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https://doi.org/10.5109/7236905

出版情報：Evergreen. 11 (3), pp.2659-2667, 2024-09. 九州大学グリーンテクノロジー研究教育センター
バージョン：

Optimization and Analysis of Excess Heat Utilization from an Exhaust Outlet in a Waste Incinerator Plant - Case Study of The Hydro Drive Incinerator, West Java, Indonesia

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(Received May 7, 2024: Revised June 19, 2024: Accepted August 2, 2024).

Abstract: A novel strategy is presented for the utilization of the excess heat released from the exhaust gas of the incinerator system. Incineration technology is a flammable waste treatment process by means of oxidation at a very high temperature to produce waste heat from combustion. This wasted heat can be converted to electricity as part of an additional product from waste destruction. This study focuses on the binary cycle approach to generate electricity with a thermodynamic model. The simulation uses a hydro drive incinerator plant with a capacity of 30 tones/day that has been developed and established in Soreang, West Java, Indonesia. The simulations are carried out using EES software, which is used to solve the mass and energy balance according to the equation. Exergy analysis is used to identify the location, magnitude, and origin of the thermodynamic inefficiencies. In this research, the binary cycle incinerator hydro drive power plant use n-pentane as an organic working fluid. The simulation results of the n-pentane steam temperature in the turbine at about 120ºC and a pressure of 8.3 bar obtained a gross electric power of about 100kW with a cycle thermal efficiency of 15.59% and a flow rate of n-pentane of about 3.51 kg/s. The total destructive exergy value generated was 365.27 kW, with the largest value observed in the condenser. This result is quite feasible to be applied as additional output for the waste power plant pilot project in Soreang.

Keywords: waste incinerator; power plant; excess heat; binary cycle; exergy analysis

1. Introduction

Binary cycle power plant is one of the power generation technologies capable of generating electricity from energy sources with low enthalpy. Energy sources with low enthalpy can be obtained from potential energy such as geothermal, waste heat from burning waste, biomass, and others. The binary cycle is a method for generating electrical power from low-enthalpy heat sources (<150ºC) with two separate cycles, which are generally known as the Kalina cycle and the Organic Rankine cycle (ORC), which have different working fluids.[1,2]. The working fluid in binary cycles had a low boiling point to exploit a previously unusable low heat source, as in geothermal plants[3–5], solar power plant[6–8], biomass[9–11], and waste heat recovery from low heat sources[12–15].

The utilization of binary cycle technology in geothermal plants is increasing. Several studies suggest that varying pressure and working fluid can improve the efficiency of the binary cycle system. Shokati et al.[16] found that the dual-pressure ORC system generates more net electrical power than the basic ORC system, dual-fluid ORC, and Kalina cycle. In another study, Shokati et al.[17] reported that the single flash/ORC combination system with R141b fluid had higher efficiency than the NH3 working fluid and the double flash system. Asnawi[18] explores how certain zeotropic mixtures affect an ORC-VCR system's efficiency, with the R245fa/butane mixture showing the highest performance for specific mixture ratios. Xie[19] studied the unrecoverable losses in the evaporator of an ORC system and proposed using an organic Rankine double flash cycle to improve system efficiency. Diaz[20] compared the use of low-temperature geothermal energy in a poly-generation system and found that the ORC had an energy efficiency of 30.68% and exergy of 27.43%, making it more economically feasible than the Kalina Cycle (KAC) and Goswami Cycle (GOC) systems. The effect of varying turbine inlet temperature (TIT) on working fluids and different configurations is investigated. The results indicate that for low-temperature power generation, the most reasonable option is the reheat and recuperation cycle[21].

Currently, the issue of municipal waste has become a critical concern. During the subsequent phase of waste processing, where the waste is incinerated, the heat generated from waste combustion can be harnessed to produce electricity using ORC technology. Several studies have shown that low-heat incinerators can be used to heat the working fluid in ORC systems. An optimized modified organic Rankine cycle incinerator that uses R124a as a working fluid has been analyzed. This system produces a power output capacity of 3.19 MW when processing 40 tons of municipal solid waste daily[22]. The economic viability assessment of using an Organic Rankine Cycle (ORC) to utilize landfill gas showed a net output of 64.33 kW.[23]. The Organic Rankine Cycle Combined incinerator, which utilizes R245fa as the working fluid, generates 23.65 kW of power while treating 184.42 kg/hour of infectious medical waste of type 3 (RDF-3). The corresponding energy and exergy efficiencies achieved are 0.91% and 0.89%, respectively.[24,25].

This study focuses on optimization and analysis of excess heat utilization from an exhaust outlet in a waste incinerator plant with 30 tones /day in Soreang city, West Java. Incineration technology is a flammable waste treatment process by means of oxidation at a very high temperature to produce waste heat from combustion. This wasted heat can be converted to electricity as part of an additional product from waste destruction, one of the conversion technologies from heat to electricity is the ORC. This ORC technology uses a working fluid from the organic fluid group, which can be a hydrocarbon fluid or a refrigerant. Within the framework of the Hydro Drive Incinerator Organic Rankine Cycle (ORC) Power Plant, waste heat is harnessed as the principal heat source for the cycle. The working fluid employed in this primary cycle is thermal oil. The primary thermal oil cycle facilitates the evaporation of the organic working fluid in the subsequent cycle, referred to as the binary cycle. The evaporation process of the working fluid propels a turbine that is directly coupled to the generator.

This study aims to simulate the Organic Rankine Cycle (ORC) Incinerator Hydro Drive Power Plant, employing n-pentane as the organic working fluid. The simulation outcomes reveal that the steam temperature of n-pentane in the turbine is approximately 120°C, and the pressure is around 8.3 bar. These conditions yield a gross electrical power of about 100 kW, a cycle thermal efficiency of 4.61%, and an n-pentane flow rate of approximately 3.51 kg/s. These results are potentially applicable as supplementary output for the waste power plant pilot project in Soreang, West Java, Indonesia.

2. System Modeling

2.1. Hydro drive Incinerator Waste Destruction Pilot Plant

The incinerator is the most used waste destruction technology worldwide because it rapidly reduces significant volumes of waste to ash[26]. However, incinerators have a disadvantage in that they are less capable of burning wet waste, requiring additional heat energy to do so. The Hydro drive Incinerator is equipped with a rotary dryer that dries wet waste by passing it through and spraying it with hot combustion gas before entering the incinerator combustion chamber for burning. The hot, dry steam also acts as a catalyst in the combustion chamber, increasing the calorific value of waste and raising the temperature to at least 800°C. For the system to be both efficient and cost-effective, it is crucial that its operation does not depend on fossil fuels. Nevertheless, it is important to acknowledge that the combustion process, when conducted at elevated temperatures, could lead to substantial losses in exhaust heat.[27].

The pilot project incinerator for the Hydro drive 'Water Fuel' waste disposal process has been developed and operated at the Soreang waste area in Bandung Regency, with a capacity of 30 tons per day, as shown in Fig 1. However, the waste processing installation still generates excess heat of approximately 200°C.

Fig. 1: Hydro drive Incinerator Plant Bumi Resik, Soreang[28].

Table 1. Hydro drive Specifications[28]

Parameter	Specifications
Capacity	30 Ton/day
Waste characteristic	Domestic Waste
Gas flow system	Straight Flow
Combustion Effectiveness	+/- 95 %
Electricity requirement	380 VAC, 50 Hz, 3 Phase, 80 kW
Furnace boiler	
Chamber volume	1,5 m^3
Temperature	800 ^oC
Pressure	10 Bar
Rotary dryer temperature	500 ^oC

2.2 Binary Cycle Power plant

Waste is burned in an incinerator equipped with a rotary drum. The destruction capacity of 30 tons per day generates exhaust heat from the combustion. The waste combustion process occurs in the incinerator, but wet waste is first carried out on a rotary drum to dry before entering the incinerator combustion chamber. Under optimal combustion conditions (30 tons per day), the exhaust heat from the rotary drum will be used to dry the waste. The drum is 2181 kW (waste heating value LHV 1500 kcal/kg), assuming an ORC cycle increase efficiency of 10 %. This exhaust heat conversion has the potential to generate electricity with a capacity of 218 kW[29]. However, the installation of the hydro drive Incinerator ORC Power Plant, for now, is only designed at a gross power capacity of 100 kW. Figure 2 presents a schematic representation of the process involved in this waste-to-energy technology, specifically illustrating the basic cycle scheme of the hydro drive incinerator for an ORC power plant.

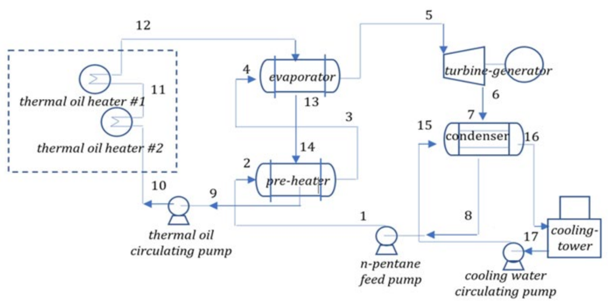


Fig. 2: Simplified Schematic Diagram of the Hydro drive Incinerator ORC Power Generation Process

3. Calculation and Optimization

3.1 Selection of Working Fluid and Key Technology in Binary Cycles

The turbine is the primary technology that be used in binary cycle systems. It converts heat energy from organic working fluids into mechanical and electrical energy. Turbines in binary cycles are called ORC turbines[30]. Along with the turbine, the working fluid selection is also crucial. Based on Table 2, Figure 3, and numerous studies on working fluids indicate that n-pentane is a preferred choice for ORC power plants. In comparison to other working fluids, such as HCFC 123, PF 5050, and ammonia, n-pentane demonstrates better performance[31]. Regarding thermal efficiency, n-pentane demonstrates the second-best performance after benzene (24.28%), with a value of 17.04%. n-pentane possesses low toxicity, with critical pressure and temperature values of 33.3 bar and 196.6°C, respectively. Its condensation pressure is 1 bar at 38°C, a flammable fluid. At a subsequent stage, Animesh et al.[32] conducted a study in which they tested R_{32} as an eco-friendly medium, which proved to be more environmentally regulated and safer to use than other working fluids.

Table 2. Properties related to thermodynamics, health, and the environment of several potential working fluids for binary cycles modified from DiPippo, 2007[1]

Fluid	Formula	Critical temp. (°C)	Critical pressure (Bar)	Molar Mass (Kg/Kmol)	Toxicity	Flammability	ODP**	GWP**
Propane	C_3H_8	96.95	42.36	44.09	Low	very high	0	3
i-Butane	i-C_4H_{10}	135.9	36.85	58.12	Low	very high	0	3
n-Butane	C_4H_{10}	150.8	37.18	58.12	Low	very high	0	3
i-Pentane	i-C_4H_{12}	187.8	34.09	72.15	Low	very high	0	3
n-Pentane	C_5H_{12}	193.9	32.4	72.15	Low	very high	0	3
R-12	CCl_2F_2	112	41.14	120.9	non-toxic	non-flam.	1	4.500
R-114	$C_2Cl_2F_2$	145.7	32.89	170.9	non-toxic	non-flam.	0.7	5.850
R134a	CH_2FCF_3	101	40.59	102	Low	non-flam.	0	1.430
R254fa	$C_3H_3F_5$	154	36.51	134	Low	non-flam.	0	1030
Ammonia	NH_3	133.6	116.27	17.03	Toxic	Lower	0	0
Water	H_2O	374.1	220.89	18.02	non-toxic	non-flam.	0	-

*Ozone Depletion Potential ** Global Warning Potential

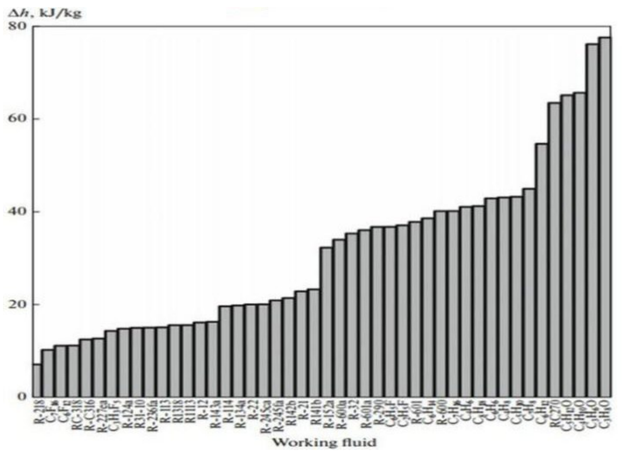


Fig. 3: Projected variation in the thermal energy of the working fluid within the 2.5 MW binary turbine, given a geothermal fluid temperature of 120°C[1]

3.2 Thermodynamic Calculations

The basic thermodynamic process analysis of ORC can be shown as follows[33,34] :

Binary cycle:

Turbine power

$$\dot{P}_t = \dot{m}_{np}(h_5 - h_6) \quad (1)$$

Calorific output on the condenser side:

$$\dot{Q}_{out} = \dot{m}_{np}(h_7 - h_8) \quad (2)$$

Energy balance on the condenser side:

$$\dot{m}_{ct}(h_{16} - h_{15}) = \dot{m}_{np}(h_7 - h_8) \quad (3)$$

Power of n-pentane feed pump:

$$\dot{P}_{pnp} = \dot{m}_{np}\,(h_1 - h_8\,) \quad (4)$$

Water circulation pump power:

$$\dot{P}_{pcws} = \dot{m}_{cws}\,(h_{15} - h_{17}\,) \quad (5)$$

Energy balances pre-heater:

$$\dot{m}_{toil}\bar{c}_{toil}(T_{oil14} - T_{oil9}) = \dot{m}_{np}(h_3 - h_2) \quad (6)$$

Pre-heater capacity:

$$\dot{Q}_{pre} = \dot{m}_{np}(h_3 - h_2) \tag{7}$$

Heat enters the evaporator:

$$\dot{Q}_{eva} = \dot{m}_{np}(h_5 - h_4) \tag{8}$$

Primary cycle

Thermal oil pump ~~work~~ power:

$$\dot{P}_{toil} = \dot{m}_{toil}\ (h_{10} - h_9\ ) \tag{9}$$

Energy balance of the evaporator:

$$\dot{m}_{toil}\bar{c}_{toil}(T_{oil12} - T_{oil13}) = \dot{m}_{np}(h_5 - h_4) \tag{10}$$

The binary cycle system efficiently converts thermal energy into mechanical power. The turbine's power output is determined by the mass flow rate of n-pentane and the enthalpy difference at the turbine's inlet and outlet. The condenser's calorific output measures the heat rejected from n-pentane, balancing with the cooling water's heat absorption. The n-pentane feed and water circulation pump powers are based on their respective enthalpy differences.

The pre-heater's energy balance ensures that the heat transferred from thermal oil to n-pentane matches the thermal oil's temperature change. The pre-heater capacity and evaporator heat input represent the heat absorbed by n-pentane. The thermal oil pump power indicates the energy needed to circulate the thermal oil. The evaporator energy balance confirms consistent heat transfer from thermal oil to n-pentane. These equations collectively define the thermodynamic relationships and energy flows, ensuring efficient energy conversion.

3.3 Binary cycle heat dissipation

Since the amount of unused heat is much greater than the amount of electricity produced, the heat dissipation system is critical for binary cycle power plants [35,36]. The primary heat loss in the cycle occurs during the condensation process of the working fluid.

$$Q_{rej} = Q_{in}\ (1 - \eta_{th}\ ) \tag{11}$$

The heat lost to atmosphere per unit work is:

$$Q_{rej} = P_{net}\frac{1-\eta_{th}}{\eta_{th}} \tag{12}$$

Table 3. Estimation data

Parameter	Value
Atmospheric pressure (p_o)	1 atm
Ambient temperature (T_x)	27 ^{0}C
Turbine inlet temperature (T_5)	120 ^{0}C
Turbine outlet temperature (T_6)	79.6 ^{0}C
Pressure	8.6 bars
Mass flow rate	3,5 kg/s
Generator efficiency	80 %
Gross power	100 kW

Numerous strategies exist for the incorporation of waste heat dissipation systems in binary cycle power plants. The two most prevalent and commercially accessible systems are those that utilize water-cooled condensers and air-cooled condenser heat exchanger systems. The former option is more cost-effective if makeup water is available. The latter option uses an air-cooled condenser, which is more economical. Nevertheless, its power capacity is significantly influenced by meteorological conditions, with its net power output typically varying between 20% and 25%. Power plants that utilize air-cooled condensers tend to yield greater power output during nighttime hours[37].

Then, thermal cycle efficiency can be calculated using the first law of thermodynamics articulates the concept of thermal efficiency as follows:

$$\eta_{cycle} = \frac{\cancel{W_{net}}\,P_{net}}{Q_{in}} \tag{13}$$

So

$$\eta_{cycle} = \frac{(\dot{P}_t - \dot{P}_{pnp} - \dot{P}_{toil} - \dot{P}_{pcws})}{\dot{Q}_{eva}} \tag{14}$$

For binary cycle power plants, the thermal efficiency is generally in the range of 10-15% [38,39].

3.4 Exergy analysis

Thermodynamic analysis examines exergy, as it effectively identifies energy losses within components and subsystems. This approach enables the development of methods to minimize system losses, thereby enhancing exergy efficiency.

The fundamental equation of exergy analysis is employed to ascertain the extent of exergy destruction for each component and the overall system[40,41]:

$$\dot{E}_{x.n} = \dot{m}(h - h_0 - T_0(s - s_0)) \tag{15}$$

The equation represents the specific flow exergy, which quantifies the maximum useful work obtainable from a fluid stream as it reaches equilibrium with the environment. This equation helps identify inefficiencies in thermodynamic processes by accounting for deviations from the ideal state, thereby highlighting the portion of energy that is irreversibly lost.

The binary system of Hydro drive Incinerator ORC power generation process is further described in Fig 2 and equilibrium equations for each main component of the system are given in Table 4.

Table 4. Exergy balance equations of hydro drive system

System Components	Mass balance	Exergy balance
Pre-Heater	$\dot{m}_2 + \dot{m}_{14} = \dot{m}_3 + \dot{m}_9$	$\dot{E}x_2 + \dot{E}x_{14} = \dot{E}x_3 + \dot{E}x_9 + \dot{E}x_{D\ PreH}$
Evaporator	$\dot{m}_4 + \dot{m}_{12} = \dot{m}_5 + \dot{m}_{13}$	$\dot{E}x_4 + \dot{E}x_{12} = \dot{E}x_5 + \dot{E}x_{13} + \dot{E}x_{D\ Evp}$
Turbine	$\dot{m}_5 = \dot{m}_6$	$\dot{E}x_5 = \dot{E}x_6 + \dot{P}_T + \dot{E}x_{D\ Turb}$
Condenser	$\dot{m}_7 + \dot{m}_{15} = \dot{m}_8 + \dot{m}_{16}$	$\dot{E}x_7 + \dot{E}x_{15} = \dot{E}x_8 + \dot{E}x_{16} + \dot{E}x_{D\ Con}$
Feed Pump	$\dot{m}_8 = \dot{m}_1$	$\dot{E}x_8 + \dot{P}_{pnp} = \dot{E}x_1 + \dot{E}x_{D\ Pump}$

4. Simulation Results and Discussion

The boundary conditions of the proposed model are shown in Table 3. Figure 4 validated the thermal distribution of the incinerator, which is intended for use in an ORC power plant. The peak temperature of the waste heat generated in the combustion chamber is approximately 568°C, and the exhaust is 215 °C. In other components such as the inside of the rotary dryer, the average temperature is 120 °C, while the exhaust is 78 °C. The heat will be converted into electricity using ORC technology. Note that, with low temperatures, ORC technology can generate electricity.

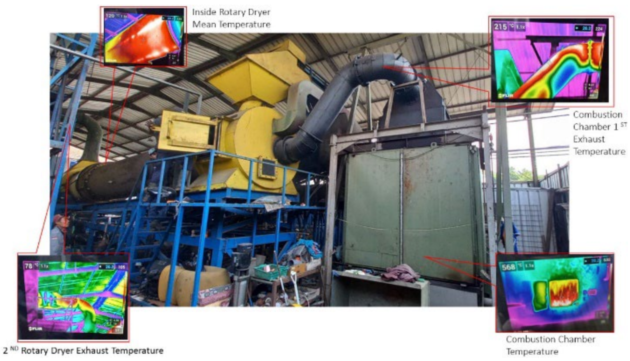


Fig. 4: Temperature distribution of Incinerator in Soreang

Figure 5 illustrates the schematic diagram of hydro drive incinerator ORC power generation process and the thermal profile of the incinerator, which is intended for use in an ORC power plant. demonstrates that the introduction of n-pentane in the saturated steam phase into the turbine occurs at a temperature of 120.5°C (point 1). As the working fluid expands within the turbine, this results in a reduction in both steam pressure and temperature. The fluid then enters the condenser at 79.6°C (point 2), where it undergoes a heat exchange with water from the cooling tower to maintain an energy balance. At point 3, n-pentane from the condenser output becomes the saturated liquid phase. Then it will be pumped to the pre-heater (point 4) and the evaporator (point 5). The results are presented in Fig 6.

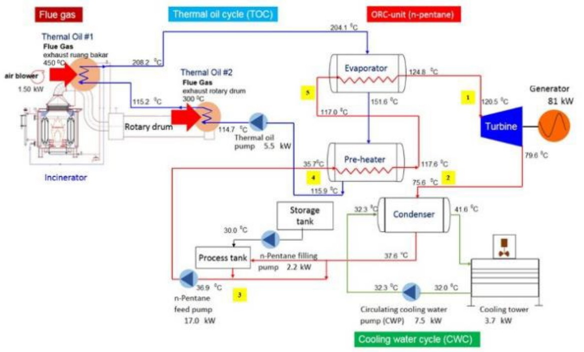
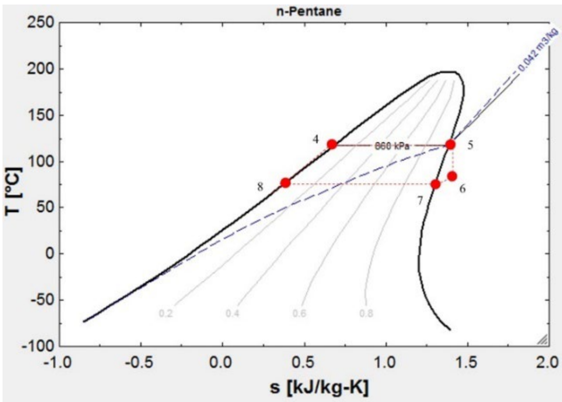
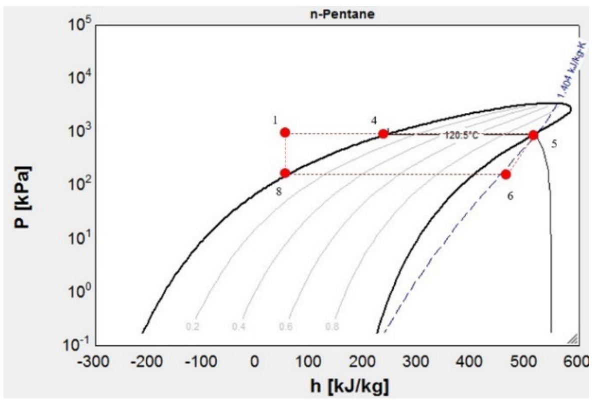


Fig. 5: Schematic Diagram of Hydro drive Incinerator ORC Power Generation Process

Figure 6 shows a representation of the ORC incinerator simulation using n-pentane, where the turbine inlet pressure is 860 kPa (8,6 bar). This steam expands through a turbine, where mechanical work is converted into electrical energy. Pressure drops after expansion and going to the condenser.



(a) T-s diagram



(b) P-h diagram

Fig. 6: (a) T-s and (b) P-h diagram of n-Pentane fluid for ORC Incinerator Power Generation cycle

Based on the simulation, optimal conditions for the inlet pressure to turbine are 120 ºC and 860 kPa (8,6 bar). The calculation result of some parameters uses equations (1) to (14) obtained: the flow working fluid 3.51 kg/s, the cycle thermal efficiency 15.59% and the turbine power around 100kW. The value of thermal efficiency when compared to several studies conducted by Prasetyo et al [42], Ping et al.[43], Sim et al.[44] is still have values within the same range.

It is evident that in certain instances, the degree of thermal efficiency can be considerably impacted by various factors. These include the temperature of the heat source, the characteristics of the working fluid, the configuration of the system, the performance of the individual components, and the external environmental conditions.[45]. In this context, there exist numerous strategies that can be employed with the objective of enhancing the efficiency and performance of a thermal system.

The overall exergy destruction rate of each component is presented in Table 5. The results indicate that the condenser component exhibits the highest destructive exergy, with a value of 160 kW. This is followed by the evaporator, preheater, turbine, and feed pump components, with values of 143.79 kW, 54.56 kW, 5.37 kW, and 1.20 kW, respectively. A total of 365.27 kW of exergy destruction occurs in the system.

Table 5. Exergy destruction of main ORC components

Component	Exergy Destructive ($\dot{E}_x$)	Units
Turbine	5.37	kW
Condenser	160.35	kW
Feed Pump	1.20	kW
Pre Heater	54.56	kW
Evaporator	143.79	kW
Total exergy destruction		**365.27 kW**

In essence, condensers and evaporators are components that must undergo repairs. The result researched of Garcia et al.[46] indicate that one method to enhance the destructive exergy value of the condenser is to elevate the ORC condensation temperature and the evaporator temperature. Therefore, reducing the exergy destruction value of condensers and evaporators has the potential to significantly impact system performance[47].

Although exergy destruction in turbines represents only a modest proportion of the overall phenomenon, it is nonetheless a significant factor. However, it is possible that increasing the efficiency of turbines through technical changes and the introduction of new technologies may have a more pronounced effect on the system. In addition, the optimization of isentropic efficiency and operational parameters can result in a reduction of exergy destruction in the turbine[48].

5. Conclusion

The optimization and analysis of excess heat utilization from an exhaust outlet in a waste incinerator plant - Case Study of the hydro drive incinerator has been studied in this work. The excess heat from a Hydro drive Incinerator Waste Destruction Pilot Plant will be converted to electricity as part of an additional product from waste destruction using the Organic Rankine Cycle technology. The working fluid used in this main cycle is n-pentane. The main cycle of thermal oil results in the evaporation of the organic working fluid in the cycle below it (binary cycle). The simulation results of the n-pentane steam temperature in the turbine at about 120ºC and a pressure of 8.3 bar obtained a gross electric power of about 100 kW with a cycle thermal efficiency of 15.59% and a flow rate of n-pentane of about 3.51 kg/s. The total exergy destruction value generated was 365.27 kW, with the largest value observed in the condenser and evaporator. Improvements such as increasing the condensation temperature need to be made to make the system improve. The result is quite feasible to be applied as additional output for hydro drive incinerator project, where a binary cycle in a small-scale incinerator plant has not applied before in Indonesia.

Acknowledgements

This research was funded by a grant from the Indonesia Endowment Fund for Education (LPDP) Ministry of Finance Indonesia, grant No. PRJ-30/LPDP/2020, and BRIN research grant 2023.

Nomenclature

$\dot{P}_t$	Turbine power (kW)
$\dot{P}_{pnp}$	n-pentane feed pump power (kW)
$\dot{P}_{ptoil}$	Thermal oil pump power (kW)
$\dot{P}_{pcws}$	Cooling water circulation pump power (kW)
η_{cycle}	Thermal cycle efficiency (%)
η_{th}	Turbine efficiency (%)
$\dot{m}$	Mass flow rate (kg/s)
$\dot{m}_{np}$	Mass flow rate of n-pentane (kg/s)
$\dot{m}_{toil}$	Thermal oil mass flow rate (kg/s)
$\dot{m}_{ct}$	Specific heat of thermal oil (kJ/kg)
$\bar{c}_{toil}$	Pump enthalpy n-feed discharge (kJ/kg)
h	Enthalpy (kJ/kg)
s	Entropy (kJ/kg.K)
T_{gas}	Incinerator gas temperature (°C)
T_{oil}	Thermal oil temperature (°C)
T_{np}	n-pentane temperature (°C)
T_{ct}	CT cooling water temperature (°C)
$\dot{Q}_{eva}$	Evaporator heat (kW)
$\dot{Q}_{con}$	Condenser heat (kW)

$\dot{Q}_{pre}$	Pre-heater heat (kW)

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