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Optimizing Grids Demand Reduction through Enhanced Heat Transfer in Low-Temperature Waste Heat Driven ORC Systems

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Abstract

With increasing awareness of energy conservation and environmental protection, the Organic Rankine Cycle (ORC) system has gained significant attention. This technology enables the recovery of industrial waste heat, waste incineration heat, and renewable energy sources such as geothermal heat, biomass energy, and solar energy at lower temperatures. However, the low-grade heat source utilized in ORC systems faces a challenge to achieving high power generation efficiency and output power. Therefore, enhancing the power generation capacity of ORC systems is a key research focus in this field. An entranced heat exchanger ORC system with the screw expander driven by the low-temperature heat source is established to investigate the relevant performance. Hot water temperature from 77˚C to 132˚C is adopted for performance analysis, while the environmental temperature is approximately 25˚C. Refrigerant R245fa is selected as the working fluid, and the screw expander is employed for power generation. It is worth noting that the entranced heat exchanger ORC system has significant potential for low-temperature heat recovery. Experimental results indicate that the maximum power output is 12.83 kW, which is obtained at around 105˚C hot water inlet temperature. Correspondingly, the average power output remains 11.75 kW, revealing the system's high stability for power generation. The implementation of a plate heat exchanger for enhanced heat transfer has enabled a 50% reduction in system size compared to traditional shell-tube type ORC systems. Besides, economic calculations demonstrate substantial benefits associated with the ORC system. The calculations indicate an internal benefit of 560,000 RMB/year, accompanied by notable external benefits such as an energy saving and emission reduction potential of up to 784 t CO_2 per year. Moreover, the payback period is 2.23 years. It shows a remarkable improvement in terms of performance and excellent economic benefits. As a result, the novel ORC presents a promising alternative for low-grade heat utilization as compared to conventional small-scale ORC systems.

Keywords

ORC (Organic Rankine Cycle), Plate Heat Exchanger, Screw Expander, Power Output, Economic Analyse, Energy Saving

1. Introduction

The Organic Rankine Cycle (ORC) is a heat-driven power generation technology that operates in the low and medium temperature zones. It offers a simple and flexible solution for converting waste heat into electricity, thereby achieving energy savings and reducing emissions. **Figure 1** illustrates the wide range of applications for this technology, including the recovery of industrial waste heat from sources such as iron and steel mills, glass wool factories, and waste incineration plants. Additionally, it can be employed in renewable energy sources like geothermal energy [1], biomass energy [2], solar energy [3], and ocean temperature differences. However, the efficiency and net power output of ORC power generation technology have been limited by the low temperature or low grade of the heat source. This poses a challenge to the further development of the technology. To overcome this limitation and enhance the utilization of low and medium temperature waste heat, researchers have conducted optimization studies focusing on expander selection, phase change heat exchanger performance optimization, and the selection of organic working materials. Overall, the ORC technology holds great potential for transforming low and medium temperature waste heat into valuable electricity, contributing to energy efficiency and sustainable development [4].

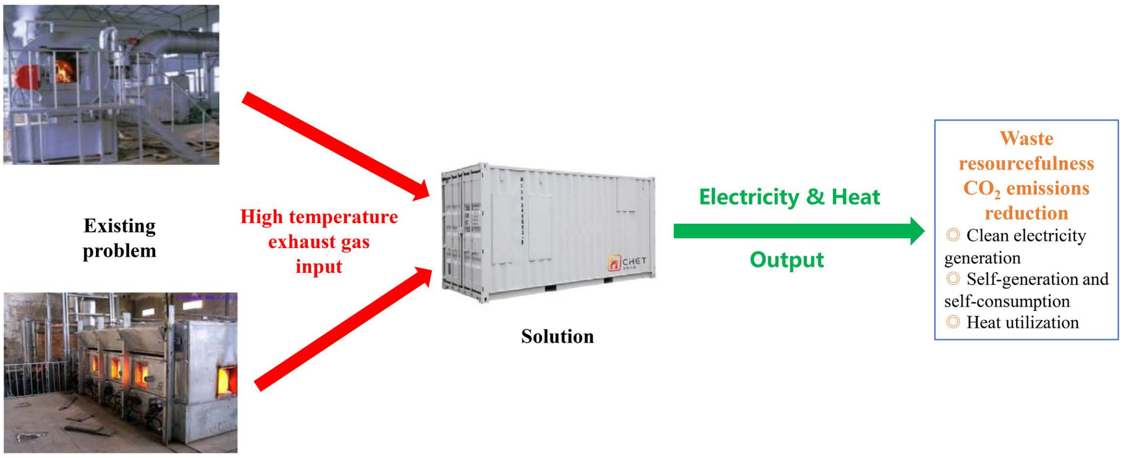


Figure 1. The diagram of ORC system application scenario.

The expander, as the central component of the ORC system, plays a crucial role in determining the system's performance. Its choice and performance directly influence the power output, thermal efficiency, and reliability of the system. Dumon *et al.* [5] presented experimental comparisons of various expanders, including piston, screw, scroll, and root types. They utilized extrapolated predictions from semi-empirical models and practical considerations based on measurements to establish guiding principles for expander selection in ORC systems of different sizes. These principles serve as valuable guidelines for choosing the most suitable expander based on performance characteristics and practical requirements. The thermal properties and environmental friendliness of low-boiling point organic substances as the working fluid in ORC systems also have a crucial impact on the system. Kankeyan *et al.* [6] employed MATLAB and the thermophysical properties database REFPROP to model and analyse the performance of various working fluids. The results of their analysis revealed that different working fluids exhibited better performance within specific temperature ranges. For the temperature range of 50˚C - 100˚C, MD2M and cyclopentane were identified as suitable options. For the temperature range of 100˚C - 150˚C, butane, neopentane, and R245fa were found to be better choices. Ethanol, methanol, and acetone were identified as suitable options for the temperature range of 150˚C - 200˚C. Furthermore, water, m-xylene, and p-xylene were identified as suitable working fluids for the temperature range of 200˚C - 320˚C. Eyerer S *et al.* [7] used a dual approach to assess R1224yd (Z) and R1233zd (E) as replacements for R245fa. The results have shown that in terms of system performance, the highest power output can still be achieved using the high GWP fluid R245fa. The maximum power output of R245fa is 326 W, which is 9% higher than R1233zd (E) and 12% higher than R1224yd (Z). In terms of the thermal efficiency of the ORC system, the R1233zd (E) is about 2% more efficient. In contrast, the thermal efficiencies of R245fa and R1224yd (Z) are equal over a wide range of operating conditions.

Phase change heat exchangers, as devices responsible for evaporation and condensation processes, play a crucial role in power generation efficiency. However, they can be subject to certain challenges, such as heat loss due to the thermodynamic properties of phase change heat and limitations in heat exchange caused by low-temperature heat sources. Imran *et al.* [8] used the Non-dominated Sorting Genetic Algorithm-II (NSGA-II) to optimize the development of a hydraulic and thermal design model of a herringbone plate evaporator and its geometrical parameters for a low-temperature geothermal ORC system, and the results of the optimization are presented in the form of the Pareto front solution, which helps the designer to select the appropriate geometrical parameters of the plate evaporator based on the allowable pressure drop and the cost of the evaporator. Therefore, an optimized air-cooled condenser using R245fa as the working fluid is proposed to enhance heat transfer and improve overall system performance.

In this paper, an enhanced heat transfer ORC system is established and expected to improve the performance and power output by optimizing the structure of the air-cooled condenser. The system utilizes a screw expander and employs R245fa refrigerant as the working fluid for experimental investigation. By recovering thermal energy from hot water or steam above 77˚C, this system overcomes the challenges associated with low-grade heat sources for power generation. It exhibits a broader range of applications and offers distinct advantages as a compact, modular ORC system with excellent scalability.

2. Method

2.1. System Principle

The ORC system consists of an evaporator, an expander-generator set, a separator, a condenser, a vessel and an electric pump. The principle of this system is shown in Figure 2, and the specific flow of its work is as follows:

1) The organic liquid in the storage tank enters the preheating tank for preheating.

2) Organic liquid into the evaporator, in the evaporator is into the evaporator after the waste heat pressurization, the work liquid evaporation into organic thermal vapor.

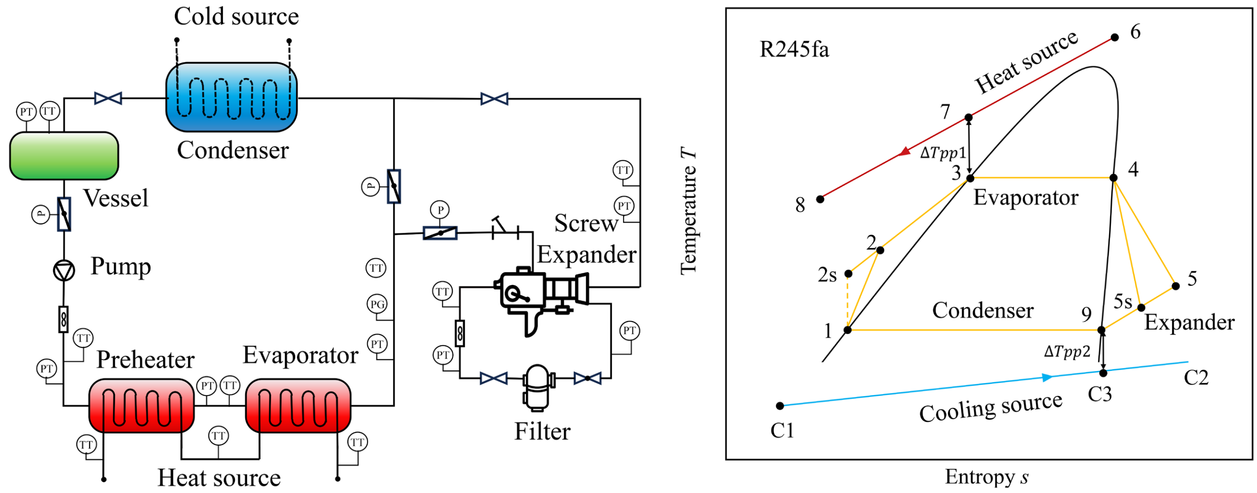
3) Organic vapor into the screw expander expansion, generating electricity.

4) In the expansion machine to do the work of the spent gas, and then into the condenser for cooling expansion, so that it is restored to liquid.

5) After cooling the liquid back to the liquid storage tank, and then through the mass pump to re-pressurize and send into the evaporator, so as to continue the next cycle.

2.2. System Devices

In this study, the experimental setup of the system is depicted in Figure 3.



(a) (b)

Figure 2. Schematic diagrams (a) and T-s diagram (b) of the ORC system.

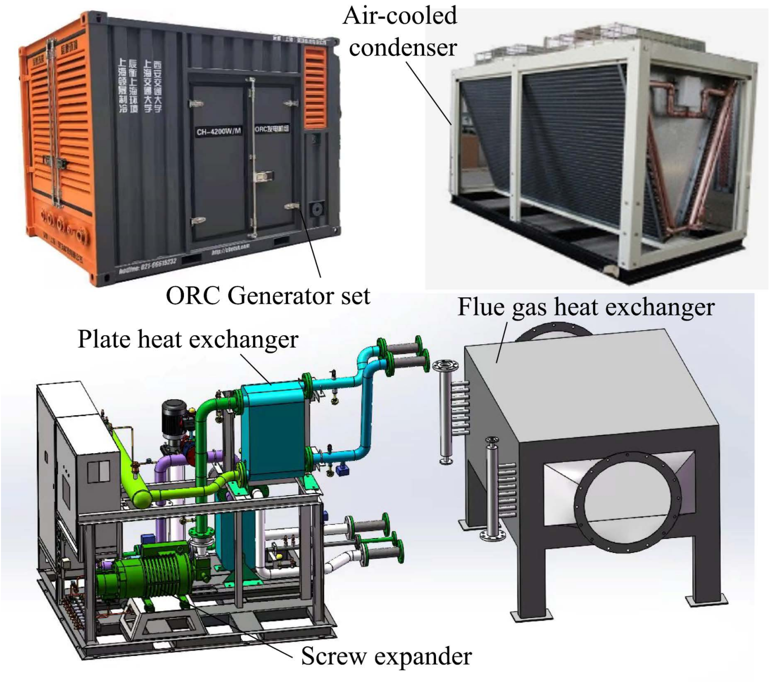


Figure 3. Prototype of reinforced heat exchanger type ORC system.

Specifically, the system incorporates the German BITZER semi-closed twin-screw expander, which serves as the core component [9]. The expander features a grid-connected induction power generation function, a patented process lubrication mechanism, and outstanding entropy efficiency and durability. Furthermore, stainless steel plate heat exchangers are employed in this study due to their compact structure and high heat transfer efficiency. This selection contributes to the overall performance of the system. For comprehensive automation, a standard programmable logic controller (PLC) has been integrated, and customized software has been developed. This combination enables the unit to effectively handle fluctuating thermal loads and vapor-liquid biphasic operating media, ensuring excellent performance even under low load conditions. Additionally, the system is designed for unattended operation and can be remotely monitored through RS485 or Ethernet communication interfaces. The piping design adheres to CE standards, while the cabinet meets the IP54 protection class requirements, ensuring safety and reliability. Considering the specific conditions of the application site and the heat exchanger structure, pressurized hot water has been chosen as the heat source, while cooling water has been selected as the cold source (we). This selection aligns with the requirements of the system and allows for efficient heat transfer. To accurately measure and monitor the system parameters, various essential devices such as temperature sensors, pressure sensors, flow meters, and other relevant instruments are employed. Last but not least, the size of the system is decreased by 50% compared with shell-tube type ORC systems. Table 1 provides an overview of the main measuring devices and their corresponding parameters.

Table 1. Main parameter of the system.

Model	CH-4200	CH-4400	CH-6500
Maximum net power generation	35 kW	70 kW	120 kW
Nominal voltage	380 - 500 V/three-phase/50Hz		
Operating ambient temperature	0˚C - 38˚C		
Power factor correction	0.9 - 1 (Load and site related)		
Total harmonic distortion	<3%		
Cooling medium	Water cooling: water (4˚C - 65˚C) & Air cooling: ambient air		
Minimum temperature difference	Minimum temperature difference between hot and cold water is 27˚C		
Operating medium	R245fa (Pentafluoropropane)		
Heat source	Hot water/steam (77˚C - 132˚C)		
Noise level	80 dB at 1 meter		
Dimension of single machine (L × W × H)	2.4 × 2 × 2.3 m	2.4 × 2 × 2.3 m	2.4 × 2 × 2.3 m
Weight (L × W × H)	3290 kg	3290 kg	4853 kg
Extended dimensions (L × W × H)	12 × 2.4 × 2.9 m	12 × 2.4 × 2.9 m	15 × 2.3 × 2.5 m
Weight (L × W × H)	6095 kg	6095 kg	8553 kg

The experiment investigates the performance of an Organic Rankine Cycle (ORC) power generation system under specific operating conditions. The heat source was provided with a hot water flow rate of 20 t/h at a temperature of around 105˚C, while the cold source was provided with a cold circulating water flow rate of 30 t/h at a temperature of around 25˚C. In the experiments, the generation power during the operating cycle was measured to analyse the performance and dynamic characteristics of the ORC system over the entire cycle. In addition, the average generation power of the ORC system was determined by measuring the electrical output over a specific period of time and calculating the average value.

2.3. Measurement Methods

The performance evaluation of the system involves assessing various parameters, including the instantaneous and average output power. The generated electrical energy from the system is consumed by electric heaters, and an electricity meter is used to measure the output power of the ORC system.

3. Result and Discussion

The system is categorized into three models: CH-4200, CH-4400 and CH-6500, with maximum net power generation of 35 kW, 70 kW and 120 kW respectively. In this study, the experiment utilizes the CH-4200 generator set. The technical parameters of the system are shown in Table 2.

3.1. Measurement Conditions and Results

This study examines the performance characteristics of the mentioned ORC system using the waste heat recovery application site at Hebei Chenggang Group's iron and steel plant as a case study. Figure 4 illustrates the heat recovery flow chart of the iron and steel plant.

As shown in Figure 5, the curve graph illustrates the variation of power generation over time and the average power generation during a 60-minute period. The heat source is a hot water flow rate of 20 t/h at a temperature of around 105˚C, while the cold source is a cold circulating water flow rate of 30 t/h at a temperature of around 25˚C. The testing process follows a controlled cycle as depicted in Figure 2(a):

1) Startup: Begin by conducting a fault detection check. If no faults are detected, close the inlet valve of the expansion machine and open the bypass valve and inlet liquid valve. Start the working fluid pump at a low frequency, and operate the unit in preheating mode.

2) Operation in pressure ratio control mode: Once the outlet temperature of the evaporator reaches the target value, load the working fluid pump, and operate the unit in pressure ratio control mode.

Table 2. ORC system CH-4200 technical parameters.

Model	CH-4200	**Factory number**	20210910001
Nominal voltage	380 - 500 V/Three-phase/50Hz	**Input power source**	Three-phase/ 380V/50Hz
Operating medium	R245fa (Pentafluoropropane)	**Refrigeration oil**	B320SX 5 kg
Cooling source temperature	Water 4˚C - 40˚C	**Cooling source flow**	46 t/h
Heat source temperature	Water/Steam 100˚C - 140˚C	**Heat source flow**	35 t/h
Maximum working pressure	2.8 MPa	**Maximum heat source temperature**	150˚C
Ambient temperature	0˚C - 38˚C	**gas pressure**	0.4 - 0.8 MPa
Protection level	IP54	**Noise level**	80 dB
Overall dimensions	3200 mm (L) × 2200 mm (W) × 2519 mm (H)		
Weight	5000 kg		

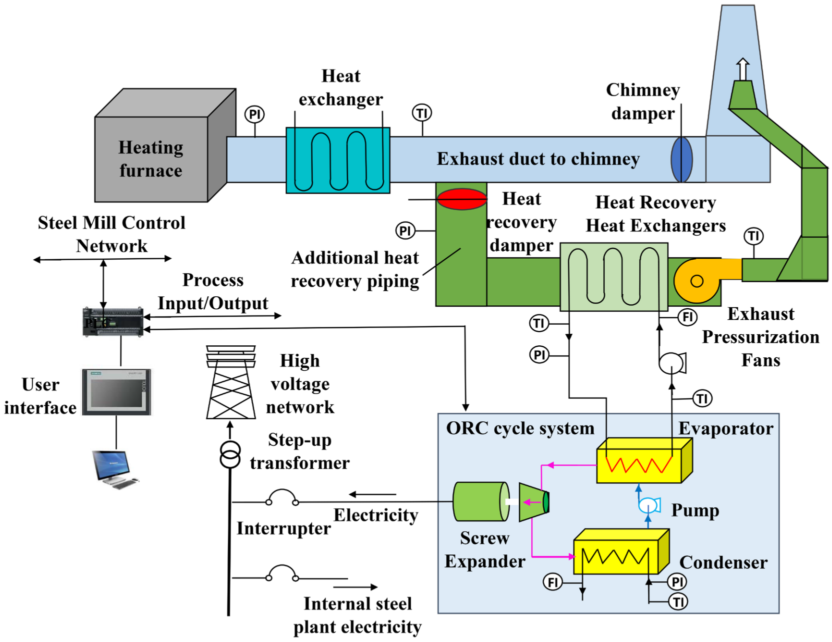


Figure 4. Heat recovery flowchart for steel mills.

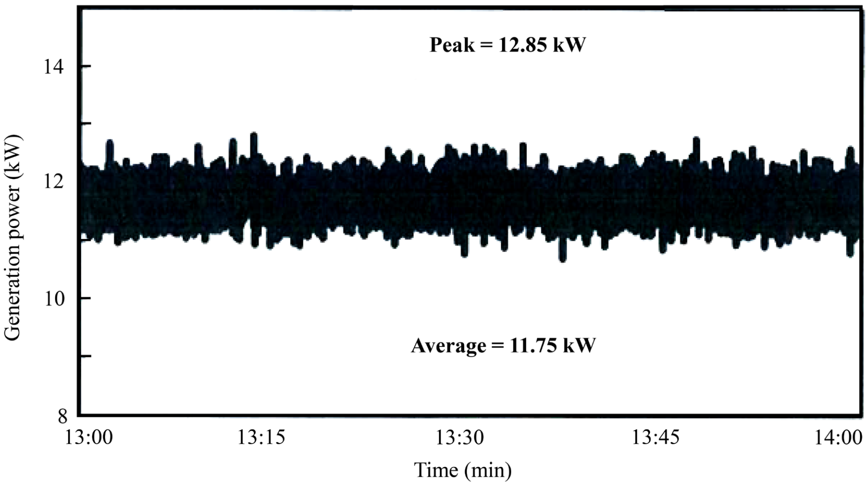


Figure 5. Variation of generating power with time.

3) Operation in superheat control mode: When the pressure ratio reaches the target value, close the bypass valve and open the inlet valve. The working fluid gas enters the expansion machine, driving its rotation. The unit operates in superheat control mode.

4) Grid connection: Once the expansion machine reaches the target rotational speed, engage the grid contactor, allowing the unit to generate electrical power.

5) Continued operation in superheat control mode: The system continues to operate in superheat control mode, and the working fluid pump continues to load until reaching the maximum electrical power output frequency for the current operating conditions. This completes the start-up process of the ORC system.

During the stable operation of the system, the power generation exhibits fluctuations over time. The system achieves an average power generation of 11.75 kW, with peak power generation reaching 12.83 kW. This demonstrates the system's capability to deliver stable and continuous power output.

3.2. Economic Analysis

Screw expansion generators have the capability to recover waste heat emissions and reduce throttling losses during steam desuperheating and depressurization processes. They offer compelling economic advantages, with a short payback period, and the electrical output can be accurately quantified and economically assessed. Within approximately three years, customers are able to recoup their investment costs. Moreover, these generators have a lifespan of up to 20 years, with no major repairs required in the first decade, low maintenance costs, and minimal staffing requirements of only two to three mechanics and electricians.

In some cases, for instance, the heat source is characterized by 75 t/h of hot water with an inlet temperature of 132˚C, an outlet temperature of 117˚C, and a pressure of 400 kPa. The cold source involves 107 t/h of cooling water with an outlet temperature ranging from 28˚C to 37˚C. The equipment operates for 8000 hours per year. By utilizing the industrial electricity prices prevalent in Shanghai, investment efficiency of the system is assessed.

As illustrated in Table 3, the investment for the screw expansion generator amounts to 1.25 million yuan. This includes fixed asset investments of 0.98 million yuan and a power supply cost of 0.24 yuan/kWh. The net power generation

Table 3. Investment and return of the system.

ORC power generation project investment (million yuan)	1.25	**Benefits**	
Investment in fixed assets (million yuan)	0.98	**Electricity price (yuan/kWh)**	0.7
Power generation (kW)	120	**Profit from electricity sales (million yuan/year)**	0.56
Net power generation (kWh)	100		
Annual power generation (kWh)	800,000	**Carbon savings (t/year)**	784
Cost of power supply (yuan/kWh)	0.24		
Assessment of investment benefit			
Payback period	2.23		

Note: The above table is calculated according to the following working conditions. 1) Heat source: 75 t/h hot water, inlet temperature is 132˚C, outlet temperature is 117˚C, pressure is 400 kPa. 2) Cooling source: 107 t/h cooling water, inlet temperature is 28˚C, outlet temperature is 37˚C. 3) Running time is calculated as 8000 hours/year. 4) Electricity price is calculated with reference to Shanghai industrial electricity price.

of the system is 100 kWh per year, resulting in an annual power generation of 800,000 kWh. Calculations indicate an internal benefit of 560,000 RMB/year, accompanied by notable external benefits such as an energy saving and emission reduction potential of up to 784 t CO_2 per year. And the payback period is 2.23 years.

In summary, the enhanced heat exchanger ORC system offers a reliable and efficient solution for heat recovery, delivering economic and environmental benefits to businesses. With its short payback period and low maintenance costs, it stands as an ideal choice for companies seeking to optimize energy utilization and achieve energy savings.

4. Conclusions

In this paper, an enhanced heat exchanger ORC system is established to investigate the performance with a low-temperature heat source of about 105˚C. The refrigerant R245fa is selected as the working fluid, and the screw expander is employed for power generation. Conclusions are yielded as follows:

1) The size of the system is decreased by 50% compared with shell-tube type ORC systems. The system utilizes high-performance and reliable imported components. Control is achieved through a PLC and customized software, enabling full automation. The system supports unmanned operation and remote monitoring. The pipeline meets CE standards, and the cabinet has an IP54 protection level.

2) Experimental results indicate that the maximum power output is 12.83 kW, which is obtained at around 105˚C hot water inlet temperature and 25˚C cold water inlet temperature. Correspondingly, the average power output is 11.75 kW which lasts for 60 min, revealing the high stability for power generation.

3) Based on the analysis, the internal return on investment for the system is projected to be approximately 57.44%, indicating a favorable financial outcome. Furthermore, the system exhibits an impressive payback period of 2.23 years, highlighting its cost-effectiveness and potential for long-term profitability.

Considering the overall performance, the ORC system with the enhanced heat exchanger has more advantages than the conventional ORC system under the conditions of low heat source temperature and small system capacity requirement. In addition, the suitability of a scroll expander for a small-scale ORC system offers a viable alternative to the screw expander, offering significant potential for enhancing system performance.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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