Erzincan Üniversitesi
Fen Bilimleri Enstitüsü Dergisi
2024, 17(2), 426-444
ISSN: 1307-9085, e-ISSN: 2149-4584
Araştırma Makalesi

Erzincan University
Journal of Science and Technology
2024, 17(2), 426-444
DOI: 10.18185/erzifbed.1465583
Research Article

Energy Production From Flue Gas of Sinter Plant Circular Coolers

Tuba Nur AKÇALI [1], Yıldız KOÇ [2*], Özkan KÖSE [2]

[1]Iskenderun Technical University, Institute of Engineering and Science, Hatay, Türkiye
[2]Iskenderun Technical University, Hatay, Türkiye

Received: 05/04/2024, **Revised:** 10/06/2024, **Accepted:** 11/06/2024, **Published:** 31/08/2024

Abstract

This study aims to utilise from the env-friendly recovery technologies for the waste heat released from circular coolers of energy-intensive systems to the atmosphere in the sinter plant due to reaching carbon emissions to critical levels and decreasing fossil fuel sources. For sinter plant energy waste heat recovery, the organic Rankine cycle (ORC) is selected. The performance metrics, including mass flow rates, gross power, power consumption of the pump and net power output in the study scope are evaluated considering variations in exhaust gas throughout a year. The system underwent energy and exergy analyses, determining the maximum performance values for each month. This was achieved by utilizing R123 as the organic fluid within the ORC, operating between pressures ranging from 7.5 bar to 36 bar. As a result, the highest net power was achieved in August, and the efficiency of exergy was determined to be 63%. Recycling of waste energy not only meets the electricity consumption of the sinter cooler system fans but also leaves 62% excess electrical energy. Furthermore, this value corresponds to approximately 18.3% of the annual energy requirement of the entire sinter plant.

Keywords: Sinter, waste heat, organic Rankine cycle, energy, exergy

Sinter Fabrikası Dairesel Soğutucu Baca Gazından Enerji Üretimi

Öz

Bu çalışmada karbon emisyonlarının kritik seviyelere ulaşması ve fosil yakıt kaynaklarının azalması nedeniyle sinter tesisinde enerji yoğun sistemlerin dairesel soğutucularından atmosfere salınan atık ısının çevre dostu geri kazanım teknolojilerinden faydalanılması amaçlanmaktadır. Sinter tesisi enerji atık ısısının geri kazanımı için organik Rankine çevrimi (ORC) seçilmiştir. Çalışma kapsamındaki kütle akış hızları, brüt güç, pompanın güç tüketimi ve net güç çıkışını içeren performans metrikleri, bir yıl boyunca egzoz gazındaki değişimler dikkate alınarak değerlendirilmektedir. Sistemin enerji ve ekserji analizleri yapılarak her ay için maksimum performans değerleri belirlendi. Bu, 7,5 bar ile 36 bar arasında değişen basınçlar arasında çalışan, ORC içerisinde organik sıvı olarak R123 kullanılarak elde edildi. Sonuç olarak en yüksek net güce ağustos ayında ulaşılmış ve ekserji verimi %63 olarak belirlenmiştir. Atık enerjinin geri dönüşümü, sinter soğutucu sistem fanlarının elektrik tüketimini karşılamanın yanı sıra, geriye %62 oranında elektrik enerji fazlası bırakılmaktadır. Ayrıca bu değer tüm sinter tesisinin yıllık enerji ihtiyacının yaklaşık %18,3'üne karşılık gelmektedir.

Anahtar Kelimeler: Sinter, atık ısı, organik Rankine çevrimi, enerji, ekserji

---

*Corresponding Author: yildiz.koc@iste.edu.tr
Tuba Nur AKÇALI, https://orcid.org/0009-0003-6835-3347
Yıldız KOÇ, https://orcid.org/0000-0002-2219-645X
Özkan KÖSE, https://orcid.org/0000-0002-9069-1989

1. Introduction

Due to rising energy requirements driven by factors such as technological advancements, industrialization, economic growth, population increases, and urbanization, there's a consistent upward trend in energy demand in our era. The surge in global population and evolving lifestyle patterns have led to unprecedented energy needs. Moreover, challenges like inter-country conflicts, natural calamities, and erratic weather phenomena pose substantial threats to energy security. However, despite these challenges, a significant portion of heat, serving as the primary energy source for numerous industrial processes, is often generated excessively and released into the atmosphere without being harnessed [1-3]. Given the escalating demand, technologies for recovering waste heat hold paramount importance in the industrial sector owing to the substantial energy potential of waste heat. Additionally, surplus heat generated in energy-intensive operations should be actively converted into usable electricity through eco-friendly waste heat recycling technologies [4-7]. Despite the world's daily consumption of approximately 76 million barrels of fossil fuels, over fifty percent of the generated energy is dissipated as residual heat, usually falling within the temperature range of 100 to 220°C. [8-11]. This pattern is on the rise in correlation with the world population growth and the development of economies. Therefore, by incorporating practical methods and maximizing the utilization of waste heat, it is possible to reduce fuel consumption in existing energy production systems substantially. Furthermore, this approach aids in mitigating the adverse effects of several critical challenges related to the environment, including changes in the climate, the increase in Earth's average surface temperature, the reduction of ozone molecules in the Earth's stratosphere, and contamination of the air [12]. Despite challenges, there are promising indications of a shift towards clean energy gaining momentum. Both global and national initiatives for achieving net zero emissions are anticipated to result in a 1.2% decline in primary energy consumption by 2030, with projections extending to 2050 [13]. This underscores the significance of waste energy recycling technologies, highlighting the need to enhance current systems rather than building new energy production facilities. Traditional conversion of energy techniques like steam turbine processes struggles to harness waste heat at lower and moderate temperatures effectively due to their reliance on high temperatures. Consequently, several environmentally friendly technologies for converting energy, similar to the Kalina and ORC systems, have been developed to enhance energy production efficiency and decrease the usage of fuel to a certain degree [14-17].

A research indicates that cycle performance is greatly influenced by factors including the heat source, choosing the appropriate fluid used in the process, and operating conditions [18]. It is asserted that ORC is particularly well-suited for lower-temperature heat sources when contrasted with alternative cycles such as Kalina cycles [19, 20]. Also, numerous articles have been dedicated to systems utilizing waste heat. Yang et al. performed the energy and power optimization of the supercritical ORC system. The highest power output was achieved when R143 organic fluid was used. Also, as a result of optimization, thermal efficiency and power output were increased by 7.13% and 39.45% respectively [21].

Quoilin et al. [22] and Calise et al. [23] studied the optimization and efficiency of a solar-powered ORC system. Meanwhile, Liu et al. [24] focused on designing, analysing, and optimizing a third-generation system based on biomass, exploring the integration of electricity, heating, and freshwater production. Their research employed optimization techniques for multiple objectives using particle swarm optimization to identify the optimal operational parameters of the system across various optimization scenarios. In their research, Liu et al. [25] examined systems employing three different energy cycles: Supercritical Rankine Cycle (SRC), ORC, and Supercritical Brayton Cycle (SBC). Through their investigation, they highlighted the specific pros and cons of each cycle. Their findings suggest that ORC is best suited for recovering waste heat at low temperatures, and SRC is ideal for tasks involving moderate temperatures. In contrast, SBC is most effective for producing energy under high-temperature conditions. Yu et al. [26] have developed a simplified theoretical approach to predict the thermal degradation temperatures of organic process fluid, aiming to enhance the effectiveness and safety of ORC systems. Their analysis indicates that calculating the primary reactions identified can reduce costs while maintaining prediction accuracy. In their research, Feng et al. [27] suggest that utilizing low-quality sinter cooling flue gas employing an ORC cycle utilizing R245 fluid and a single heat source can significantly boost the thermal energy recovery rate of sinter waste. They propose that effective energy conservation can be achieved by determining optimal temperature and thermal parameters. By employing these optimal parameters, the energy recovery rate from sinter waste can increase up to 64.86%. Akkaya et al. [28] conducted an assessment of the energy efficiency of integrated power generation systems based on fuel cells and ORC. Their study revealed that integrating waste heat from fuel cells enhanced the overall energy efficiency of the integrated system by approximately 14% to 25%. The selection of operational media is a critical factor impacting the thermodynamic efficiency of the ORC system. Although ORC systems can employ various organic fluids as process media, selecting the optimal one requires a thorough analysis considering both environmental impacts and the performance of the system. Wang et al. [29] proposed a multi-criteria optimization framework to evaluate the influence of process fluids on ORC performance. Thirteen fluids were examined, with R123 identified as the best option for source temperatures ranging from 100 to 180 degrees Celsius, while R141b was deemed optimal for temperatures exceeding 180 degrees Celsius. However, they highlighted that the ORC cycle would not be economically feasible if the source temperature falls below 100 degrees Celsius. Xu et al. [30] discussed the effects of 30 different fluids on the maximum achievable thermal efficiency and its constraints on thermodynamic excellence in both basic and regenerative ORCs, which vary based on the working temperatures. They developed charts to aid in selecting suitable process fluids for both s-ORC and r-ORC setups. Haervig et al. [31] offered guidelines for choosing the optimal process media for ORC systems, examining twenty-six process fluids employed in ORC systems with temperatures of the heat source ranging from 50 to 280°C. They found that process fluids containing isopentane, pentane, and ethanol, such as R124, R245FA, R23, R123, R7146, R141b, R218, R236EA and R227EA yielded the utmost power generation over the temperature span of 50 to 280°C. Jeong et al. [32] investigated many organic working fluids. They obtained more power output (250 kW) from R245ca compared to R245fa. However, they asserted that R245fa notably drew attention due to its lower compact turbine size. Elmaihy et al. [33] examined the ORC system for utilizing the cooling water released into the atmosphere through the car engine. They analyzed 16 working fluids. The best thermal efficiencies were calculated as 7.49 and 7.76% when using R123 and R245fa in the ORC system, respectively.

Above, many studies have been carried out on organic Rankine cycles and working fluids. However, there are almost no studies examining the thermodynamic performances of the ORC cycle using R123 fluid to evaluate the flue waste gas of the sintering system operating with coke gas. In addition, there is almost no study that analyses the performance of the waste heat recycling system by measuring the exhaust gas temperature of the sintering system from a facility separately for each month throughout the year.

In this study, sintering system facility cooler chimney exhaust gas temperature values were measured for every month throughout the year. The actual exhaust gas chemical content was then determined. Then, an organic fluid that could operate between these temperatures was determined. ORC, which uses R123 as the working fluid, was examined between 7.5 bar and 36 bar turbine inlet pressures, and the values showing maximum performance were calculated for each month. Moreover, energy and exergy analyzes of the system were carried out.

2. Material and Methods

2.1. System Description

The objective of this study is to assess the thermodynamic performance of the exhaust gas of a Sinter cooler system operating in a sinter facility in Türkiye. This research aims to enhance heat recovery efficiency by integrating the exhaust gas released into the air with an ORC. Figure 1 illustrates the schematic layout of the system for recovering waste heat, planned for the facility.

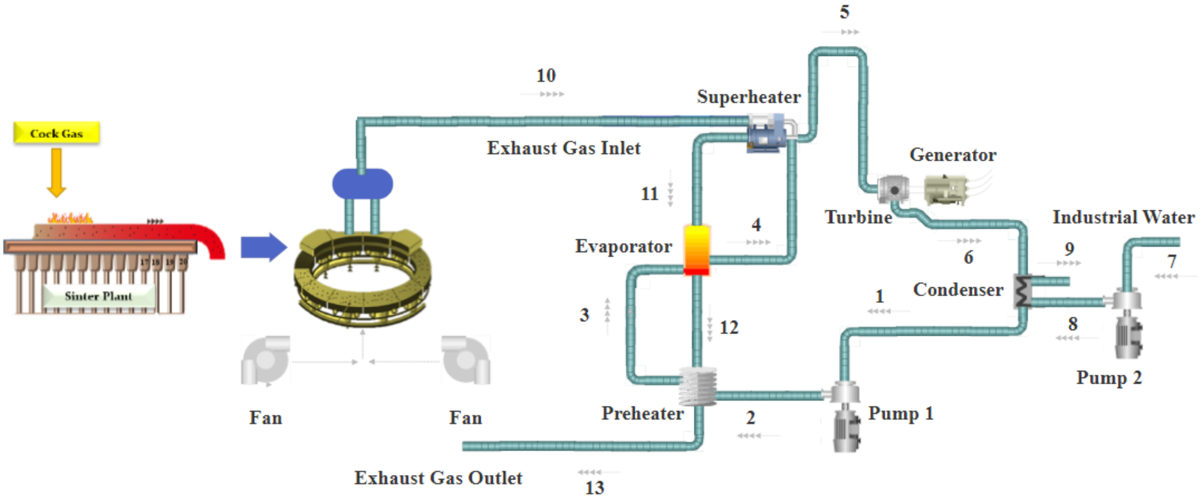

Figure 1. ORC cycle energy production from the waste heat of the circular coolers of the sinter system

As well known, the operational principle of the ORC system appears to be similar to that of the traditional Rankine cycle, there exist notable distinctions between the two cycles, particularly in terms of the process media. Figure 1 depicts an ORC system utilizing an organic process media. The exhaust gas from the Circular Cooler Stack of the Sintering Plant enters the ORC system (Point 10) at varying temperatures each month throughout the year, and after thermal energy exchange occurs in the superheater, evaporator, and preheater (10 → 13), it is released into the atmosphere from the stack. Once the system is pressurized using the pump (1 → 2), the organic media vaporized by the preheater (2 → 3), evaporator (3 → 4), and superheater (4 → 5) is transmitted to the ORC turbine and generator, which produce mechanical energy and electricity (5 → 6). The process media undergoes cooling in the condenser, causing it to transition from gas to liquid phase as it exits the ORC turbine (6 → 1). Approximately 20°C water from the factory service water line, at a pressure of 3 bars, is pressurized by the pump (7 → 8) and facilitates heat transfer with entry and exit to the condenser (8 → 9). Thus, the organic fluid undergoes a phase change from gas to liquid (6 → 1). A hybrid cycle has been engineered and optimized to recuperate excess heat emitted by gases released from the Circular Cooler Stacks of the Sintering Plant. The aim is to enhance the overall system effectiveness through this approach. The specified nominal parameters for the designed ORC are outlined in Table 1.

Table 1. Nominal parameters for the designed ORC

Parameter	Value	Unit
$\eta_{Pum;is}$	80	%
$\eta_{Tur;is}$	88	%
$T_{CW;in}$	20	°C
$T_{CW;out}$	25	°C
$\dot{m}_{sin;exh}$	803662	kg/h
$P_{sin;exh}$	2	bar
$T_{sin;exh,in}$	137-235	°C
$T_{sin;exh,out}$	90-165	°C
T_{Pinch}	10	°C
Fuel Type	Coke gas	-

2.2. Mathematical Model

An ORC system has been incorporated into the Circular Cooler exhaust gas system of the Sintering Plant to efficiently harness the waste heat. ORC systems employ organic process media, and it's widely recognized that the selection of these fluids significantly influences the ORC system's performance. Hence, this study undertook an in-depth examination of the energy and exergy analyses of the system, grounded in the fundamental principles of thermodynamics. The aim was to observe the thorough impacts of the chosen process media on the entire system. The data utilized in this analysis were sourced from Steag GmbH's EBSILON® Professional software. The energy and exergy equations for the ORC design are outlined below [34-43].

General mass, energy and exergy equations are provided below:

The equation for mass balance utilized in these calculations is as follows:

$$\sum \dot{m}_{in} = \sum \dot{m}_{out} \tag{1}$$

The equation for energy balance employed in these calculations is as follows:

$$\dot{Q} + \dot{W} = \sum \dot{m}_{out} h_{out} - \sum \dot{m}_{in} h_{in} \tag{2}$$

Within this equation, Q ˙and Ẇ represent heat and power generation, respectively. The equation for exergy balance utilized in these computations is as follows:

$$\dot{E}_{in} = \dot{E}_{out} + \dot{E}_{dest} \tag{3}$$

Exergy flow is represented by Ė, with subscripts "in", "out", and "dest" denoting exergy in, exergy out, and exergy destruction, respectively. Exergy flow is calculated as follows:

$$\dot{E} = \dot{m}\psi \tag{4}$$

The symbol for specific exergy is ψ, which can be ascertained utilizing the subsequent expression:

$$\psi = (h - h_0) - T_0(s - s_0) \tag{5}$$

Exergy represents utilisable work. Therefore, the exergetic work is assumed to be 100%. However, the exergetic efficiency for heat is typically less than 100%. The calculation for the exergy flow related to heat is as follows:

$$\dot{E} = \left(1 - \frac{T_0}{T_{sur}}\right)\dot{Q} \tag{6}$$

In this context, T_0 stands for the ambient temperature, while T_{sur} indicates the temperature of the surface engaged in transferring heat. While computing, the average value of the inlet and outlet temperatures of an element is considered as the temperature of the heat transfer surface. T_0 is assumed to reflect the average ambient temperature, set at 20°C.

The equations for energy and exergy in the ORC can be presented as follows:

The evaluation of the ORC based on energy and exergy principles is implemented for both the entire cycle and individual components. The overall heat exchange from the exhaust to the organic process media is derived as follows:

$$\dot{Q}_{in;ORC} = \dot{m}_{exh}(h_{10} - h_{13}) = \dot{m}_{ORC}(h_5 - h_2) \tag{7}$$

In this context, represents the rate of mass flow of the organic process media within the ORC. The computation for the resultant power generated by the ORC is expressed as follows:

$$\dot{W}_{net;ORC} = \dot{W}_{Tur;ORC} - \dot{W}_{Pum;ORC} \tag{8}$$

Here, $\dot{W}_{Tur;ORC}$, the power output from the ORC turbine, and $\dot{W}_{Pum;ORC}$, is the power utilized by the ORC pump. The exergy input to the ORC from the exhaust is calculated as follows:

$$\dot{E}_{in;ORC} = \dot{m}_{exh}(\psi_{10} - \psi_{13}) \tag{9}$$

The thermal and exergetic efficiencies of the ORC system are established using the subsequent formulations:

$$\eta_{ORC} = \frac{\dot{W}_{net;ORC}}{\dot{Q}_{in;ORC}} \tag{10}$$

$$\varepsilon_{ORC} = \frac{\dot{W}_{net;ORC}}{\dot{E}_{in;ORC}} \tag{11}$$

In the computations, steady-state conditions are presumed, and kinetic and potential energies are disregarded. The surrounding temperature of 20°C is taken into account.

2.3. Working Fluid

The choice of process media has a substantial impact on the efficiency in terms of heat utilization of ORC systems [43,44]. Choosing the right process media can minimize thermodynamic inefficiencies, allowing for increased enhanced efficiency in converting energy and reduced initial investment requirements [45]. Consequently, the selected media should exhibit ideal thermodynamic and transport characteristics under suitable temperature and pressure conditions, while also meeting requirements such as non-toxicity, cost-effectiveness, environmental compatibility, safety, non-flammability and enabling efficient energy utilization from available heat sources [46,47]. Moreover, the gradient of the fluid's saturation curve is vital for ORC system design, cost, and performance. Wet fluids may cause inefficiencies at certain operating conditions, while dry or isentropic fluids tend to offer more consistent performance. Therefore, careful consideration of the process media is pivotal as it directly impacts ORC system efficiency and reliability [43]. In this study, dichlorotrifluoroethane (R123, CF3CHCL2) is employed as the process media, possessing a molar mass of 152.9 g/mole, a normal boiling point of 300.97 K at 1 atmosphere, a pivotal temperature of 456.8 K, and a pivotal pressure of 3.66 MPa.

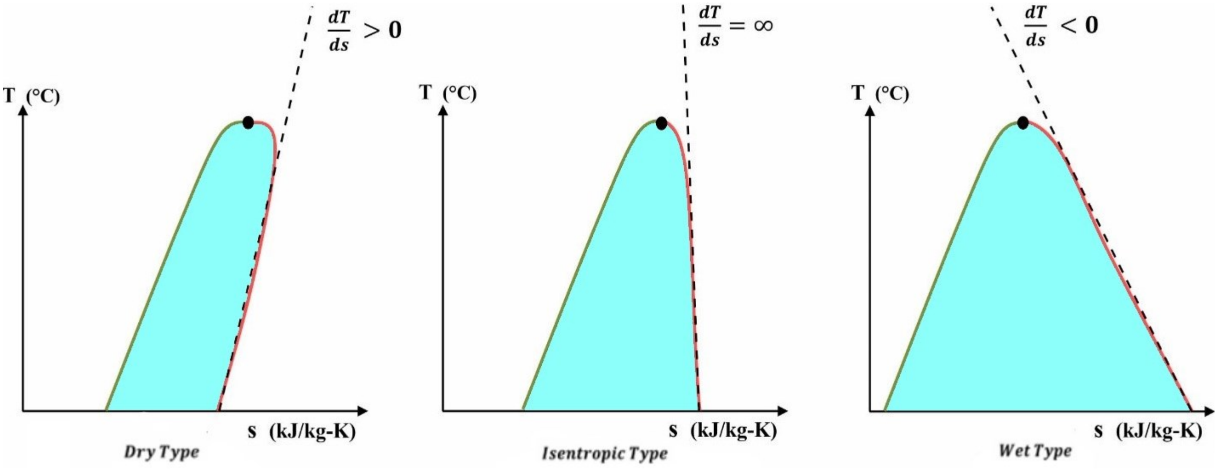

Figure 2. Temperature-entropy (T-s) diagram illustrates the thermodynamic properties of organic fluids in various states

When a process media demonstrates high performance values, its environmental repercussions can become significant. Conversely, a process media with low performance may lead to substantial environmental drawbacks. To evaluate environmental impact, factors like Ozone Depletion Potential (ODP) and Global Warming Potential (GWP) must be considered. ODP, originally outlined in the Montreal Protocol, is determined by comparing the process media to R11 [48]. GWP represents the impact ratio over a 100-year period compared to CO2. Given these definitions and criteria, an ideal organic fluid should exhibit high thermodynamic performance while maintaining ODP values close to zero and GWP values below 200 for environmental sustainability [48]. In this study, the proposed process media, R123, has an ODP value of 0.020 and a GWP of 77 [49]. Consequently, it is evident that R123 poses a significantly low environmental impact as a process media.

3. Result and Discussion

The most effective approach to assess a system's performance is to consider parameters derived from both the principles of the first and second laws of thermodynamics. This method offers crucial insights into the system's current status. Therefore, it's highly important to conduct both energy and exergy analyses based on operating pressure and temperature to make well-informed decisions. This section presents a thorough parametric optimization of the ORC, concentrating on pressure and temperature at the inlet of the turbine. The optimization includes a spectrum of pressures, from 7.5 to 36 bar, and temperatures ranging from 99°C to 225°C. Variations in the maximum thermodynamic performance metrics resulting from the parametric optimization of the ORC were examined for each month throughout the year. Subsequently, the maximum performance values for each month were compared based on the measured waste heat value. The variation of the temperature and pressure at the inlet of the turbine, at maximum performance for each month throughout the year is depicted in Figure 3.

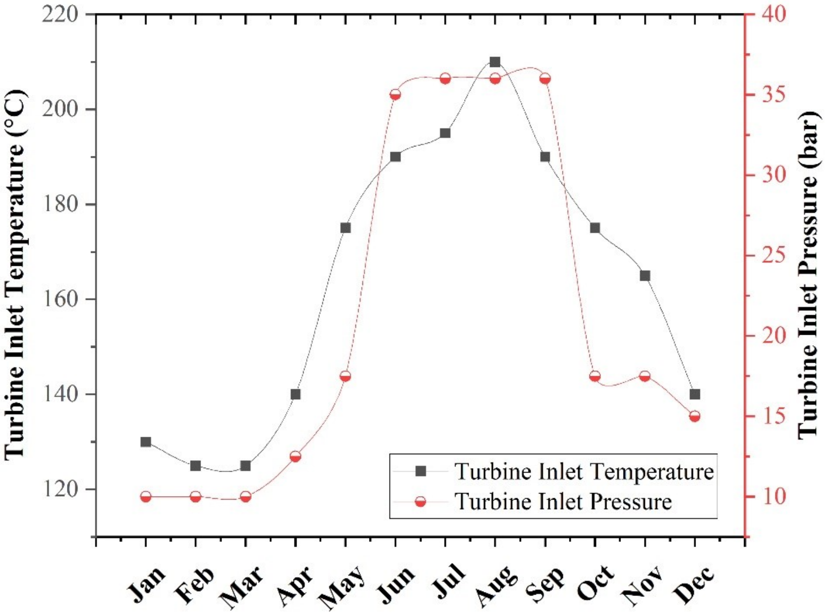

Figure 3. The Changes in the turbine inlet temperature and pressure of the ORC at maximum performance for each month throughout the year

The temperature at the turbine inlet is observed to be unstable, peaking during the summer months. This instability in the exhaust gas temperature of the sintering machine's cooling stack is attributed to the variability of parameters such as the chemical and physical properties of the bed material during the sintering process, material temperature, ore layer thickness, sinter machine speed, coke powder ratio, amount of water supplied for moistening, and most importantly, cooling efficiency, alongside the variability in weather conditions. Additionally, due to inevitable uncertainties in operating parameters within the sinter cooling process, such as flow and temperature fields, the performance of sinter cooling processes can exhibit uncertainties. Several parameters affect the exhaust gas outlet temperature of the sinter cooling stack every month, with weather conditions being one of the most notable. The minimum turbine inlet temperature is 125°C in February and March, with sinter production being 56,336 tons in February and 75,532 tons in March. The maximum turbine inlet temperature is 210°C in August, with sinter production reaching 336,376 tons in that month. Dry fluids tend to perform at their maximum near-saturation temperature. In January, February, and March, the turbine's inlet temperature ranges from 125°C at its lowest to 130°C at its highest, with a turbine inlet pressure of 10 bars for all three months. The point where maximum performance is achieved is at 36 bars. As the inlet temperature increases, the pressure at which maximum performance is achieved varies, attributed to the fluid being dry. Figure 4 illustrates the fluctuations in mass flow rate and power consumption of the pump within the ORC system across each month of the year.

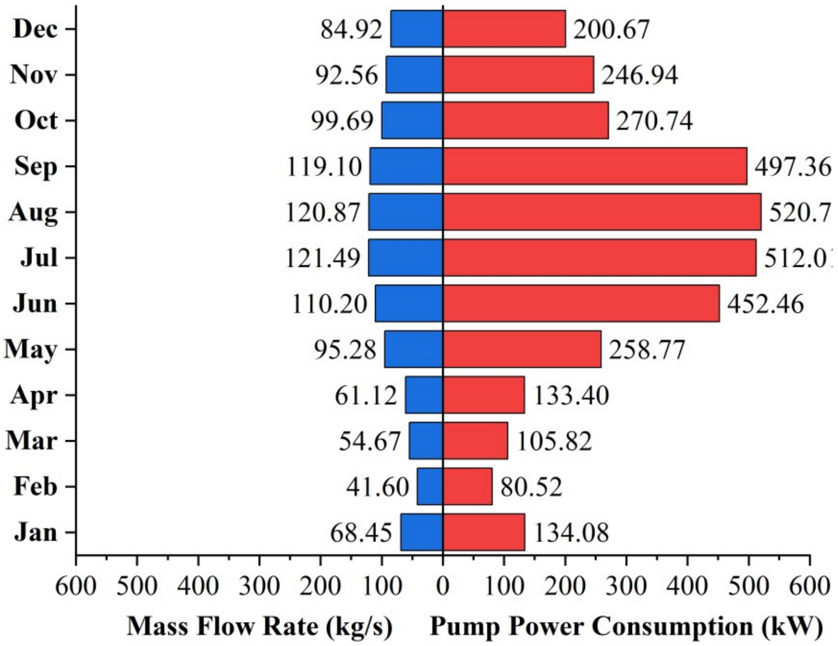

Figure 4. The variation in mass flow rate and pump power consumption within the ORC system at its maximum efficiency for the course of each month throughout the year

The amount of power consumed by the pump exhibits fluctuations throughout the year, with peaks observed in July, August, and September, as depicted in the graph. For example, the power consumption of the pump was found to be 512 kW when the rate at which mass flows through a system was 121.49 kg/s, 520.7 kW when the mass flow rate decreased to 120.87 kg/s, and subsequently reduced to 497.36 kW when the mass flow rate further decreased to 119.1 kg/s. The fluctuation in exhaust gas inlet temperature over the course of the year has a notable impact on both the mass flow rate and pump power consumption. The exergy destruction of the utilized equipment in the ORC system at maximum performance for each month throughout the year is depicted in Figure 5.

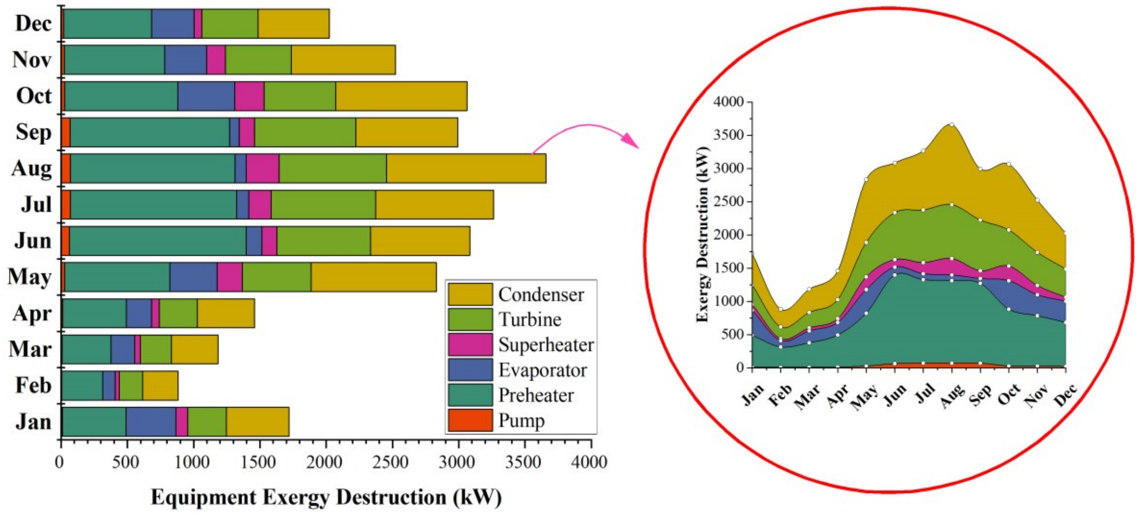

Figure 5. The exergy destruction of the equipment utilized in the ORC system at its maximum performance for each month throughout the year

Throughout the year, the preheater equipment showed the highest exergy destruction among all components within the ORC system, with a magnitude of 1333 kW, while the lowest exergy destruction was in the pump equipment, with a magnitude of 6 kW. The condenser equipment followed closely behind, ranking second in terms of notable exergy degradation, with a magnitude of 1204 kW. Hence, it is evident from the calculation results that there is considerable potential for improvement in the preheater and condenser equipment. The exergy efficiency of the equipment used in the ORC system at maximum performance for each month over the course of the year is depicted in Figure 6.

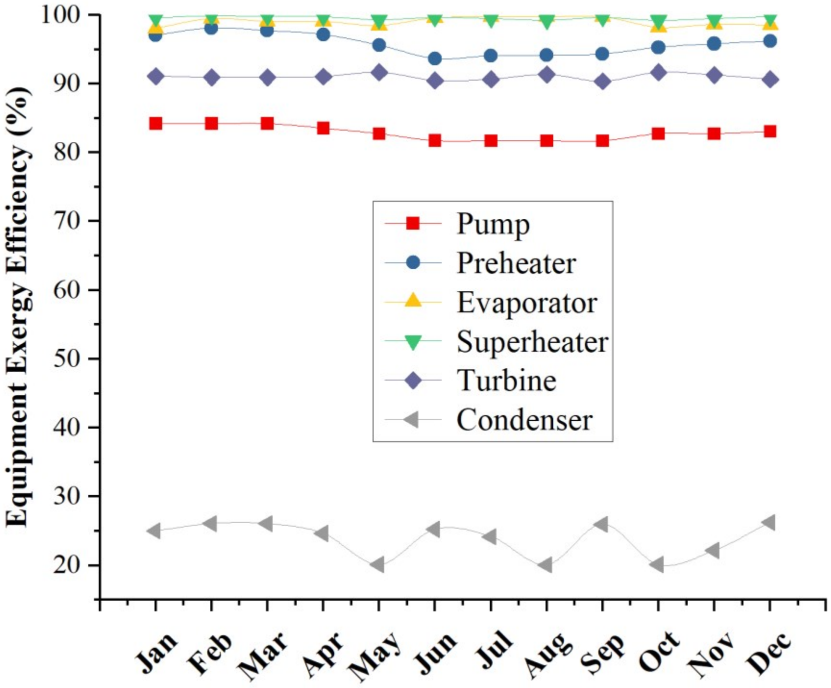

Figure 6. The equipment's exergy efficiency at its maximum performance for each month throughout the year

Throughout the year, it is observed that the exergy efficiencies of the pump, preheater, evaporator, superheater, and turbine do not undergo significant fluctuations, indicating that the system operates as desired. However, it is noted that the condenser exhibits notably lower exergy efficiency and exhibits more variability compared to the efficiencies of other equipment. Therefore, there appears to be more potential for improvement in the condenser equipment, offering the possibility of making the system more efficient. Additionally, decreases in exergy efficiency are observed in May, August, and October, with efficiency values of 20.13%, 20.10%, and 20.13%, respectively. The efficiencies of the evaporator and superheater are found to be very close to each other on a monthly basis. The superheater demonstrates a maximum efficiency of 99.84% throughout the year, whereas the evaporator reaches a maximum efficiency of 99.73%. The overall power produced by the ORC system and the exhaust gas heat input from the sinter cooler stack at maximum performance for every month across the year is depicted in Figure 7.

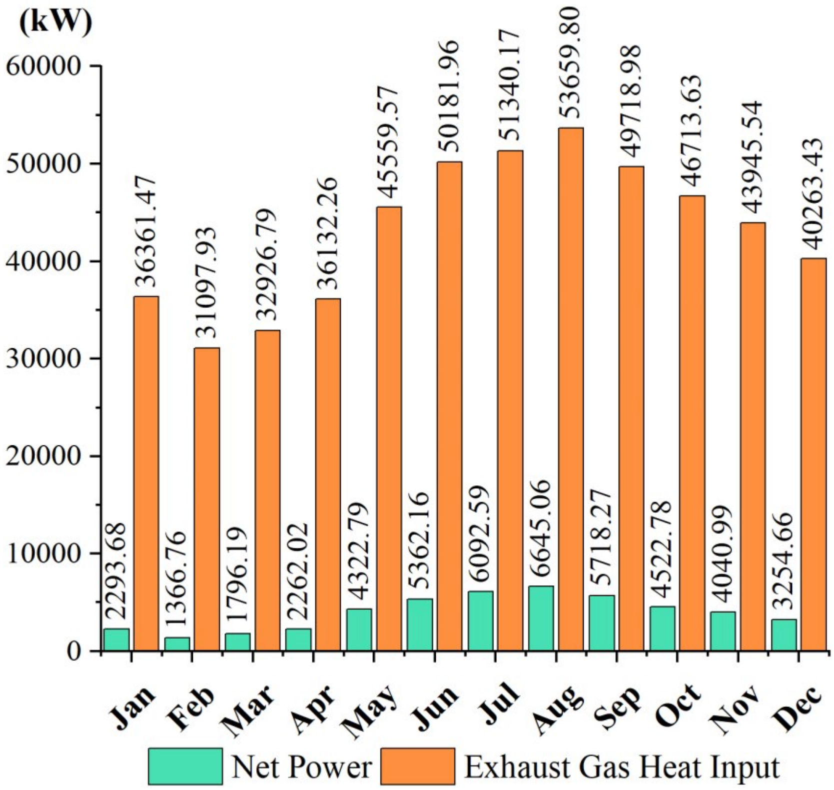

Figure 7. The net power of the ORC system and the exhaust gas heat input from the sinter cooler stack at maximum performance for every month across the year

From the graph, it was noted that as the exhaust gas heat input from the sintering system's cooler stack increases, there is a linear rise in the overall power output. In August, a peak in both heat input and variations in the net power were noticed owing to climatic conditions. The highest achievable net power output of the ORC system at peak performance was 6645 kW in August and 1367 kW in February. Throughout the year, the highest net power was obtained in July, August, and September, while the lowest was in February, March, and April. With this system, a total of 33374.563 MW of annual waste heat was recovered from the exhaust gases, out of a total of 362531.076 MW released from the sinter cooler stack to the atmosphere over the year. The average annual power consumption of the sinter plant's cooler system fans was calculated to be 20539.400 MW. Waste energy recovery not only meets the electricity consumption of the sinter cooler system fans but also leaves an excess of 62%, which accounts for approximately 18.3% of the sinter plant's annual energy demand. Therefore, the importance of heat recovery in sinter cooler stacks is crucial for systems to generate own energy consumption. Heat recovery in industrial facilities will contribute significantly to reducing emission rates and lowering new investment costs. The efficiency of thermal and exergy in the ORC system at peak performance for each month throughout the year is shown in Figure 8.

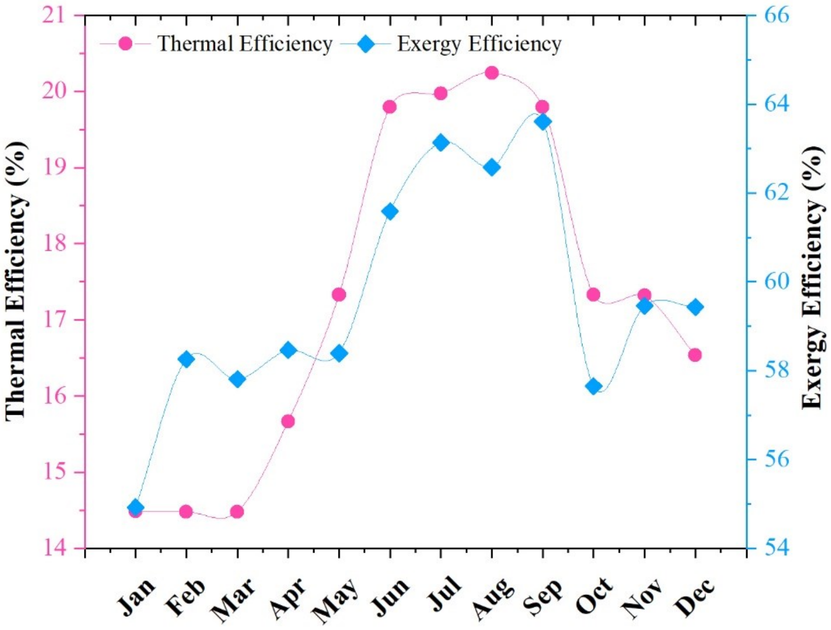

Figure 8. The thermal and exergy efficiency of the ORC system at its maximum performance for every month during the year

The maximum thermal and exergetic efficiencies of the ORC system performance for each month have been analysed throughout the year. It is observed from the graph that the efficiencies in both thermal and exergy are not constant and reach their highest levels during the summer months. Particularly in the summer months, the high exhaust gas temperature of the sintering system allows the turbine inlet pressure to reach higher levels due to the thermophysical characteristics of the fluid, significantly affecting thermal and exergy efficiency. The thermal efficiency peaks in August at 20.24%, while the exergy efficiency peaks in September, reaching its highest value at 64%. Conversely, the thermal efficiency is lowest in March at 14.48%, while the exergy efficiency is lowest in January at 54.92%.

4. Conclusion

As widely recognized, the choice of the process media employed in an ORC system is pivotal for its thermodynamic efficiency. Therefore, choosing the suitable process medium before system design can mitigate thermodynamic inefficiencies can lead to higher net power output with reduced capital expenditures. In this investigation, the R123 fluid, anticipated to exhibit optimal cycle conditions, has been employed. The research investigates multiple performance parameters of the ORC, covering exergy efficiency, net thermal efficiency, as well as metrics such as total power output, overall power, power consumed by the pump, and flow rates of mass. These are analysed across different turbine inlet pressures and temperatures. Thermodynamic parameters for each ORC component were sourced from Steag GmbH's EBSILON® Professional software utilized thereafter to compute performance metrics using thermodynamics' fundamental laws. This thorough optimization endeavour has produced several significant findings:

- When examining the variation in flow rate of mass and power consumed by the pump at maximum performance throughout the year for the ORC system, it's clear that the pump's power consumption fluctuates throughout the year, peaking in July, August, and September, as observed from the graph. Correspondingly, when the flow rate of mass is 121.49 kg/s, the pump power consumption is calculated to be 512 kW, while it reaches 520.7 kW when the mass flow rate is 120.87 kg/s. Furthermore, it was discovered that when the mass flow rate is 119.1 kg/s, the pump's power consumption measures 497.36 kW. The fluctuation in the exhaust inlet temperature throughout the year impacts both pump power consumption and the flow rates of mass.
- When examining the degradation of exergy within the equipment used in the ORC system at maximum performance throughout the year, it was noted that the preheater equipment experienced the highest level of exergy destruction. The condenser equipment followed closely behind, ranking second in terms of notable exergy degradation, with a magnitude of 1204 kW. In contrast, the pump equipment exhibited the lowest level of exergy destruction, with a magnitude of 6 kW. Therefore, it is evident from the calculation results that there is considerable potential for improvement in the preheater and condenser equipment.
- It has been determined that the condenser's exergy efficiency is considerably lower and more fluctuating compared to the efficiencies of other equipment. Therefore, it is observed that there is a greater potential for improvement in the condenser equipment, and there is a possibility of making the system more efficient.
- Throughout the year, it was observed from the graph that as the exhaust gas thermal input from the sintering system's cooling stack increased, there was a linear increase in the overall power output of the ORC system. The highest net power was obtained during July, August, and September, while the lowest was during February, March, and April. For one year, this system facilitated the recycling of 33,374.56 MW of waste heat out of a total of 362,531.08 MW released from the sinter cooling stack into the atmosphere. The average annual power consumption of the sinter plant's cooling system fans was calculated to be 20,539.40 MW. With waste energy recycling, not only does it cover the electricity consumption of the sinter cooling system fans, but there is also an excess of 62% electricity. Additionally, this amount corresponds to roughly 18.3% of the total yearly energy demand for the entire sinter plant.
- Throughout the year, the efficiencies in both thermal and exergetic domains within the ORC system at peak performance were examined for each month. It was observed from the graph that both thermal and exergy efficiencies were not constant and reached their highest levels during the summer months. Particularly in the summer months, the high exhaust gas temperature of the sintering system and the fluid's capability to raise the pressure at the turbine inlet to higher levels due to its thermophysical properties were found to significantly affect both thermal and exergy efficiency. August saw the peak thermal efficiency at 20.24%, whereas September marked the highest exergy efficiency at 64%. Conversely, the least thermal efficiency was observed in March, standing at 14.48%, whereas the lowest exergy efficiency was observed in January at 54.92%.

The ORC system is one of the most remarkable energy conversion systems among recovery systems with low waste heat. It has become widespread in the iron and steel industry. In this study, The analyzes were made considering that the sinter plant was operating continuously. However, in real industrial processes, downtimes can be long. In future studies, an assisted system will be designed and thermodynamic analysis of the ORC system will be carried out against undesirable situations.

Ethics in Publishing

There are no ethical issues regarding the publication of this study.

Author Contributions

Tuba Nur AKÇALI – Conceptualization; Methodology; Data collection; Formal analysis; Methodology; Writing – review & editing. Yıldız KOÇ – Conceptualization; Advisor; Data curation; Formal analysis; Investigation; Methodology; Resources; Software; Validation; Roles/Writing - original draft; Writing – review & editing. Özkan KÖSE - Conceptualization; Advisor; Software; Visualization Methodology; Data curation; Formal analysis; Methodology; Writing – review & editing.

Nomenclature

$\dot{E}$	exergy flow (kW)
GWP	global warming potential
h	enthalpy (kJ/kg)
$\dot{m}$	mass flow rate (kg/s)
ODP	ozone depletion potential
ORC	organic Rankine cycle
$\dot{Q}$	heat flow (kW)
P	pressure (bar)
s	entropy (kJ/kgK)
T_0	ambient temperature (ºC)
T	temperature (ºC)
$\dot{W}$	power (kW)

Greek letters

ψ	specific exergy (kJ/kg)
ε	exergetic efficiency (%)
η	thermal efficiency (%)

Subscripts

$boil$	boiling
$crit$	critical
CW	cooling water
$dest$	destruction
exh	exhaust gas

in	inlet
max	maximum
out	exit
Pum	pump
sur	heat transfer surface
Tur	turbine

References

[1] B. Dai, C. Liu, S. Liu, D. Wang, Q. Wang, T. Zou, X. Zhou, Life cycle techno-enviroeconomic assessment of dual-temperature evaporation transcritical CO2 hightemperature heat pump systems for industrial waste heat recovery, Appl. Therm.Eng. 219 (2023), 119570.

[2] H. Jouhara, N. Nieto, B. Egilegor, J. Zuazua, E. Gonz´alez, I. Yebra, A. Igesias, B. Delpech, S. Almahmoud, D. Brough, J. Malinauskaite, Waste heat recovery solution based on a heat pipe heat exchanger for the aluminium die casting industry, Energy 266 (2023), 126459.

[3] Y. Zhang, L. Yu, K. Cui, H. Wang, T. Fu, Carbon capture and storage technology by steel-making slags: recent progress and future challenges, Chem. Eng. J. 455(2023), 140552.

[4] Cheng, H., Liu, Y., Cao, F., Zhang, Q., & Ouyang, J. (2022). Integration of an electronic thermoelectric material with ionogels to harvest heat from both temperature gradient and temperature fluctuation. Chemical Engineering Journal, 450, 138433.

[5] Shan, K., Luo, Q., Yun, P., Huang, L., Huang, K., Cao, B., ... & Jiang, H. (2023). All-day working photovoltaic cooling system for simultaneous generation of water and electricity by latent heat recycling. Chemical Engineering Journal, 457, 141283.

[6] Luo, Q., He, A., Xu, S., Miao, M., Liu, T., Cao, B., ... & Jiang, H. (2023). Utilization of low-grade heat for desalination and electricity generation through thermal osmosis energy conversion process. Chemical Engineering Journal, 452, 139560.

[7] C. Ononogbo, E.C. Nwosu, N.R. Nwakuba, G.N. Nwaji, O.C. Nwufo, O. C. Chukwuezie, M.M. Chukwu, E.E. Anyanwu, Opportunities of waste heat recovery from various sources: Review of technologies and implementation, Heliyon. (2023).

[8] Mahmoudi A, Fazli M, Morad MR. A recent review of waste heat recovery by Organic Rankine Cycle. Appl Therm Eng 2018;143:660–75.

[9] Koç A, Yağlı H, Koç Y, Uğurlu İ. Dünyada ve Türkiye'de Enerji Görünümünün Genel Değerlendirilmesi. Eng Machin Mag 2018;59(692).

[10] Achinas S, Euverink GJW. Elevated biogas production from the anaerobic co-digestion of farmhouse waste: Insight into the process performance and kinetics.Waste Manage Res 2019. 0734242X19873383.

[11] Achinas S, Krooneman J, Euverink GJW. Enhanced biogas production from the anaerobic batch treatment of banana peels. Engineering 2019.

[12] Bao J, Zhao L. A review of working fluid and expander selections for organic Rankine cycle. Renew Sustain Energy Rev 2013;24:325–42.

[13] İnternet: IEA, World Energy Outlook 2023, URL: World Energy Outlook 2023 – Analysis - IEA, Son Erişim Tarihi: 21.02.2024.

[14] Yağlı, H., Koç, Y., Koç, A., Görgülü, A., & Tandiroğlu, A. (2016). Parametric optimization and exergetic analysis comparison of subcritical and supercritical organic Rankine cycle (ORC) for biogas fuelled combined heat and power (CHP) engine exhaust gas waste heat. Energy, 111, 923-932.

[15] Yagli, H., Koc, A., Karakus, C., & Koc, Y. (2016). Comparison of toluene and cyclohexane as a working fluid of an organic Rankine cycle used for reheat furnace waste heat recovery. International Journal of Exergy, 19(3), 420-438.

[16] Takleh, H. R., & Zare, V. (2019). Employing thermoelectric generator and booster compressor for performance improvement of a geothermal driven combined power and ejector-refrigeration cycle. Energy Conversion and Management, 186, 120-130.

[17] Takleh, H. R., & Zare, V. (2019). Performance improvement of ejector expansion refrigeration cycles employing a booster compressor using different refrigerants: Thermodynamic analysis and optimization. International Journal of Refrigeration, 101, 56-70.

[18] Bao, J., & Zhao, L. (2013). A review of working fluid and expander selections for organic Rankine cycle. Renewable and sustainable energy reviews, 24, 325-342

[19] Chen, H., Goswami, D. Y., & Stefanakos, E. K. (2010). A review of thermodynamic cycles and working fluids for the conversion of low-grade heat. Renewable and sustainable energy reviews, 14(9), 3059-3067.

[20] Sprouse III, C., & Depcik, C. (2013). Review of organic Rankine cycles for internal combustion engine exhaust waste heat recovery. Applied thermal engineering, 51(1-2), 711-722.

[21] Yang, W., Feng, H., Chen, L., & Ge, Y. (2023). Power and efficiency optimizations of a simple irreversible supercritical organic Rankine cycle. Energy, 278, 127755.

[22] Quoilin, S., Orosz, M., Hemond, H., & Lemort, V. (2011). Performance and design optimization of a low-cost solar organic Rankine cycle for remote power generation. Solar energy, 85(5), 955-966.

[23] Calise, F., Capuozzo, C and Vanoli, L. (2013). Design and parametric optimization of an Organic Rankine Cycle powered by solar energy. American Journal of Engineering and Applied Sciences, 6(2), 178-204.

[24] Liu, X., Hu, G., & Zeng, Z. (2022). Potential of biomass processing using digester in arrangement with a Brayton cycle, a Kalina cycle, and a multi-effect desalination; thermodynamic/environmental/financial study and MOPSO-based optimization. Energy, 261, 125222.

[25] Liu, X., Hu, G., & Zeng, Z. (2023). Performance characterization and multi-objective optimization of integrating a biomass-fueled brayton cycle, a kalina cycle, and an organic rankine cycle with a claude hydrogen liquefaction cycle. Energy, 263, 125535.

[26] Yu, W., Liu, C., Ban, X., Li, Z., Yan, T., Xin, L., & Wang, S. (2024). A novel method for predicting the thermal stabilization temperature of organic Rankine cycle system working fluids based on transition state theory. Energy, 130378.

[27] Feng, J., Cheng, X., Wang, H., Zhao, L., Wang, H., & Dong, H. (2024). Performance analysis and multi-objective optimization of organic Rankine cycle for low-grade sinter waste heat recovery. Case Studies in Thermal Engineering, 53, 103915.

[28] Akkaya, A. V., & Sahin, B. (2009). A study on performance of solid oxide fuel cell-organic Rankine cycle combined system. International Journal of Energy Research, 33(6), 553-564.

[29] Wang, Z. Q., Zhou, N. J., Guo, J., & Wang, X. Y. (2012). Fluid selection and parametric optimization of organic Rankine cycle using low temperature waste heat. Energy, 40(1), 107-115.

[30] Xu, W., Deng, S., Zhao, L., Su, W., Zhang, Y., Li, S., & Ma, M. (2018). How to quantitatively describe the role of the pure working fluids in subcritical organic Rankine cycle: A limitation on efficiency. Energy conversion and management, 172, 316-327.

[31] Hærvig, J., Sørensen, K., & Condra, T. J. (2016). Guidelines for optimal selection of working fluid for an organic Rankine cycle in relation to waste heat recovery. Energy, 96, 592-602.

[32] Jeong, Y. S., Park, K., Jang, Y. C., & Moon, S. J. (2024). Optimal working-fluid selection for organic Rankine cycle integrated into a combined cycle cogeneration plant. Journal of Mechanical Science and Technology, 38(4), 2073-2080.

[33] Elmaihy, A., Rashad, A., Elweteedy, A., & Nessim, W. (2023). Energy and exergy analyses for organic Rankine cycle driven by cooling water of passenger car engine using sixteen working fluids. *Energy Conversion and Management: X*, *20*, 100415.

[34] Cengel, Y.A. and Boles,, M.A. (2008) Thermodynamics: an engineering approach, McGraw-Hill Inc., 6th. Ed., New York, 2008.

[35] Dincer, I., & Rosen, M. A. (2013). Exergy: energy, environment and sustainable development. Elsevier, 2nd. Ed., 2013.

[36] Kotas, T. J. (2013). The exergy method of thermal plant analysis. Elsevier.

[37] Safari, F., & Dincer, I. (2019). Development and analysis of a novel biomass-based integrated system for multigeneration with hydrogen production. International Journal of Hydrogen Energy, 44(7), 3511-3526.

[38] Yağlı, H., Karakuş, C., Koç, Y., Çevik, M., Uğurlu, İ., & Koç, A. (2019). Designing and exergetic analysis of a solar power tower system for Iskenderun region. International Journal of Exergy, 28(1), 96-112.

[39] Koç, Y., Yağlı, H., & Koç, A. (2019). Exergy Analysis and Performance Improvement of a Subcritical/Supercritical Organic Rankine Cycle (ORC) for Exhaust Gas Waste Heat Recovery in a Biogas Fuelled Combined Heat and Power (CHP) Engine Through the Use of Regeneration. Energies, 12(4), 575.

[40] Koc, Y., Kose, O., & Yagli, H. (2019). Exergy analysis of a natural gas fuelled gas turbine based cogeneration cycle. Int. J. Exergy, 30, 103-125.

[41] Ayub, A., Sheikh, N. A., Tariq, R., Khan, M. M., & Invernizzi, C. M. (2018). Exergetic optimization and comparison of combined gas turbine supercritical CO2 power cycles. Journal of Renewable and Sustainable Energy, 10(4), 044703.

[42] Abid, M., Adebayo, V. O., & Atikol, U. (2019). Energetic and exegetic analysis of a novel multi-generation system using solar power tower. International Journal of Exergy, 29(2-4), 211-235.

[43] Vélez, F., Segovia, J. J., Martín, M. C., Antolín, G., Chejne, F., & Quijano, A. (2012). A technical, economical and market review of organic Rankine cycles for the conversion of low-grade heat for power generation. Renewable and Sustainable Energy Reviews, 16(6), 4175-4189

[44] Andersen, W. C., & Bruno, T. J. (2005). Rapid screening of fluids for chemical stability in organic Rankine cycle applications. Industrial & Engineering Chemistry Research, 44(15), 5560-5566.

[45] Pethurajan, V., Sivan, S., & Joy, G. C. (2018). Issues, comparisons, turbine selections and applications–An overview in organic Rankine cycle. Energy conversion and management, 166, 474-488.

[46] Yang, A., Su, Y., Shen, W., Chien, I. L., & Ren, J. (2019). Multi-objective optimization of organic Rankine cycle system for the waste heat recovery in the heat pump assisted reactive dividing wall column. Energy Conversion and Management, 199, 112041.

[47] Yang, A., Su, Y., Chien, I. L., Jin, S., Yan, C., & Shen, W. (2019). Investigation of an energy-saving double-thermally coupled extractive distillation for separating ternary system benzene/toluene/cyclohexane. Energy, 186, 115756.

[48] Agromayor, R., & Nord, L. O. (2017). Fluid selection and thermodynamic optimization of organic Rankine cycles for waste heat recovery applications. Energy Procedia, 129, 527-534.

[49] Shu, G., Zhao, M., Tian, H., Huo, Y., & Zhu, W. (2016). Experimental comparison of R123 and R245fa as working fluids for waste heat recovery from heavy-duty diesel engine. Energy, 115, 756-769.