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Research Article

Optimizing Waste Heat Recovery with a Triple Combined Power Cycle

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Abstract:

This study aims to utilize waste heat released from an industrial facility at 566 °C and 1.9 bar pressure to generate additional power for the facility. The goal is to reduce the environmental impact of waste heat while enhancing energy efficiency through the application of a triple combined cycle. Initially, the high-temperature waste heat is employed as a thermal source in a gas turbine cycle. The waste heat from the gas turbine is then transferred to an organic Rankine cycle (ORC), where it is used to generate low-temperature steam. In the final stage, the remaining waste heat is harnessed in a Kalina cycle to produce additional power. This triple combined cycle allows for the efficient utilization of waste heat across different temperature ranges, minimizing its environmental impact. The proposed system not only increases the facility's energy output but also mitigates the adverse environmental effects of waste heat. The results demonstrate that the system offers an effective solution for waste heat recovery. Using the model, an additional power of 1688 kW can be produced, which contributes 29.82 % to the actual system..

1. Introduction

Recently, the continuous increase in energy demand and the limited availability of fossil fuel resources have made it necessary to explore more sustainable and efficient energy production methods. In this context, the recovery of waste heat in industrial facilities not only increases energy efficiency, but also reduces costs and alleviates environmental impacts. Studies have shown that the waste heat produced in biogas plants has a significant energy potential [1], [2], [3], [4], [5], [6]. For this reason, the effective use of this potential can contribute to additional electricity production. In this study, power production with the waste heat in the biogas facility via the gas turbine cycle, organic Rankine cycle and Kalina cycle was modelled. When current literature is examined, it has been determined that the three mentioned systems are the most common power generation systems in studies where waste heat is integrated into existing systems [6], [7], [8], [9], [10], [11]. Therefore, modelling all three systems together as a single system has been considered from a thermodynamic perspective.

The important part in the evaluation of waste heat should be the thermal source temperature ranges for gas turbine cycle (GT), organic Rankine cycle (ORC) and Kalina Cycle (KC). Because it has been shown in the studies that each cycle is advantageous in different temperature ranges and applications [6], [12], [13], [14], [15], [16]. Gas turbine cycles are the most suitable option for waste heat recovery by using high temperature heat sources (usually above 500 °C). It works very efficiently at high temperature and pressure differences and can be used directly in electricity generation. It is preferred in industries such as steel, glass and cement for the recovery of high temperature waste gases. However, it does not work at low temperatures and its initial investment cost is high [17], [18]. In medium and low temperature ranges (90–350 °C), Organic Rankine Cycle (ORC) stands out. This cycle can work efficiently at low temperatures using organic fluids and is widely used in geothermal energy, biomass and low temperature waste heat sources. While the compact structure of the system and low maintenance requirement offer advantages, it is not as effective as gas turbine at high temperatures [8], [9]. For lower temperatures (50–350 °C), the Kalina

Cycle can be considered as advantageous. Thanks to the use of a dual-component fluid such as ammonia-water mixture, it increases thermodynamic efficiency in a wide temperature range and is better adapted to low temperature differences. It is preferred in applications such as geothermal energy and seawater desalination. However, the complexity of its design and high maintenance requirements limits its prevalence [11], [19], [20], [21].

In this study, the exhaust gas waste heat released to the atmosphere at high temperature (567 ºC) is designed to generate additional power by using it in the gas turbine, ORC and Kalina Cycle, respectively. The use of waste heat in the GT, ORC and KC order offers a more efficient option.

2. Material and Methods

In this study, a model evaluating the exhaust gas waste heat of a biogas plant in Gaziantep was developed. The model produces additional power using waste heat as a thermal source in the gas turbine cycle (GT), organic Rankine cycle (ORC), and Kalina cycle (KC). The schematic layout of the GT-ORC-KC is given in the Figure 1.

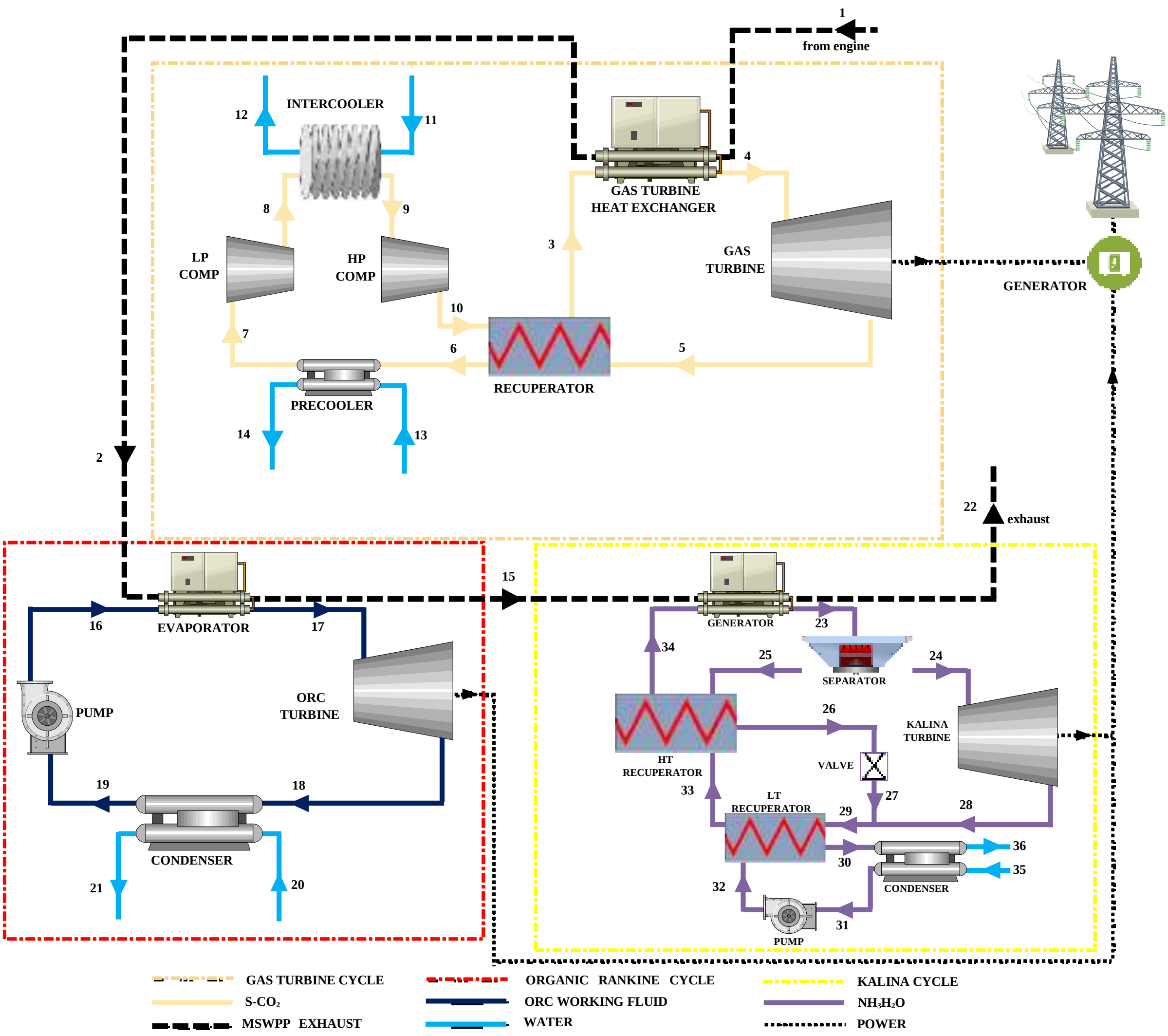

Figure 1. *The schematic layout of the GT-ORC-KC*

The system consisted of three main cycles that gradually converted waste heat into energy at different temperature levels. In the first stage, a gas turbine cycle is used. Here, the exhaust gas heats CO_2 in the gas turbine heat exchanger and increases it to a supercritical level. Energy was then produced when S-CO_2 passed through the turbine. S-CO_2 exiting the turbine increases efficiency by preheating the inlet air through the recuperator. The precooler and intercooler reduce the heat generated in the compressors. Low-pressure and high-pressure

compressors support the overall efficiency of the system by compressing the CO_2.
In the second stage, the remaining waste heat from the gas turbine cycle vaporizes the organic liquid in the ORC evaporator. Here, "Toluene" which has a high decomposition temperature, was used as the organic fluid. The steam expands in the ORC turbine and produces energy. Then, the steam turns into a liquid in the condenser, is used again in the system, and is directed to the evaporator again with the ORC pump. The Kalina cycle comes into play in the final stage. In this cycle, the generator vaporizes the ammonia-water mixture using the waste heat of the exhaust gas. The steam is separated by a separator, and the high-energy-carrying part expands in the Kalina turbine and produces energy. The low-temperature recuperator and high-temperature recuperators optimize the energy transfer, while the pump and valves circulate the fluid. This system aims to provide high efficiency for the conversion of waste heat into energy. Sustainable energy production is achieved by utilizing each temperature level to the maximum extent owing to the integration of different cycles.

3. Results and Discussions

The engineering equation solver (EES) program was used to perform thermodynamic analyses. Thermodynamic properties, and exergy rates of flow streams are given in Table 1.

Table 1. *Thermodynamic properties, and exergy rates in the plant*

St.	Fluid	T (°C)	P (bar)	$\dot{m}$ (kg/s)	h (kJ/kg)	X (%)	s (kJ/kg-K)	ex (kJ/kg)	$\dot{E}x$ (kW)
1	Air	566	1.9	16	865.5	-	6.59	305.9	4895
2	Air	380	1.9	16	663.5	-	6.318	183.7	2939
3	CO_2	374	207.2	14.5	-8596	-	4.603	419.7	6087
4	CO_2	546	207.2	14.5	-8400	-	4.871	537.1	7789
5	CO_2	428.8	74	14.5	-8539	-	4.882	397.2	5761
6	CO_2	130.5	74	14.5	-8846	-	4.314	253.6	3677
7	CO_2	40	74	14.5	-8928	-	4.086	238.9	3465
8	CO_2	83.11	123.8	14.5	-8894	-	4.091	272.1	3946
9	CO_2	40	123.8	14.5	-8928	-	3.989	267.4	3878
10	CO_2	83.11	207.2	14.5	-8894	-	3.994	300.6	4360
11	Water	20	1	5.081	84.01	-	0.2965	0	0
12	Water	42	1	5.081	176	-	0.599	3.287	16.7
13	Water	20	1	11.33	84.01	-	0.2965	0	0
14	Water	42	1	11.33	176	-	0.599	3.287	37.23
15	Air	294	1.9	16	572.9	-	6.169	136.7	2187
16	Toluene	289.3	40.85	28.1	427.6	-	0.8921	188	5284
17	Toluene	303.6	40.85	28.1	473	-	0.9718	210.1	5903
18	Toluene	236.5	13.62	28.1	459.1	-	0.9766	194.8	5474
19	Toluene	286.5	27.59	28.1	424.6	-	0.8913	185.3	5208
20	Water	20	1	9.27	84.01	-	0.2965	0	0
21	Water	42	1	9.27	176	-	0.599	3.287	30.47
22	Air	80	1.9	16	353.9	-	5.686	59.43	950.8
23	NH_3H_2O	286.5	40	1.606	2128	80	5.683	17049	27375
24	NH_3H_2O	286.5	40	1.124	2000	93	5.429	19528	21949
25	NH_3H_2O	286.5	40	0.4817	2428	49.67	6.097	10859	5231
26	NH_3H_2O	54.84	40	0.4817	8.843	49.67	0.6412	10038	4836

27	NH_3H_2O	55.25	13.33	0.4817	8.843	49.67	0.6513	10035	4834
28	NH_3H_2O	190	13.33	1.124	1781	93	5.514	19246	21632
29	NH_3H_2O	103.8	13.62	1.606	1222	80	4.039	16460	26431
30	NH_3H_2O	47.98	13.33	1.606	420.1	80	1.721	16338	26234
31	NH_3H_2O	32.34	13.33	1.606	11.27	80	0.4363	16306	26183
32	NH_3H_2O	32.98	40	1.606	15.82	80	0.4385	16310	26188
33	NH_3H_2O	39.84	13.33	1.606	46.85	80	0.5514	16307	26185
34	NH_3H_2O	72.5	40	1.606	207.8	80	1.028	16329	26219
35	Water	20	1		84.01	-	0.2965	0	0
36	Water	42	1		176	-	0.599	3.287	20.64

Energy and exergy analyses of the system were performed using actual operating data from the Gaziantep Municipality Solid Waste Power Plant. The heat transfer rates, work, exergy destruction, and exergy efficiencies of all sub-components were evaluated through equations related to continuity, energy, and exergy [5], [6], [17], [18]. The energetic and exergetic analyses of subcomponents are given in Table 2.

Table 2. *Thermodynamic results of the GT-ORC-KC*

Component	$\dot{Q}$ (kW)	$\dot{W}$ (kW)	$\dot{E}x_F$ (kW)	$\dot{E}x_P$ (kW)	$\dot{E}x_D$ (kW)	ε (%)
GTHE	3231	0	1956	1703	253.20	0.8705
GT-LPC	0	491.9	491.9	471.4	20.55	0.9582
GT-HPC	0	491.9	491.9	471.4	20.55	0.9582
GT-REC	4353	0	2047	1737	309.60	0.8487
GT-TUR	0	2021	2066	2021	44.87	0.9783
GT-INT	467.3	0	57.89	16.7	41.19	0.2885
GT-PRE	1184	0	212.2	37.23	175	0.1754
EVAP	1449	0	752.1	619.1	133	0.8232
ORC-TUR	0	389.6	429.2	389.6	39.57	0.9078
ORC-PUMP	0	82.95	82.95	76.46	6.49	0.9218
ORC-CON	968.8	0	266.4	30.47	236	0.1144
GEN	3504	0	1236	1156	80.27	0.9351
SEP	0	0	27375	21949	5426	0.8018
KAL-TUR	0	246.1	316.9	246.1	70.83	0.7765
VAL	0	0	4836	4834	1.43	0.9997
KAL-LTR	1887	0	245.4	45.5	199.9	0.1854
KAL-CON	656.4	0	51.23	20.64	30.58	0.4030
KAL-PUMP	0	7.304	7.304	5.727	1.577	0.7841
KAL-HTR	1166	0	395.2	34.11	361	0.08633
GT-ORC-KAL			Energy efficiency (%)			20.62
			Exergy efficiency (%)			42.79

4. Conclusions

In this study, thermodynamic analyses of a GT-ORC-KAL cycles are performed. The exhaust gas of an actual solid waste power plant which has a 5.66 MW installed power capacity is used as heat source of the cycle. The thermodynamic analyses are conducted with Engineering Equation Solver (EES). Results are summarized according to thermodynamic analyses as follows:

- As a result of the thermodynamic analyses net power output of the GT, ORC and KAL cycles were evaluated as 1037 kW, 307 kW and 344 kW, respectively. Thus, a total power production of 1688 kW was achieved.
- By means of 1688 kW, 29.82 % additional power can be produced to the actual system.
- The energy efficiencies of the GT, ORC and KAL cycles were found to be 32.09 %, 21.16 % and 9.82 %, respectively. The exergy efficiencies of the GT, ORC and KAL cycles were also obtained as 53.02 %, 40.77 % and 27.84 %, respectively.
- The total energy and exergy efficiencies of the GT-ORC-KAL were calculated as 20.62 % and 42.79 %, respectively.
- The exergy efficiencies of heat exchangers can be expected lower when compared to other components in thermodynamic systems because of their high amount of exergy destructions. The highest exergy destruction rates were produced by GT precooler, ORC condenser and Kalina high temperature recuperator.
- On the other hand, the exergy destruction in power-generating and consuming equipment is generally lower because these devices undergo less irreversible heat transfer, convert energy directly into mechanical work more efficiently, and have lower entropy generation. Their design focuses on optimizing efficiency and minimizing irreversibilities, leading to reduced exergy losses. Unlike heat exchangers, where large temperature differences and high entropy production cause significant exergy destruction, power equipment operates with more controlled processes and utilizes high-quality energy forms, contributing to their lower exergy destruction. Due to this, the lowest exergy destruction rates were produced by turbine, compressors, pumps and valve.
- The importance of waste heat recovery is presented with this theoretical study. The model was developed and analysed for an actual power plant in terms of the additional power that can be supplied to this plant. For further studies, thermoeconomic analyses and optimizations can be integrated to this study.

Author Statements:

- **Ethical approval:** The conducted research is not related to either human or animal use.
- **Conflict of interest:** The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

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- **Data availability statement:** The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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