

## COMPARISON OF FIVE DEVELOPED POWER CYCLES IN THE FRAME OF WASTE HEAT RECOVERY

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### Abstract

A thermodynamic comparison of five developed power cycles which are gas turbine (GT), Kalina (KAL), organic Rankine (ORC), gas turbine-Kalina (GT-KAL) and gas turbine-organic Rankine (GT-ORC) fed by the waste heat of an actual power plant system in Gaziantep is presented in this paper. The waste heat has a temperature and a pressure of 566 °C and 1.9 bar, respectively. In order to compare the thermodynamic performance of the power cycles, various parametric studies were performed by using the effect of the values of the pressure ratio of the cycles, the temperature of the exhaust gas, the logarithmic mean temperature difference of the heat exchangers and the turbine inlet and the outlet pressures in the given ranges. The net power output of GT, KAL, ORC, GT-KAL and GT-ORC was found to be 1095 kW, 955 kW, 585 kW, 1508 kW and 1594 kW, respectively. The thermodynamic results showed that the GT-KAL cycle has the best thermodynamic performance in terms of energetic and exergetic efficiencies such as 19.71% and 40.53%, respectively, as well as in terms of the highest net power production of 1594 kW from the available exhaust gas.

**Keyword:** Waste Heat Recovery, Gas Turbine, Kalina, Organic Rankine, Energetic Efficiency, Exergetic Efficiency.

### 1. Introduction

There are many parameters in power plants that should be taken into account for improvements of system efficiencies. The

efficiency improvement is a big problem for the companies, which are not only related to technical reasons, but also it is fundamentally related to economic reasons.

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Due to this, all possibilities to improve the total efficiencies of the systems should be utilized. Therefore, it is possible to develop thermodynamic systems with power production methods that can be added to existing power plants. It can be possible to mention that there are many studies in this field in the literature [1-10]. In this manner, the gas turbine, the organic Rankine and the Kalina cycles are adapted to an actual power plant, which is located in Gaziantep in order to increase its total efficiency. In order to power production, all gas turbine systems are operated by means of Brayton cycle principles.

Gas turbines can be classified into three groups, which are open cycle in which air is working fluid, closed cycle with air or other fluid as working fluid and semi-closed cycle. In addition to this, heat sources such as fossil, biomass, nuclear and solar are other parameters for classification of closed cycle gas turbines. Low-grade heat sources of gas turbine and diesel engine exhausts are recently considered to supply global energy requirements due to their significant energy potential [11-14].

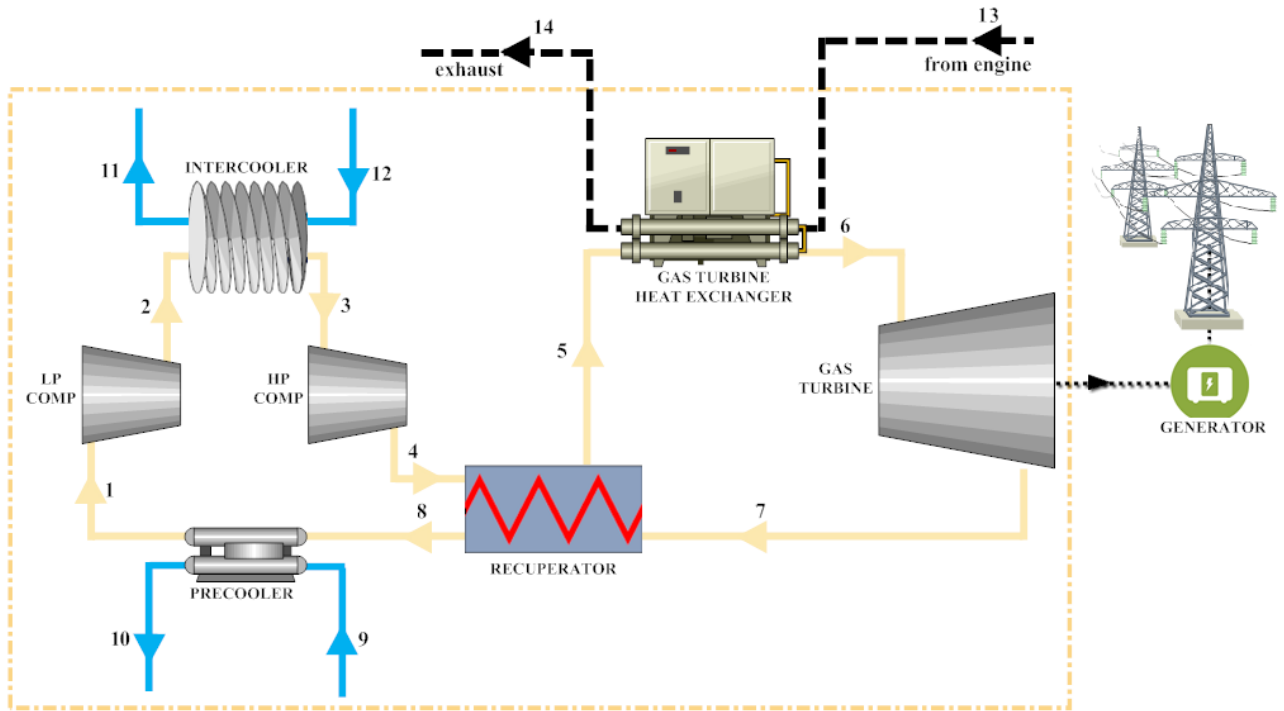
Organic Rankine cycle (ORC) is also an important low-grade thermal energy recovery technology because of its small-scale feature. ORC can be used for all kinds of low-temperature heat sources including geothermal energy, solar energy, biomass energy, and especially waste heat energy [15-17].

In addition to these, two power cycles, Kalina cycle can be considered as another alternative power production method for increasing the overall system efficiency. Kalina cycle was designed for a new cycle called as the Kalina using a bottoming cycle instead of the Rankine cycle in combined cycle power plants in 1989. Usage of an ammonia-water mixture instead of water as

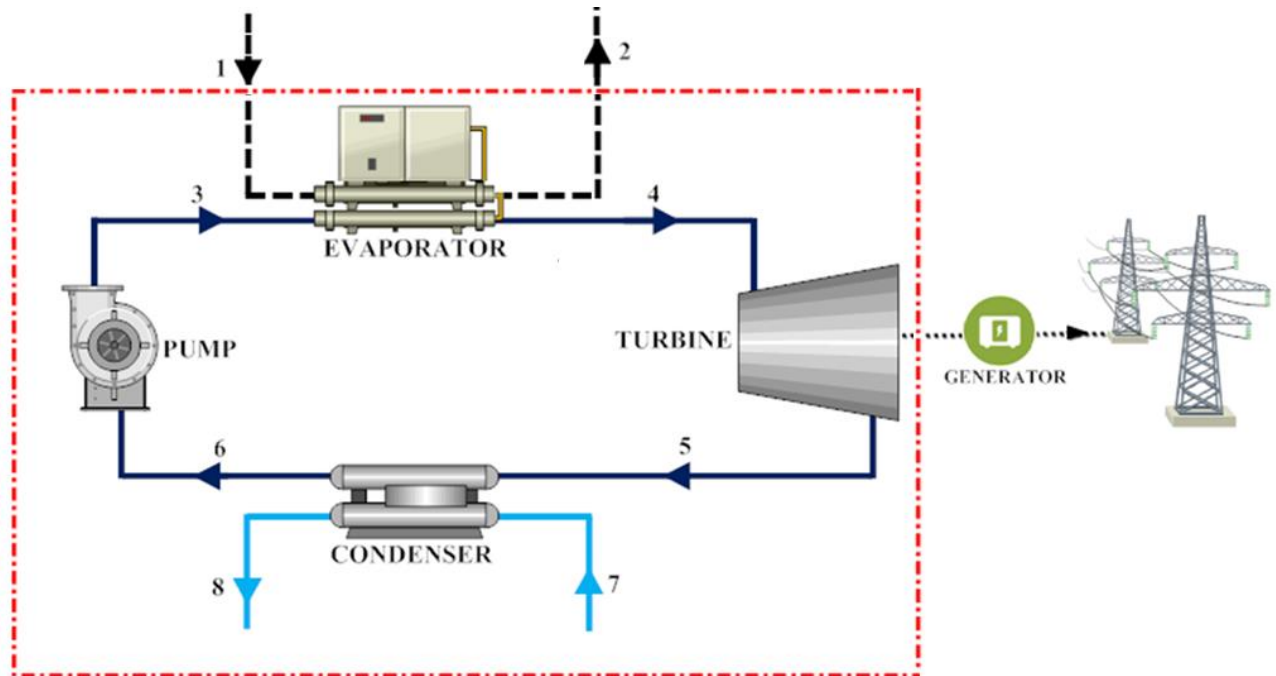
working fluid was a possible way to improve the efficiency of steam turbine processes [18-19].

## 2. Materials and Methods

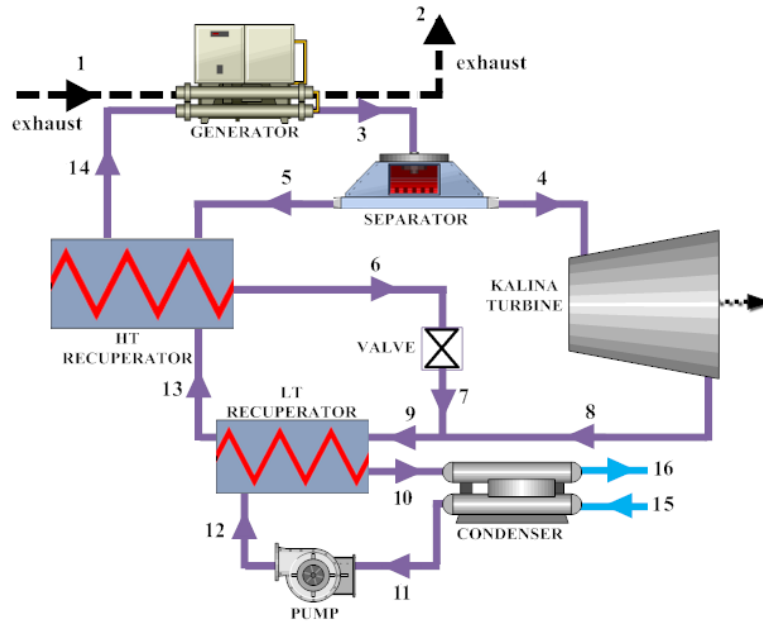
In this study, renewable and sustainable models adapted to the actual system are considered from the point of view of their thermodynamic analyses. All adapted models are designed so as to produce more electrical power in addition to the existing power production capacity of the Gaziantep Municipal Solid Waste Power Plant by utilizing the exhaust gases of the plant as a heat source. The temperature, pressure and mass flow rate of the exhaust gases of the plant are 566.7 °C, 1.9 bar and 16 kg/s, respectively. System descriptions of all models are given and then thermodynamic analyses of all models are performed with respect to their design parameters [1, 4, 7]. The schematics of designed models are given in Figures from 1 to 5. A gas turbine heat exchanger (GTHE), a gas turbine (GT), a recuperator (REC), a low pressure compressor (LPC), a high pressure compressor (HPC), a precooler (PRE) and an intercooler (INT) are used for the gas turbine cycle. Organic Rankine cycle consists of an evaporator (EVAP), an ORC turbine (OT), an ORC condenser (OC) and an ORC pump (OP). Lastly, in order to create the Kalina cycle, a generator (GEN), a separator (SEP), a turbine (KT), a valve (VAL), a low temperature recuperator (LTR), a condenser (KCON), a pump (KP) and a high temperature recuperator (HTR) are used [1, 4, 7]. The last two cycles, GT-ORC and GT-KAL, are composed of gas turbine, Kalina and organic Rankine cycles. The working fluids used in gas turbine, organic Rankine and Kalina cycles are supercritical CO<sub>2</sub>, toluene and ammonia-water mixture, respectively.



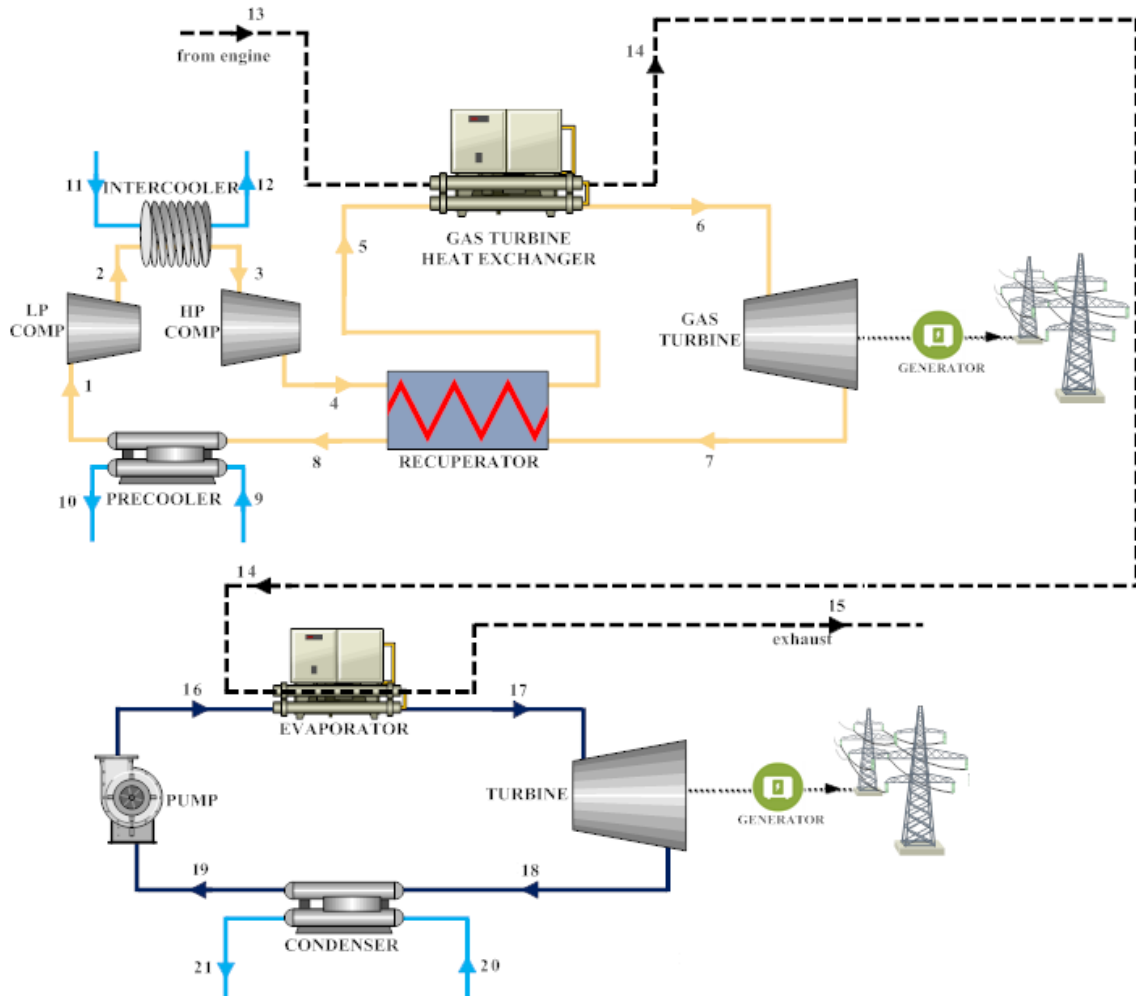
**Figure 1.** Schematic layout of the gas turbine cycle



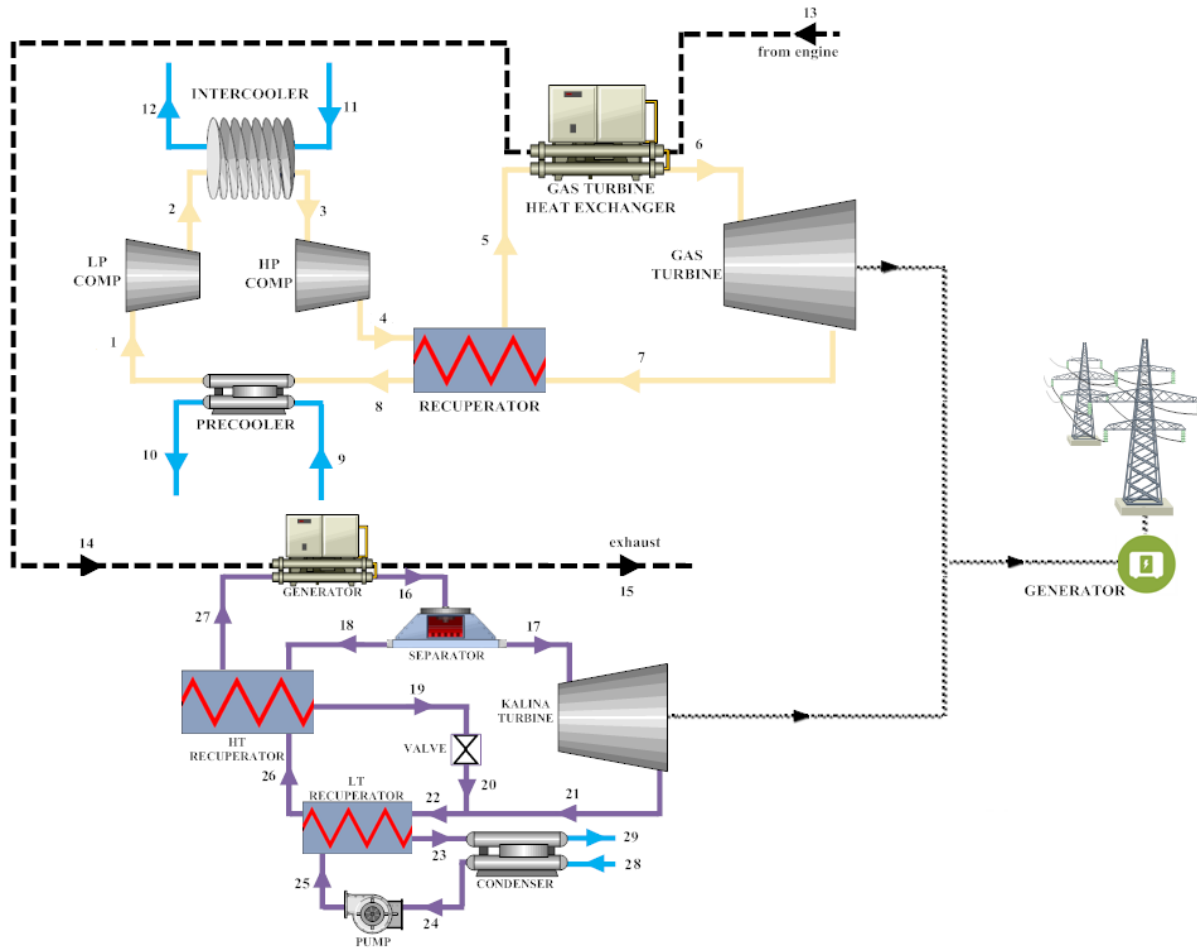
**Figure 2.** Schematic layout of the organic Rankine cycle



**Figure 3.** Schematic layout of the Kalina cycle



**Figure 4.** Schematic layout of the gas turbine-organic Rankine cycle



**Figure 5.** Schematic layout of the gas turbine-Kalina cycle

### 3. Results and Discussion

The heat transfer rates, the work, the exergy destructions and the exergy efficiencies of all sub-components are evaluated by means of the governing equations related to

continuity, energy and exergy equations. Thus, the energy and exergy efficiencies of each cycle are evaluated [1, 4, 7]. The thermodynamic results for each cycle are given in Table from 1 to 5.

**Table 1.** Thermodynamic results of the gas turbine cycle

Component	$\dot{Q}$ (kW)	$\dot{W}$ (kW)	$\dot{E}x_F$ (kW)	$\dot{E}x_P$ (kW)	$\dot{E}x_D$ (kW)	$\varepsilon$ (%)
GTHE	2730	-	1946	1391	555.6	71.5
GT	-	1463	1517	1463	53.69	96.5
REC	5726	-	1948	1880	68.12	96.5
PRE	723.3	-	75.87	14.23	61.64	18.8
LPC	-	231.5	231.5	202.6	28.97	87.5
HPC	-	136.7	136.7	118.3	18.45	86.5
INT	1394	-	186.9	49.82	137.1	26.7
GT System	Energy efficiency (%)			34.1		
	Exergy efficiency (%)			56.3		

**Table 2.** Thermodynamic results of the organic Rankine cycle

Component	$\dot{Q}$ (kW)	$\dot{W}$ (kW)	$\dot{E}x_F$ (kW)	$\dot{E}x_P$ (kW)	$\dot{E}x_D$ (kW)	$\varepsilon$ (%)
EVAP	7226	-	3725	2294	1430	61.6
OT	-	590.8	647.7	590.8	56.91	91.21
OC	5558	-	1652	168.9	1483	10.22
OP	-	6.237	6.237	5.53	0.7062	88.68
ORC System	Energy efficiency (%)			8.09		
	Exergy efficiency (%)			15.69		

**Table 3.** Thermodynamic results of the Kalina cycle

Component	$\dot{Q}$ (kW)	$\dot{W}$ (kW)	$\dot{E}x_F$ (kW)	$\dot{E}x_P$ (kW)	$\dot{E}x_D$ (kW)	$\varepsilon$ (%)
GEN	8197	-	3952	2956	996.4	74.79
KT	-	976	1056	976	80.17	92.41
LTR	5836	-	954.2	52.72	901.5	5.525
KCON	227	-	7.749	1.627	6.123	20.99
KP	-	21.4	21.36	13.65	7.711	63.89
HTR	3535	-	1049	355	693.6	33.85
KC	Energy efficiency (%)			11.65		
	Exergy efficiency (%)			24.15		

**Table 4.** Thermodynamic results of the gas turbine-organic Rankine cycle

Component	$\dot{Q}$ (kW)	$\dot{W}$ (kW)	$\dot{E}x_F$ (kW)	$\dot{E}x_P$ (kW)	$\dot{E}x_D$ (kW)	$\varepsilon$ (%)
GTHE	2758	-	1964	1405	559.3	71.52
GT	-	1509	1565	1509	55.65	96.44
REC	5734	-	1949	1857	92.05	95.28
PRE	724.3	-	72.89	14.25	58.64	19.55
LPC	-	234.7	234.7	205.3	29.37	87.48
HPC	-	142.2	142.2	123	19.25	86.46
INT	1403	-	187.3	50.15	137.1	26.78
EVAP	4791	-	1959	1233	725.8	62.94
OT	-	469.1	536.2	469.1	67.06	87.49
CON	4406	-	779.1	134.2	644.9	17.22
OP	-	93.83	93.83	82.3	11.53	87.72
GT-ORC	Energy efficiency (%)			18.76		
	Exergy efficiency (%)			38.43		

**Table 5.** Thermodynamic results of the gas turbine-Kalina cycle

Component	$\dot{Q}$ (kW)	$\dot{W}$ (kW)	$\dot{E}x_F$ (kW)	$\dot{E}x_p$ (kW)	$\dot{E}x_D$ (kW)	$\varepsilon$ (%)
GTHE	2758	-	1964	1405	559.3	71.52
GT	-	1509	1565	1509	55.65	96.44
REC	5734	-	1949	1857	92.05	95.28
PRE	724.3	-	72.89	14.25	58.64	19.55
LPC	-	234.7	234.7	205.3	29.37	87.48
HPC	-	142.2	142.2	123	19.25	86.46
INT	1403	-	187.3	50.15	137.1	26.78
GEN	4840	-	1968	1676	291.8	85.17
KT	-	469.7	496.7	469.7	26.96	94.57
HTR	1705	-	614.9	114.9	500.1	18.68
LTR	2177	-	347.9	109	238.8	31.34
KP	-	8.506	8.506	7.847	0.6593	92.25
KCON	899.3	-	70.19	6.446	63.74	9.184
GT-KAL Cycle	Energy efficiency (%)			19.71		
	Exergy efficiency (%)			40.53		

#### 4. Conclusions

The renewable and sustainable models that can be adapted to the actual system in order to utilize the exhaust gas of the Gaziantep Municipal Solid Waste Power Plant as an energy source have been analyzed in terms of thermodynamic aspects.

The results are summarized as follows;

- The net power output, the energy and the exergy efficiencies of GT cycle were found to be 1095 kW, 34.1 % and 56.3 %, respectively.
- The net power outputs obtained from the ORC system in using toluene is 584.6 kW. The exergy and energy efficiencies of the ORC system is calculated as 15.69 % and 8.09 %, respectively.
- The thermodynamic analysis of Kalina cycle has shown that, the net power output, the energy and the exergy efficiencies are 954.6 kW, 11.65 % and 24.15 %, respectively.
- As a result of the thermodynamic analysis carried out for GT-ORC, the net power output, the energy and the exergy efficiencies are found to be 1508 kW, 18.76 % and 38.43 %, respectively.

- The thermodynamic analysis of GT-KAL cycle, the net power output, the energy and the exergy efficiencies are calculated as 1594 kW, 19.71 % and 40.53 %, respectively. This power output puts another 28.16 % power on top of the existing power output of the system.

When all cycles are considered from the point of thermodynamic relations, the results show that the GT-KAL cycle is the best performance in terms of energetic and exergetic efficiencies such as 19.71% and 40.53%, respectively. In addition to this, it is concluded that the highest net power production, which is found to be 1594 kW, can also be ensured by GT-KAL cycle from the available exhaust gas.

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