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Article

A Comparative Exergoeconomic Analysis of Waste Heat Recovery from a Gas Turbine-Modular Helium Reactor via Organic Rankine Cycles

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Abstract: A comparative exergoeconomic analysis is reported for waste heat recovery from a gas turbine-modular helium reactor (GT-MHR) using various configurations of organic Rankine cycles (ORCs) for generating electricity. The ORC configurations studied are: a simple organic Rankine cycle (SORC), an ORC with an internal heat exchanger (HORC) and a regenerative organic Rankine cycle (RORC). Exergoeconomic analyses are performed with the specific exergy costing (SPECO) method. First, energy and exergy analyses are applied to the combined cycles. Then, a cost-balance, as well as auxiliary equations are developed for the components to determine the exergoeconomic parameters for the combined cycles and their components. The three combined cycles are compared considering the same operating conditions for the GT-MHR cycle, and a parametric study is done to reveal the effects on the exergoeconomic performance of the combined cycles of various significant parameters, e.g., turbine inlet and evaporator temperatures and compressor pressure ratio. The results show that the GT-MHR/RORC has the lowest unit cost of electricity generated by the ORC turbine. This value is highest for the GT-MHR/HORC. Furthermore, the GT-MHR/RORC has the highest and the GT-MHR/HORC has the lowest exergy destruction cost rate.

Keywords: gas turbine-modular helium reactor; organic Rankine cycle; exergy; exergoeconomics; SPECO; waste heat utilization

1. Introduction

The world faces numerous sustainability challenges. Energy is necessary for economic and social development and increasing the quality of life. Much of the world's energy is currently produced and consumed in ways that cannot be sustained. Although global energy resources are decreasing, the amount of energy needed by people is increasing. The dependency of humanity on energy is increasing, due to improving technology and increases in the living standards of people in the world. This situation is becoming increasingly important. One approach to overcoming this problem is to develop and improve renewable energy sources. Another approach is to improve conventional energy converting systems, so that they efficiently utilize all the energy that can be obtained from a source [1,2].

Among highly efficient power producing systems, gas-cooled reactors (GCRs) and, especially, modular helium reactors (MHRs) have had a lot of attention paid to them in recent years, because of their resistance to proliferation, good safety, sustainability and low costs of operation and maintenance [3]. The working fluid (helium) in the gas turbine modular helium reactor (GT-MHR) is compressed in two sequential stages. Cooling the helium before compression processes is favorable, as a reduction in the compressor inlet temperature reduces the required compression work. A large amount of low-grade heat is rejected to a heat sink in this process [4]. This is a potentially advantageous energy source for organic Rankine cycles for electrical power generation [5].

ORCs, compared to other bottoming cycles, have many promising features. One of the interesting features of working fluids used in ORCs (compared to water in the Rankine cycle) is their relatively low enthalpy drop through the expander, which reduces gap losses and, in turn, increases the turbine adiabatic efficiency. Another advantage of these cycles is having superheated vapor at the turbine exit, which avoids droplet corrosion and permits fast start-up and reliable operation for the ORC [6,7].

Recently, some research has focused on the use of the GT-MHR waste heat for electrical power generation in ORC cycles. Yari and Mahmoudi [5] proposed a combined cycle in which waste heat from the GT-MHR precooler and intercooler are used separately to drive two ORCs for power generation. In that work, the energy and exergy efficiencies of the combined cycle were both shown to be around 3 percentage-points greater than for the GT-MHR cycle. Yari and Mahmoudi also investigated the combinations of three configurations of ORCs with the GT-MHR cycle and concluded that, from a thermodynamic viewpoint, the simple ORC is the best for combination with the GT-MHR [8].

A combination of thermodynamic and economic principles is taken in to consideration in the analysis and optimization of energy conversion systems. The second law of thermodynamics plays an important role in this regard. The combination forms the basis of the relatively new field, called exergoeconomics (or thermoeconomics). In exergoeconomics, the costs associated with thermodynamic inefficiencies are taken in to account in calculating the total product cost for the system [9]. Exergoeconomics ascertain that exergy and not energy should be used in assessing monetary costs associated with the energy interactions between a system and its surrounding and also with the causes of thermodynamic inefficiencies [10].

Much exergoeconomic research has been reported in the literature for energy conversion systems. Sahoo presented an exergoeconomic analysis and optimization by the evolutionary programming of a cogeneration system that produced 50 MW of electrical power and 15 kg/s of saturated steam at 2.5 bar. The product cost under the optimized condition was found to be 9.9% lower than that for the base case, and this is attained with a 10% higher capital investment [11]. An exergoeconomic performance assessment of a diesel engine-based combined heat and power (CHP) system is reported by Mohammadkhani *et al.*, who state that their objective function under the optimized condition was about 8% lower than that obtained for the base case [12]. Abusoglu and Kanoglu provided a general review for an exergoeconomic analysis/optimization of combined heat and power systems, including various exergoeconomic and optimization methods [13].

In the present work, employing different configurations of ORCs for the utilization of waste heat from the precooler of the GT-MHR are examined from an exergoeconomic viewpoint. The three considered ORC configurations are: the simple organic Rankine cycle (SORC), ORC with an internal heat exchanger (HORC) and the regenerative organic Rankine cycle (RORC). First, energy and exergy analyses of combined GT-MHR/ORC cycles are performed. Then, a cost-balance, as well as auxiliary equations are developed for the components and exergoeconomic parameters of the combined cycles, and their components are calculated. Lastly, a parametric study is performed to reveal the influences of several important parameters on the exergoeconomic performance of the combined cycles.

2. Configurations of GT-MHR/ORC Combined Cycles

A schematic diagram of the turbine-modular helium reactor/simple organic Rankine cycle (GT-MHR/SORC) is shown in Figure 1a. In this system, which has a capacity of 297.7 MW, the helium is first heated in the reactor and then expanded in the turbine to generate electrical power. Then, the helium flows through the recuperator, the evaporator and the precooler. The compressed helium from the low pressure (LP) compressor is cooled in the intercooler and compressed further in the high pressure (HP) compressor. From the HP compressor outlet, after being heated in the recuperator, the helium returns to the reactor core. As mentioned before, the helium is cooled in the evaporator and provides a large amount of thermal energy that is suitable for ORCs for electrical power generation [5]. Two other configurations of ORCs that are considered for this purpose include the ORC with an internal heat exchanger (HORC) and the regenerative organic Rankine cycle (RORC). Schematics of the GT-MHR/HORC and GT-MHR/RORC combined cycles are shown in Figure 1b,c respectively. The working fluid of the ORCs is considered to be R123, because it is not harmful to the environment and has suitable thermophysical properties for use in the ORC [14].

The following assumptions are made in this work:

- The combined cycles operate in a steady-state condition.
- Pressure drops through pipes are negligible.
- Isentropic efficiencies for the turbines and pumps in the ORCs are 80% and 85%, respectively.
- Changes in kinetic and potential energies are neglected.
- The effectiveness of the intercooler, the recuperator and the precooler is considered to be 90%.

Figure 1. Schematics of the (**a**) gas turbine modular helium reactor (GT-MHR)/simple organic Rankine cycle (SORC), (**b**) GT-MHR/ORC with an internal heat exchanger (HORC) and (**c**) GT-MHR/regenerative organic Rankine cycle (RORC) combined cycles.

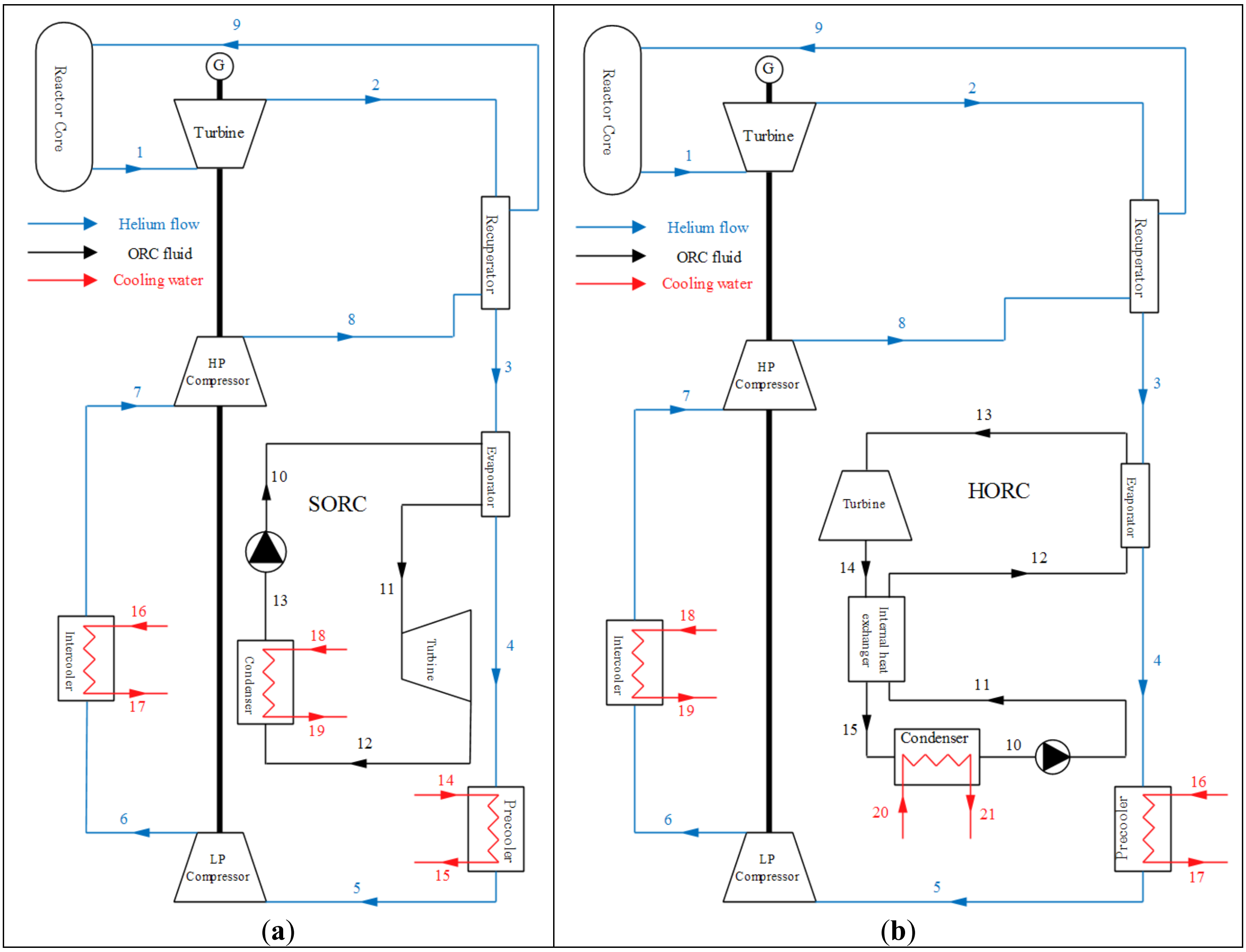
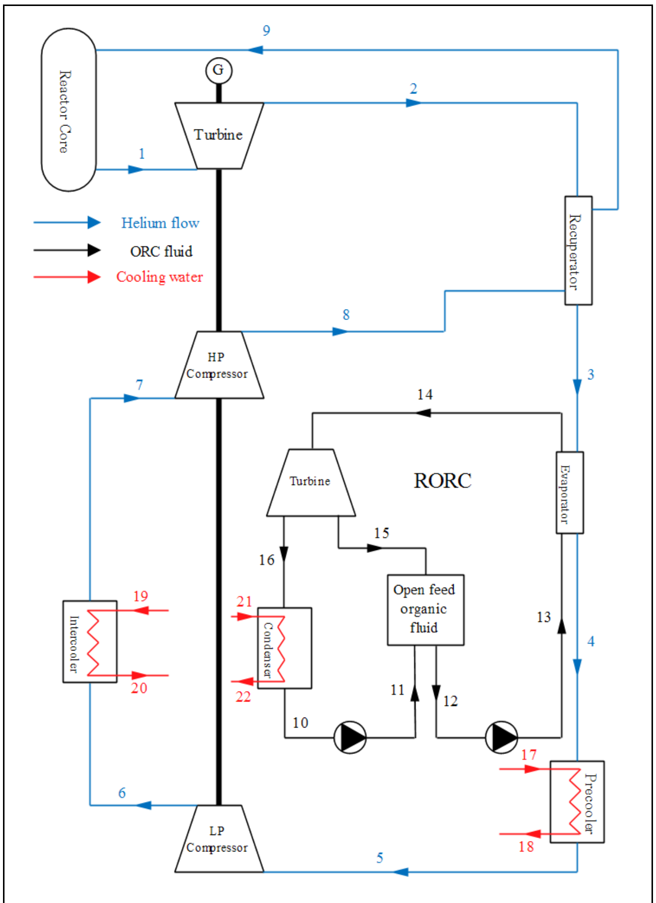


Figure 1. *Cont.*



(c)

Notes: HP = high pressure; LP = low pressure.

3. Exergoeconomic Analysis

Various exergoeconomic approaches have been reported in the literature [13]. In the present work, we use the specific exergy costing (SPECO) method [15]. This method is based on the specific exergies and costs per unit exergy, exergy efficiencies and auxiliary costing equations for the components of thermal systems.

3.1. Application of SPECO Method to the System

There are three main steps in the SPECO method, as follows: (i) quantifying the energy and exergy streams; (ii) defining the fuel and product for components; and (iii) considering the cost balance equations [15].

3.1.1. Modeling

Mass, energy and exergy balances for steady-state systems follow [16]:

$$\sum \dot{m}_i = \sum \dot{m}_e \tag{1}$$

$$\dot{Q} + \sum \dot{m}_i h_i = \dot{W} + \sum \dot{m}_e h_e \tag{2}$$

$$\dot{E}_Q + \sum \dot{m}_i e_i = \dot{E}_W + \sum \dot{m}_e e_e + \dot{E}_D \quad (3)$$

where subscripts i and e denote the control volume inlet and outlet, $\dot{E}_D$ is the exergy destruction rate in the component, $\dot{E}_Q$ is the exergy rate associated with a heat transfer rate and $\dot{E}_W$ is the exergy rate associated with mechanical power.

The specific physical and chemical exergy, respectively, of a stream are calculated as follows [17]:

$$e_{ph} = (h - h_0) - T_0(s - s_0) \quad (4)$$

$$e_{ch}{}^{mix} = \left[\sum_{i=1}^{n} X_i e_{ch_i} + RT_0 \sum_{i=1}^{n} X_i \ln(X_i) \right] \quad (5)$$

where X_i and $e_{ch,i}$ are the mole fraction and specific chemical exergy of working fluid, i, through a component, respectively.

For each component and for the combined cycles, the exergy efficiency is expressed as [5,17]:

$$\varepsilon = \left(\frac{exergy\ in\ products}{total\ exergy\ input}\right) \quad (6)$$

$$\varepsilon = \frac{\dot{W}_{net}}{\dot{E}_{in}} \xrightarrow{\dot{E}_{in} = \dot{Q}_{Core}} \varepsilon = \frac{\dot{W}_{net}}{\dot{Q}_{Core}} \quad (7)$$

where $\dot{Q}_{Core}$ is the produced energy in the reactor core.

A thermodynamic model developed for the combined cycles with two organic Rankine cycles has been described previously by the authors [8]. The input parameters used in the simulation are listed in Table 1.

Table 1. Parameters used in the simulation.

Parameters	Value
P_0 (kPa)	100
PR_C	1.5–5
$\dot{Q}_{RC}$ (MW)	600
T_0 (°C)	25
T_1 (°C)	700–900
T_C (°C)	40
T_E (°C)	80–120
ΔT_E (°C)	2–10
ΔT_{Sup} (°C)	0–15
η_P (%)	85
η_T (%)	80
Effectiveness (for IC, R, PC) (%)	90
ΔP_{RC} (kPa)	100
ΔP_E, ΔP_{IC}, ΔP_{PC} (kPa)	40
$\Delta P_{R,HP}$ (kPa)	80
$\Delta P_{R,LP}$ (kPa)	50

Notes: IC = intercooler; R = recuperator; PC = precooler.

Simulation of the combined cycles is performed using Engineering Equation Solver (EES) [18].

3.1.2. Defining the Fuel and Product for Each Component

In applying the SPECO approach, the fuel and product are defined for each component. The fuel denotes the resources required to generate the product, and the product is what we want from a component. Both the fuel and the product are expressed in terms of exergy [12].

3.1.3. Cost Balances

A cost balance states that the sum of all exiting exergy stream cost rates equals the sum of all entering exergy stream cost rates plus the cost rate of the capital investment and operating and maintenance costs ($\dot{Z}_k$). The prediction of the capital investment cost is significant in an economic analysis. In this regard, using vendor quotations or consulting with cost engineers is probably the most precise method. In consulting with cost engineers, after each design modification, the necessary thermodynamic data is submitted to the cost engineer to determine the new purchased-equipment costs. For simplicity, however, in the present work, the cost functions available in the literature are used assuming that the cost values provided by the cost engineer are in agreement with the corresponding values calculated from the cost functions [19]. The cost functions for different components are functions of the parameters important to the component, *i.e.*, the pressure ratio in compressor or turbine and the heat transfer area in heat exchangers. Considering the recuperator, the evaporator, the precooler and the intercooler as heat exchangers, equations for calculating the capital investment of the components can be expressed as described below [12,20].

For the turbine:

$$Z_{Turbine} = \left(\frac{1536\dot{m}_{gas}}{0.92-\eta_T}\right)\ln\left(\frac{P_i}{P_e}\right)\left(1+\exp(0.036T_i-54.4)\right) \tag{8}$$

For the compressor:

$$Z_{Compressor} = \left(\frac{75\dot{m}_{air}}{0.9-\eta_C}\right)\left(\frac{P_e}{P_i}\right)\ln\left(\frac{P_e}{P_i}\right) \tag{9}$$

For the pump:

$$Z_{Pump} = 3540\dot{W}_P^{\;0.71} \tag{10}$$

For the condenser:

$$Z_{Condenser} = 1773\dot{m}_{steam} \tag{11}$$

For the recuperator, the evaporator, the precooler, the intercooler and the internal heat exchanger:

$$Z_{HE} = 130\left(\frac{A_{HE}}{0.093}\right)^{0.78} \tag{12}$$

It should be noted that it is assumed that the open feed organic fluid in the RORC does not impose a capital cost on the system, as it only mixed two streams. The reactor core capital cost and the cost of nuclear reactor fuel are taken to be \$371/kW$_{th}$ (based on data for the year 2003) and \$8/MWh, respectively [8,21]. To convert the capital investment into the cost per time unit, one can write [12]:

$$\dot{Z}_k = Z_k.CRF.\varphi/(N \times 3600) \tag{13}$$

where φ is the maintenance factor (1.06), N is the number of system operating hours in a year (7446 h) and CRF is the capital recovery factor, which can be written as:

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1} \tag{14}$$

Here, i is the interest rate (assumed to be 10%) and n is the system life (assumed to be 20 years).

Now, a parameter, called flow cost rate $\dot{C}$ (\$/s), is defined for each stream, and the cost balance for a component receiving heat and producing power is written as [19]:

$$\sum_e \dot{C}_{e,k} + \dot{C}_{w,k} = \dot{C}_{q,k} + \sum_i \dot{C}_{i,k} + \dot{Z}_k \tag{15}$$

$$\dot{C}_j = c_j \dot{E}_j \tag{16}$$

where i and e indicate the entering and exiting streams for component k.

In order to estimate the exergy destruction cost in system components, we should solve the cost balance equations developed for the system. Generally, if we have N exergy streams that exit from a component, there are N unknowns and only one equation; the cost balance. Thus, ($N - 1$) auxiliary equations are needed. The auxiliary equations are formulated using the F (fuel) and P (product) principles of the SPECO approach [15].

By developing the cost balance equation and auxiliary equations (according to F and P rules) for each component, we obtained a linear system of equations. Solving this gives the costs of unknown streams. The exergoeconomic assessment of systems is accomplished using exergoeconomic parameters. These parameters include the average cost per unit exergy of fuel ($c_{F,k}$), the average cost per unit exergy of product ($c_{P,k}$), the cost flow rate associated with the exergy destruction ($\dot{C}_D$) and the exergoeconomic factor (f_k). Mathematically, exergoeconomic parameters are expressed as [19]:

$$c_{F,k} = \frac{\dot{C}_{F,k}}{\dot{E}_{F,k}} \tag{17}$$

$$c_{P,k} = \frac{\dot{C}_{P,k}}{\dot{E}_{P,k}} \tag{18}$$

$$\dot{C}_{D,k} = c_{F,k} \dot{E}_{D,k} \tag{19}$$

$$f_k = \frac{\dot{Z}_k}{\dot{Z}_k + \dot{C}_{D,k} + \dot{C}_{L,k}} \tag{20}$$

A higher value of the exergoeconomic factor, f_k, suggests purchasing a less expensive component at the expense of exergy destruction (fuel) cost.

4. Results and Discussion

4.1. Exergoeconomic Analysis

The cost rates associated with the exergy values of the streams of the combined cycles are presented in Table 2. This table shows that the cost rate of power produced by the GT-MHR turbine is calculated to be \$6.843/s for the GT-MHR/SORC and GT-MHR/HORC, and it is \$6.837/s for the GT-MHR/RORC. The value of the cost rate of power produced by the ORC turbine is determined to be \$0.458/s, \$0.461/s and \$0.449/s for GT-MHR/SORC, GT-MHR/HORC and GT-MHR/RORC, respectively. Furthermore, Table 2 indicates that the nuclear fuel cost rate has an important contribution to the power production cost. It is found to be \$2.424/s for GT-MHR/SORC and \$2.422/s for the two other combined cycles.

Table 2. Cost of streams in the combined cycles.

State No.	GT-MHR/SORC		GT-MHR/HORC		GT-MHR/RORC	
	$\dot{C}$ (\$/s)	c (\$/GJ)	$\dot{C}$ (\$/s)	c (\$/GJ)	$\dot{C}$ (\$/s)	c (\$/GJ)
1	17.17	11.83	17.15	11.83	17.20	11.83
2	10.55	11.83	10.53	11.83	10.59	11.83
3	7.428	11.83	7.419	11.83	7.444	11.83
4	7.016	11.83	7.015	11.83	7.046	11.83
5	6.936	11.83	6.927	11.83	6.953	11.83
6	8.565	12.15	8.558	12.15	8.582	12.15
7	8.347	12.15	8.338	12.15	8.362	12.15
8	10.05	12.39	10.04	12.39	10.06	12.39
9	13.18	12.56	13.17	12.56	13.22	12.56
10	0.010	32.46	0.0009	18.5	0.0008	18.05
11	0.434	18.36	0.010	32.61	0.001	24.10
12	0.045	18.36	0.021	36.05	0.007	24.22
13	0.0009	18.36	0.438	18.50	0.016	28.98
14	0	0	0.046	18.50	0.427	18.05
15	0.085	72.86	0.039	18.50	0.006	18.05
16	0	0	0	0	0.042	18.05
17	0.222	59.80	0.093	66.88	0	0
18	0	0	0	0	0.098	64.10
19	0.050	47.9	0.224	59.69	0	0
20	-	-	0	0	0.224	59.56
21	-	-	0.044	45.52	0	0
22	-	-	-	-	0.046	50.73
Nuclear fuel	2.424	4.040	2.422	4.036	2.422	4.036
$\dot{W}_T$	6.843	12.56	6.843	12.55	6.837	12.56
$\dot{W}_{C,HP}$	1.695	12.56	1.695	12.55	1.692	12.56
$\dot{W}_{C,LP}$	1.622	12.56	1.624	12.55	1.622	12.56
$\dot{W}_{T,ORC}$	0.458	26.68	0.461	26.89	0.449	26.21
$\dot{W}_{P,ORC}$	0.0085	26.68	0.0085	26.89	0.0006	26.21
$\dot{W}_{P2,ORC}$	-	-	-	-	0.008	26.21

Table 3 shows the important exergy and exergoeconomic parameters for different components of the three combined cycles.

Table 3. Important exergy and exergoeconomic parameters of the combined cycles.

Component	GT-MHR/SORC				GT-MHR/HORC				GT-MHR/RORC			
	$\dot{E}_D$ (kW)	ε (%)	$\dot{C}_D$ ($/s)	f (%)	$\dot{E}_D$ (kW)	ε (%)	$\dot{C}_D$ ($/s)	f (%)	$\dot{E}_D$ (kW)	ε (%)	$\dot{C}_D$ ($/s)	f (%)
Reactor core	198,088	87.99	1.874	45.51	198,122	87.98	1.874	45.52	197,980	88.02	1.874	45.51
Turbine	14,868	97.34	0.176	55.40	14,878	97.34	0.176	55.37	14,837	97.35	0.176	55.54
Recuperator	25,397	90.37	0.301	4.262	25,315	90.38	0.299	4.275	25,605	90.36	0.303	4.238
Evaporator	11,436	67.10	0.153	8.339	11,035	67.64	0.131	9.154	10,591	68.57	0.125	8.997
Precooler	5599	17.22	0.066	6.760	6054	18.65	0.072	6.281	6324	19.41	0.075	6.048
LP compressor	10,536	91.84	0.132	5.180	10,541	91.85	0.132	5.181	10,520	91.86	0.132	5.186
Intercooler	14,226	20.68	0.173	2.180	14,368	20.71	0.175	2.158	14,354	20.76	0.174	2.166
HP compressor	10,830	91.98	0.136	5.119	10,835	91.98	0.136	5.120	10,815	91.98	0.136	5.125
ORC turbine	4014	81.05	0.074	48.56	4013	81.03	0.074	48.37	6221	81.41	0.112	38.07
Condenser	1369	43.29	0.025	18.59	1081	46.91	0.020	22.54	1352	40.25	0.024	17.98
Pump	320	85.43	0.009	10.36	45.85	85.43	0.001	44.19	3.084	85.46	0	64.02
Pump 2	-	-	-	-	-	-	-	-	43.87	85.88	0.001	45.69
IHE	-	-	-	-	135	66.15	0.002	56.32	-	-	-	-
OFOF	-	-	-	-	-	-	-	-	78	78.73	0.002	-
Overall	296,683	49.61	3.101	38.1	296,425	49.58	3.092	38.22	298,724	49.56	3.134	37.85

Notes: IHE = internal heat exchanger; OFOF = open feed organic fluid.

Table 3 shows that the reactor core has the highest value of $\dot{C}_D$ among the other components in all three combined cycles. The f value of this component is almost 45.5% and indicates that the exergy destruction cost in this component dominates the owning and operating cost. Furthermore, the reactor core has the highest value of exergy destruction in combined cycles.

After the reactor core, the recuperator has the highest value of $\dot{C}_D$. The very low value of f for this component indicates that the exergy destruction cost rate of the recuperator is significantly higher than the owning and operating cost rate for it. Thus, selecting more expensive components will be helpful in improving the exergoeconomic performance. This can be performed through increasing the heat transfer area. The relatively higher value of exergy destruction in the recuperator is mainly due to the temperature differences between the recuperator streams.

The exergoeconomic factor and exergy efficiency for the GT-MHR turbine are found to be almost 55% and 97%, respectively, in all three combined cycles. Therefore, the exergy and exergoeconomic performance of this component is satisfactory. Considering the lower values of power production by the ORC turbine, its contribution in the system total cost will be low.

The relatively higher value of $\dot{C}_D$ and the very low value of f for the HP and LP compressors suggest that greater capital investments are appropriate, *i.e.*, higher values of the pressure ratio and isentropic efficiency.

The precooler, the intercooler and the condenser of the combined cycles have low values of the exergoeconomic factor. Therefore, increasing the capital investment of these components is suggested from the exergoeconomic viewpoint.

Changes in the exergoeconomic parameters of the pumps, internal heat exchanger and open feed organic fluid do not notably affect the exergoeconomic performance of the system, as the values of $\dot{C}_D$ associated with these components are the lowest of the combined cycles.

Among three combined cycles, the GT-MHR/RORC has the highest value and the GT-MHR/HORC has the lowest value of the exergy destruction cost rate. The exergoeconomic factor is determined to be 38.1%, 38.22% and 37.85% for the GT-MHR/SORC, GT-MHR/HORC and GT-MHR/RORC, respectively. This means that in all three cycles, the associated cost of the exergy destruction dominates the capital investment. Therefore, in general, an increase in the capital costs of the components improves the exergoeconomic performance of the combined cycles.

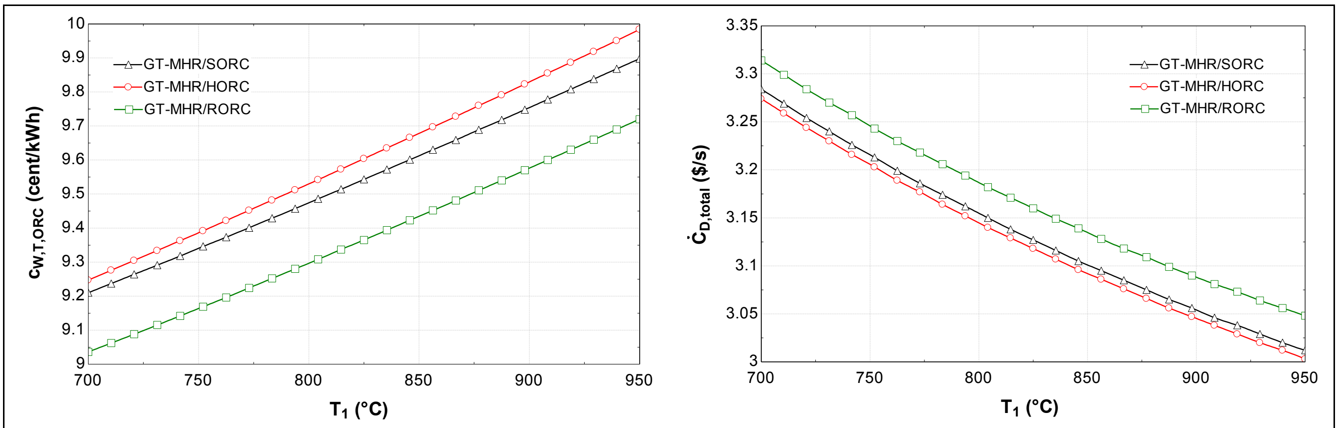
The comparison for three cycle performances has been carried out with the temperature ranges mentioned in the assumptions. However, the calculations using extended temperature ranges confirm the obtained comparison results.

4.2. Parametric Study

In this section, a parametric study is done to study the effects on the important exergoeconomic parameters of the system, such as the compressor pressure ratio, PR_C, the turbine inlet temperature, T_1, and the temperature of the evaporator, T_E. The important exergoeconomic parameters are: the unit cost of electricity produced by the ORC turbine, $c_{W,T,ORC}$, and the total exergy destruction cost rate, $\dot{C}_{D,total}$.

Figure 2 shows the effects of T_1 on $c_{W,T,ORC}$ and $\dot{C}_{D,total}$.

Figure 2. The effects of T_1 on the (**a**) unit cost of electricity produced by the ORC turbine and (**b**) the total exergy destruction cost rate.



(**a**) (**b**)

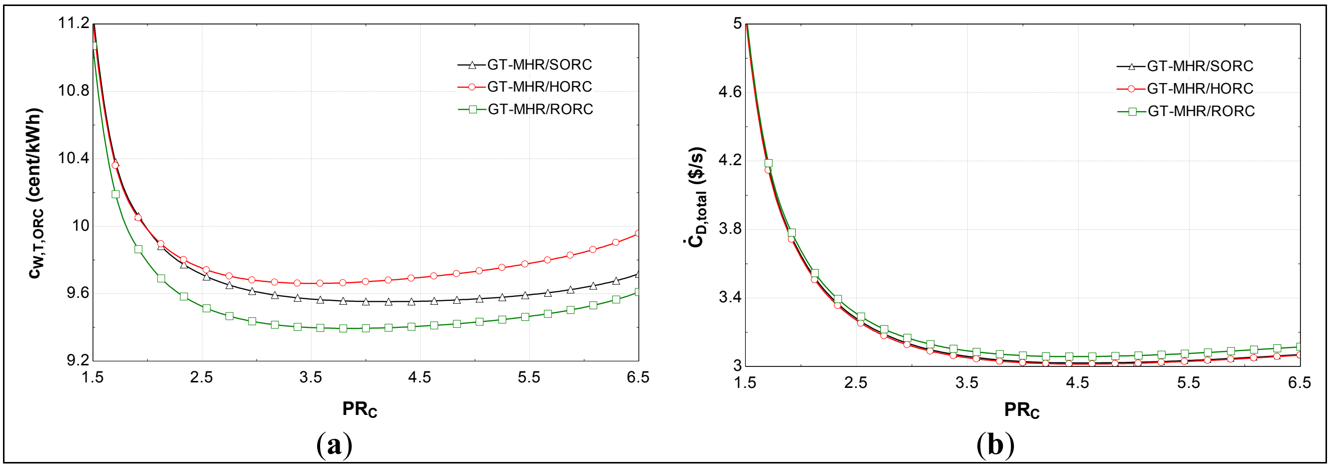
Increasing T_1 increases both the $\dot{W}_{T,ORC}$ and $\dot{C}_{W,T,ORC}$. However, these variations are such that the net effect is an increase in $c_{W,T,ORC}$, as shown in Figure 2a. Furthermore, this figure shows that the GT-MHR/RORC has the lowest $c_{W,T,ORC}$.

As shown in Figure 2b, increasing T_1 decreases $\dot{C}_{D,total}$. This is mainly due to a considerable decrease in the reactor core exergy destruction cost, which constitutes about 60% of the total exergy destruction cost (see Table 3). This trend is the same in all three combined cycles.

It should be noted that although an increase in turbine inlet temperature results in a decrease of the total exergy destruction cost rate, it causes an increase in the unit cost of electricity produced by the ORC turbine. Thus, in practice, a lower value of T_I is recommended.

The variations of $c_{W,T,ORC}$ and $\dot{C}_{D,total}$ with the compressor pressure ratio are shown in Figure 3.

Figure 3. The effects of PR_C on the (**a**) unit cost of electricity produced by the ORC turbine and (**b**) the total exergy destruction cost rate.

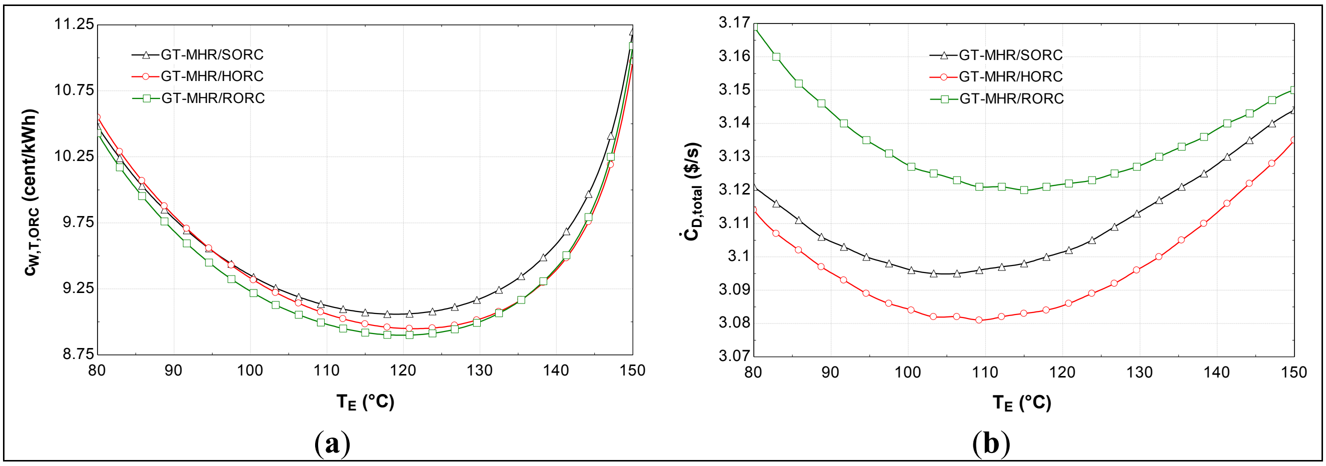


Both the $\dot{W}_{T,ORC}$ and $\dot{C}_{W,T,ORC}$ have a minimum value with respect to the PR_C. As a result, $c_{W,T,ORC}$ is minimized at a particular value of PR_C, as shown in Figure 3a.

As PR_C increases, the exergy destruction and its associated cost decreases for some components and increases for others. The net effect is shown in Figure 3b.

Figure 4 shows the effects of T_E on important exergoeconomic parameters for three considered combined cycles.

Figure 4. The effects of T_E on the (**a**) unit cost of electricity produced by the ORC turbine and (**b**) the total exergy destruction cost rate.



The effect of T_E on $c_{W,T,ORC}$ is similar to that for PR_C. However, in this case, the minimum occurs at high evaporator temperatures.

Furthermore, the exergy destruction cost is minimized at particular values of T_E, as shown in Figure 4b. The reason for this is that, as T_E increases, the enthalpy drops of the working fluids across the ORC turbines increase, while their mass flow rates decrease. However, the net effect is the maximization of the produced power and, consequently, the exergy efficiency of ORC at the mentioned value of T_E. Maximum exergy efficiency means minimum exergy destruction and its associated costs.

From the above explanation, it is revealed that both the PR_C and the T_E have optimum values from the exergoeconomic viewpoint and a lower or a higher value of these parameters results in a higher unit cost of electricity produced by the ORC turbine.

5. Conclusions

A comparative exergoeconomic analysis of waste heat recovery from a gas turbine-modular helium reactor (GT-MHR) using various configurations of organic Rankine cycles (ORCs) for electrical power production is successfully performed. For this purpose, energy and exergy analyses of combined GT-MHR/ORC cycles are performed. Then, cost balances and auxiliary equations are developed for the components, and the exergoeconomic parameters are calculated for the components and the entire combined cycles. Finally, a parametric study is performed to reveal the effects of the selected parameters on the exergoeconomic performance of the combined cycles. The considered organic Rankine cycles for electrical power production are: the simple organic Rankine cycle (SORC), ORC with an internal heat exchanger (HORC) and the regenerative organic Rankine cycle (RORC).

The results show that the reactor core has the highest value of the exergy destruction cost rate among the other components in all three combined cycles. The GT-MHR/RORC has the highest value of the exergy destruction cost rate and the lowest value of the unit cost of electricity produced by the ORC turbine. These results are reversed for GT-MHR/HORC. Furthermore, a parametric study shows that increasing the turbine inlet temperature increases the unit cost of electricity produced by the ORC turbine and decreases the exergy destruction cost rate; however, these exergoeconomic parameters have a minimum value with respect to the compressor pressure ratio and evaporator temperature in all three combined cycles.

The results of the present work can be used as a basis for the exergoeconomic optimization of the considered combined cycles.

Author Contributions

The modeling has been carried out by Naser Shokati and Farzad Mohammadkhani for an internal project in the University of Tabriz under supervision of Seyed M. S. Mahmoudi and Mortaza Yari. For the manuscript, Marc A. Rosen was advisor.

Nomenclature

A	heat transfer area (m^2)
c	cost per unit exergy ($/kJ)
$\dot{C}$	cost rate ($/s)
e	specific exergy (kJ/kg)
$\dot{E}$	exergy rate (kW)

f	exergoeconomic factor
h	specific enthalpy (kJ/kg)
IHE	internal heat exchanger
$\dot{m}$	mass flow rate (kg/s)
OFOF	open feed organic fluid
P	pressure (bar, kPa)
PR_C	compressor pressure Ratio
$\dot{Q}$	heat transfer rate (kW)
R	gas constant (kJ/kg K)
s	specific entropy (kJ/kg K)
T	temperature (°C, K)
$\dot{W}$	electrical power (kW)
X	mole fraction
Z	capital cost of a component ($)
$\dot{Z}$	capital cost rate ($/s)

Greek letters

η	isentropic efficiency
ε	exergy efficiency
ΔT_E	pinch point temperature difference in the evaporator
ΔT_{Sup}	degree of superheat at the inlet to the ORC turbine

Subscripts

0	dead (environmental) state
1, 2, 3, …	cycle locations
C	condenser
ch	chemical exergy
D	destruction
e	outlet
E	evaporator
F	fuel
HE	heat exchanger
HP	high pressure
IC	intercooler
i	inlet
j	*j*-th stream
k	*k*-th component
L	loss
LP	low pressure
P	pump, product
PC	precooler

ph	physical exergy
q	heat
R	recuperator
RC	reactor core
T	turbine
w	power

Conflicts of Interest

The authors declare no conflict of interest.

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