system |
| $0$ | Thermodynamic environment |
| $s$ | Isentropic process |
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APPENDIX A

Basic energy and exergy calculation

According to Bejan et al.,

\[ e = h - h_0 - T_0 (s - s_0) , \quad (A1) \]

\[ E = m_{wf}e, \quad (A2) \]

\[ H = m_{wf}h, \text{ and} \quad (A3) \]

\[ S = m_{wf}s. \quad (A4) \]

The fuel exergy that organic working fluids of the ORC obtain from the air in the evaporator is expressed as follows:

\[ \dot{E}_{F,\text{tot}} = \dot{E}_{F,\text{EV}} = \dot{m}_{air} (e_6 - e_8) . \quad (A5) \]

The heat exchange in the evaporator is calculated as follows:

\[ \dot{Q}_{\text{hot}} = \dot{m}_{air} (h_6 - h_8) = \dot{m}_{\text{cycle}}^{\text{cycle}} (h_1 - h_4) . \quad (A6) \]

The heat exchange in the condenser can be calculated as follows:

\[ \dot{m}_{\text{cycle}}^{\text{cycle}} (h_2 - h_3) = \dot{m}_{\text{water}}^{\text{cycle}} (h_{11} - h_9) . \quad (A7) \]

The temperature of the organic working fluid at the exit of expander is as follows:

\[ T_2 = T_1 + \frac{\eta_{\text{EX}}}{T_2} (T_{2s} - T_1) \quad (A8) \]

The temperature of the organic working fluid at the exit of pump is as follows:

\[ T_4 = T_3 + \frac{T_{4s} - T_3}{\eta_{\text{PM}}} \quad (A9) \]

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