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Article

A Comparative Exergoeconomic Analysis of Waste Heat Recovery from a GT-MHR using Organic Rankine Cycles

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Abstract: A comparative exergoeconomic analysis is reported of waste heat recovery from a Gas Turbine-Modular Helium Reactor (GT-MHR) using different arrangements of Organic Rankine Cycles (ORCs) for electrical power production. The considered organic Rankine cycles are: Simple Organic Rankine Cycle (SORC), ORC with internal heat exchanger (HORC) and Regenerative Organic Rankine Cycle (RORC). The exergoeconomic analysis is performed based on the specific exergy costing (SPECO) approach. For this purpose, the combined cycles are first thermodynamically analyzed through energy and exergy. Then cost balances and auxiliary equations are applied to subsystems and exergoeconomic parameters are calculated for the components and entire combined cycles. Based on fixed operating conditions for the GT-MHR cycle, the three combined cycles are compared. Finally a parametric study is performed to reveal the effects on the exergoeconomic performance of the combined cycles of such significant parameters as compressor pressure ratio, turbine inlet temperature and evaporator temperature. The results show that the GT-MHR/RORC has the lowest unit cost of electricity produced by the

ORC turbine. This value is highest for the GT-MHR/HORC. Also 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.

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1. Introduction

The world faces numerous sustainability challenges. Energy is necessary for economic and social development and increasing quality of life. Energy demand and production are significant issues when it comes to climate and affluence. 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 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 they efficiently utilize all the energy that can be extracted from a source. In other words, to overcome these challenges we need a transition to a more sustainable energy system based on renewable energy sources and non-polluting ways of energy generation [1,2].

Among advanced power producing systems, Gas-Cooled Reactors (GCRs) and in particular Modular Helium Reactors (MHRs) have received much attention in recent years because of their safety, proliferation resistance, sustainability and low operation and maintenance costs [3]. The circulating helium in the Gas Turbine Modular Helium Reactor (GT-MHR) is compressed in two successive stages. Cooling the helium before compression processes is favorable, as a reduction in compressor inlet temperature reduces the required compression work. There is a large amount of low grade energy 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 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 erosion and allows reliable operation and fast start-up for the ORC cycle [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 the waste heat from the precooler and the intercooler of the GT-MHR are utilized separately to drive two Organic Rankine Cycles for power production. In that work, the first and second law efficiencies of the combined cycle were both shown to be around 3%-points higher than those of the GT-MHR cycle. Yari and Mahmoudi also investigated the combinations of different configurations of ORCs with the GT-MHR cycle and concluded that the simple ORC is the best for combination with the GT-MHR from the view point of thermodynamics [8].

In the analysis of energy systems, methods which combine scientific disciplines with economic disciplines are growing and finding application in the energy industry. The second law of thermodynamics combined with economics represents a powerful tool for the systematic study and optimization of energy systems. This combination forms the basis of the relatively new field of thermoeconomics or exergoeconomics. Exergoeconomics combines the exergy analysis with economic principles and incorporates the associated costs of the thermodynamic inefficiencies in the total product cost of an energy system [9]. Exergoeconomics rests on the concept that exergy is the only rational basis for assigning monetary costs to the interactions that a system experiences with its surroundings and to the sources of thermodynamic inefficiencies within it [10].

Numerous reports of exergoeconomic analyses of energy systems have been reported. Sahoo presented an exergoeconomic analysis and optimization of a cogeneration system using evolutionary programming. The system under study was a cogeneration system which produced 50 MW of electricity and 15 kg/s of saturated steam at 2.5 bar. The results showed that for the optimum case the product cost is 9.9% lower compared to the base case and this is achieved with a 10% increase in capital investment [11]. Mohammadkhani et al. performed an exergoeconomic analysis and optimization of a Diesel engine-based combined heat and power system and reported that their objective function for optimum operation was about 8% lower than that obtained for a base case [12]. Abusoglu and Kanoglu provided a general review the exergoeconomic analysis and optimization of cogeneration systems, including coverage of various exergoeconomic approaches, and optimization from the viewpoint of exergoeconomics [13].

In the present work, methods for employing different configurations of ORCs for utilization of waste heat from the precooler of the GT-MHR are investigated from the exergoeconomic viewpoint. The three considered ORC configurations are: Simple Organic Rankine Cycle (SORC), ORC with internal heat exchanger (HORC) and Regenerative Organic Rankine Cycle (RORC). First, energy and exergy analyses of combined GT-MHR/ORC cycles are performed. Then, cost balances and auxiliary equations are applied to subsystems and exergoeconomic parameters are calculated for the components and entire combined cycles. Finally a parametric study is performed to reveal the effects of some 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, heated helium from the reactor is expanded in the turbine to produce power. Then, the helium flows through the recuperator and enters the evaporator and 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 an attractive energy source for used-in Organic Rankine Cycles for electrical power generation [5]. Two other configurations of ORCs that are considered for this purpose include the ORC with internal heat exchanger (HORC) and Regenerative Organic Rankine Cycle (RORC). Schematics of the GT-MHR/HORC and GT-MHR/RORC combined cycles are shown in Figures 1b and c, respectively. For the ORCs, R123 is selected as the working fluid because it is environmental friendly and has thermophysical properties that facilitate efficient performance of the ORC [14].

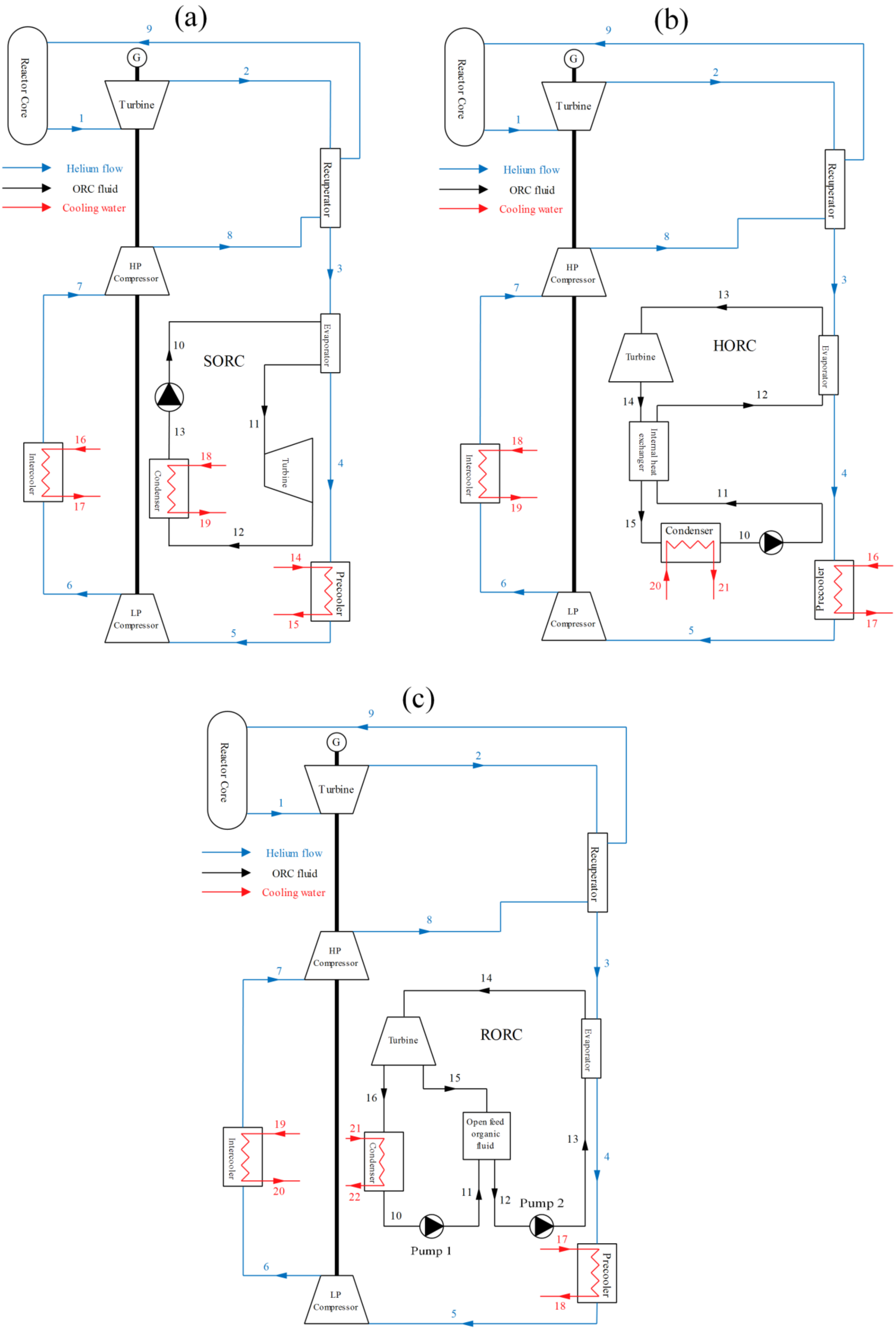


Figure 1. Schematic diagrams of the a) GT-MHR/SORC, b) GT-MHR/HORC and c) GT-MHR/RORC combined cycles

The following assumptions are considered in this work:

- The combined cycles operate in a steady-state condition.
- No pressure drops occur through pipes.
- Isentropic efficiencies for the turbines and pumps in the ORCs are 80% and 85%, respectively.
- Changes in kinetic and potential energies are neglected.
- The intercooler, the recuperator and the precooler each have an effectiveness of 90%.

3. Exergoeconomic Analysis

Exergoeconomics is the branch of engineering that appropriately combines thermodynamic assessments based on exergy analysis with economic principles, and present information that is useful to the design and operation of a cost effective system. This information, however, cannot be achieved considering either exergy or economic principles, separately [10].

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

3.1. Application of SPECO Method to the System

The SPECO method consists of three main steps: (i) identification of energy and exergy streams, (ii) definition of fuel and product for each component of thermal system and (iii) considering cost equations [15].

3.1.1. Identification and Analysis of Energy and Exergy Streams

Mass, energy and exergy balances for any steady state system can be written as [16]:

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

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

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

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.

Neglecting the kinetic and potential exergies, the physical and chemical exergy of each stream are calculated as follows [17]:

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

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

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 [17,5]:

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

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

where $_{Core}$ is the produced fission energy in the reactor core.

A detailed description of the thermodynamic model developed for the combined cycles with two Organic Rankine Cycles has been presented previously by the authors [8]. The input parameters used in the simulation are given in Table 1.

Table 1. Parameters used in the simulation

Parameters	Value
P_0 (kPa)	100
PR_C	1.5-5
$_{RC}$ (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

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* must be defined for each component. The fuel represents the resources required to generate the product and the product is what we desire 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 cost rates associated with all exiting exergy streams equals the sum of cost rates of all entering exergy streams plus the cost rate associated with the capital investment and operating and maintenance costs ($\dot{Z}_k$). Considering the recuperator, the evaporator, the precooler and the intercooler as heat exchangers, equations for calculating capital investment of the components are as follows [12,19]:

For the turbine:

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

For the compressor:

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

For the pump:

$$Z_P = 3540\dot{W}_P^{\ 0.71} \tag{10}$$

For the condenser:

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

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

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

It should be noted that it is assumed that the open feed organic fluid in the RORC does not impose a capital cost to 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 [20,8]. 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 hr) 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, for each flow line in the system, a parameter called flow cost rate $\dot{C}$ (\$/s) is defined and the cost balance equation for a component that receives heat and produces power is written as [21]:

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

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

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

For calculating the cost of exergy destruction in the components of the system, first we solve the cost balance equations for each one. Generally, if there are N exergy streams exiting the component, we have N unknowns and only one equation, the cost balance. Therefore, we need to formulate N–1 auxiliary equations. This is performed with the aid of the F and P principles in the SPECO approach [15].

Developing cost balance equation for each component of the system and auxiliary equations (according to F and P rules) leads to a linear system of equations. By solving this, the costs of unknown streams are obtained. Exergoeconomic assessments of systems can be performed 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 [21]:

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

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

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

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

The exergoeconomic factor, f_k, is a parameter which shows the relative importance of a component cost to the cost of exergy destruction and loss associated with that component.

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 the 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. Also Table 2 indicates that the nuclear fuel cost rate plays an important role in the power production cost. It is found to be 2.424 $/s for GT-MHR/SORC and 2.422 $/s for 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	198088	87.99	1.874	45.51	198122	87.98	1.874	45.52	197980	88.02	1.874	45.51
Turbine	14868	97.34	0.176	55.40	14878	97.34	0.176	55.37	14837	97.35	0.176	55.54
Recuperator	25397	90.37	0.301	4.262	25315	90.38	0.299	4.275	25605	90.36	0.303	4.238
Evaporator	11436	67.10	0.153	8.339	11035	67.64	0.131	9.154	10591	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	10536	91.84	0.132	5.180	10541	91.85	0.132	5.181	10520	91.86	0.132	5.186
Intercooler	14226	20.68	0.173	2.180	14368	20.71	0.175	2.158	14354	20.76	0.174	2.166
HP compressor	10830	91.98	0.136	5.119	10835	91.98	0.136	5.120	10815	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	296683	49.61	3.101	38.1	296425	49.58	3.092	38.22	298724	49.56	3.134	37.85

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. Although an increase in the investment cost can lead to a decrease in the cost of the exergy destruction of the reactor core, in any other design configuration of the system, this component will have the highest cost of the exergy destruction. Also reactor core has the highest value of exergy destruction in combined cycles.

After 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 done 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 ORC turbine, its contribution in the system total cost will be low.

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

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

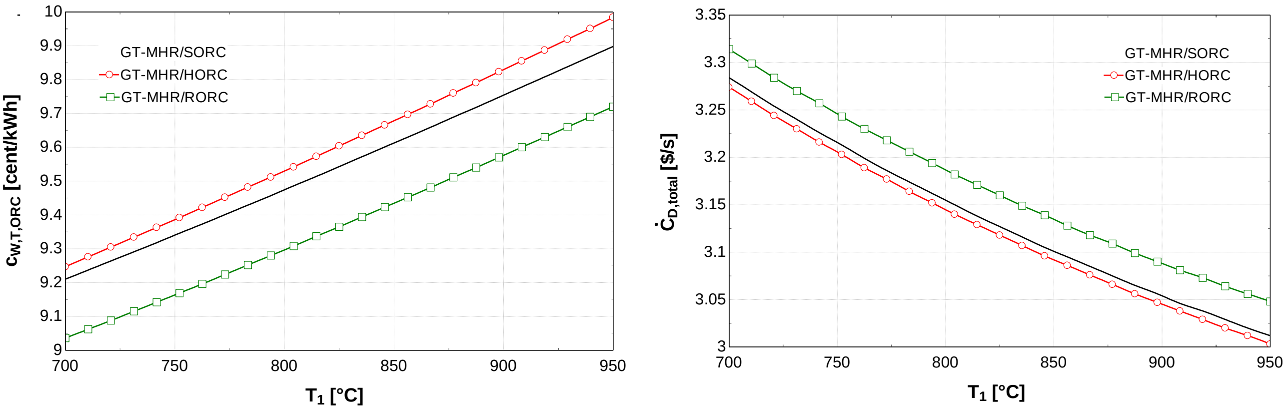
Changes in the exergoeconomic parameters of the pumps, internal heat exchanger and open feed organic fluid do not affect notably the exergoeconomic performance of the system, as the values of $\dot{C}_D$ associated with these components are the lowest of the combined cycles.

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.

4.2. Parametric Study

In this section a parametric study is performed to study the effects on the important exergoeconomic parameters of system of such parameters as compressor pressure ratio, PR_C, turbine inlet temperature, T_1 and temperature of 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 $\dot{C}_{D,total}$.



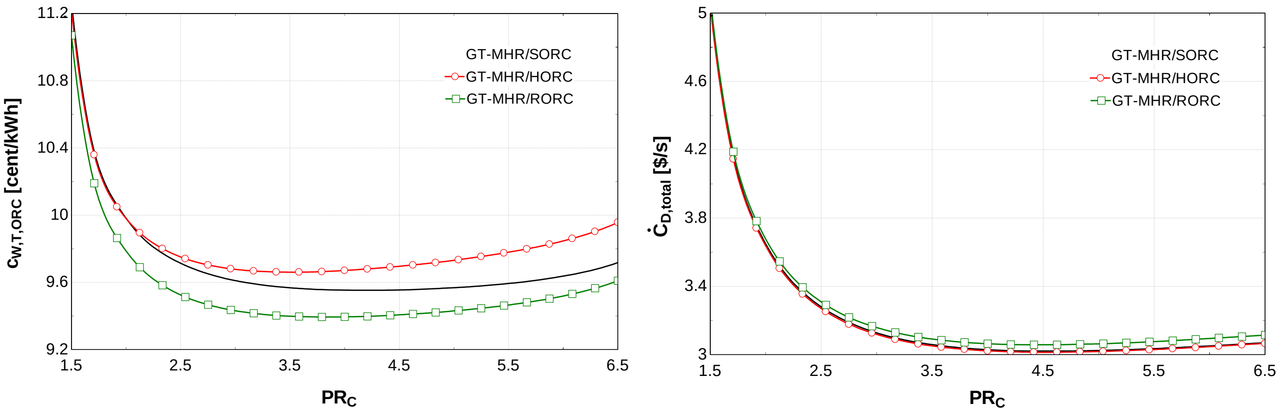
(a) (b)

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

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 $c_{W,T,ORC}$ as shown in Figure 2a. Also 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.

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



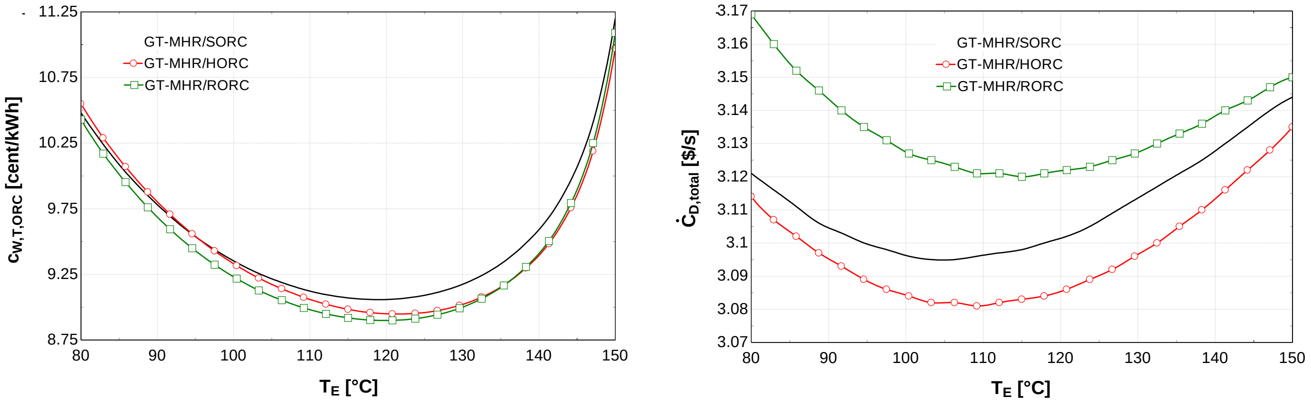
(a) (b)

Figure 3. Effects of PR_C on the (a) unit cost of electricity produced by the ORC turbine and (b) 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.



(a) (b)

Figure 4. Effects of T_E on the (a) unit cost of electricity produced by the ORC turbine and (b) 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.

Also 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.

5. Conclusions

A comparative exergoeconomic analysis of waste heat recovery from a Gas Turbine-Modular Helium Reactor (GT-MHR) using different arrangements 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 applied to subsystems and exergoeconomic parameters are calculated for the components and entire combined cycles. Finally a parametric study is performed to reveal the effects of selected parameters on the exergoeconomic performance of the combined cycles. The considered organic Rankine cycles for electrical power production are: Simple Organic Rankine Cycle (SORC), ORC with internal heat exchanger (HORC) and Regenerative Organic Rankine Cycle (RORC).

The results show that the reactor core has the highest value of 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. Also parametric study shows that increasing 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 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.

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	Pressure Ratio
	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

Subscripts

0	dead (environmental) state
1, 2, 3, …	cycle locations
C	condenser
ch	chemical exergy
D	destruction
E	evaporator
F	fuel
HP	high pressure
IC	intercooler
j	*j*th stream
k	*k*th component
L	loss
LP	low pressure
P	pump, product
PC	precooler
ph	physical exergy
R	recuperator
RC	reactor core
T	turbine

Conflict of Interest

The authors declare no conflict of interest.

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