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

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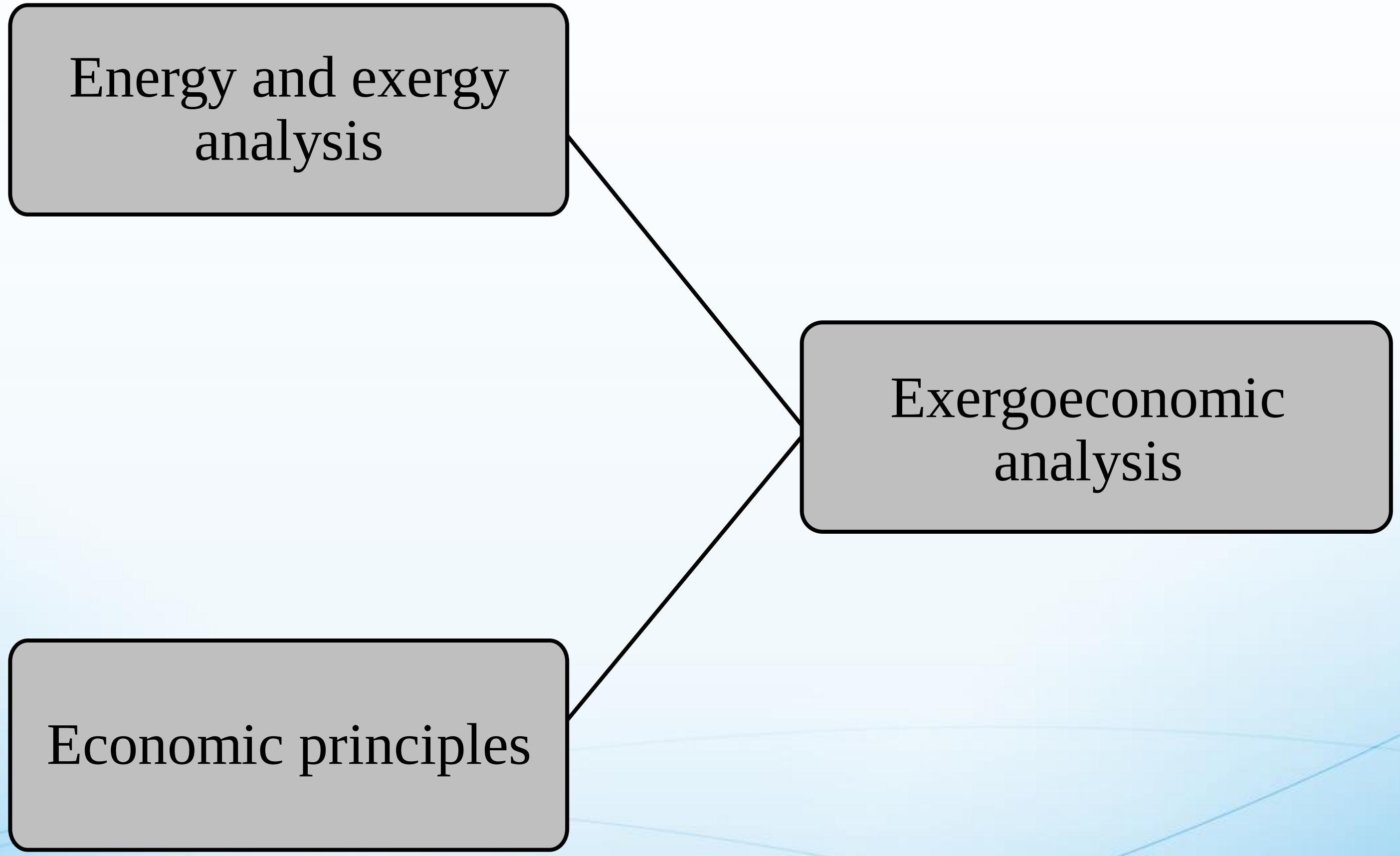
1) Introduction

The world faces numerous sustainability challenges. Much of the world's energy is currently produced and consumed in ways that cannot be sustained. 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 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.


Energy and exergy analysis
Economic principles
Exergoeconomic analysis

The exergoeconomic analysis is performed based on the specific exergy costing (SPECO) approach.

The three considered ORC configurations are:

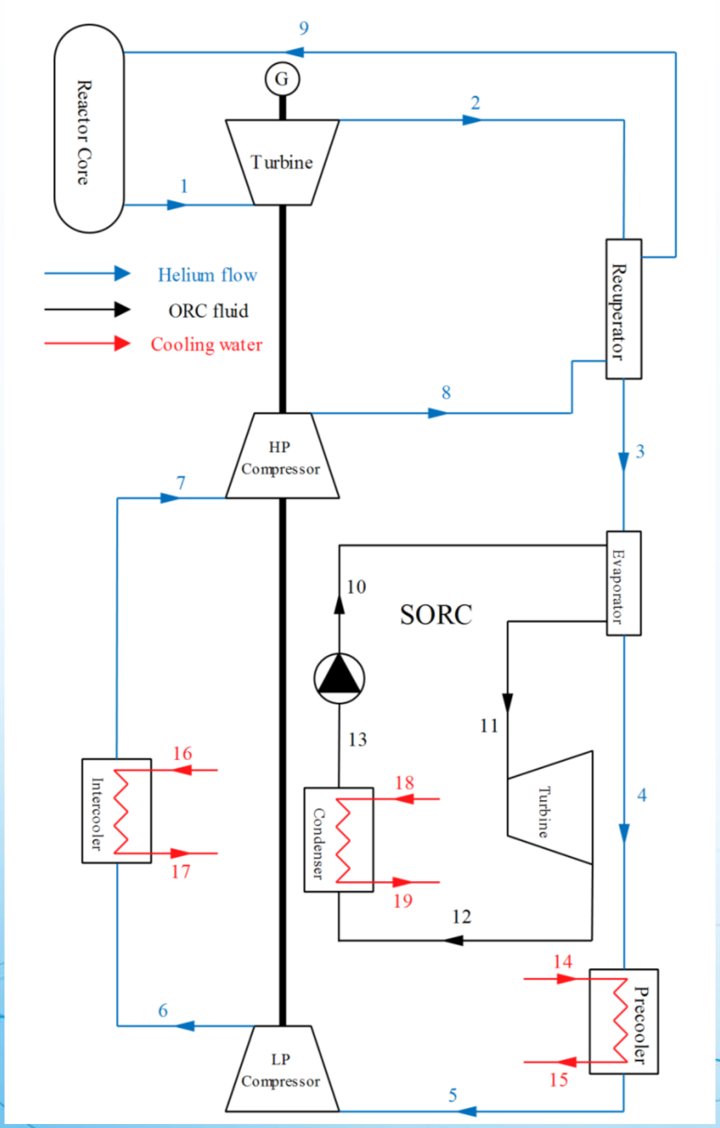
Simple Organic Rankine Cycle (SORC),

ORC with internal heat exchanger (HORC)

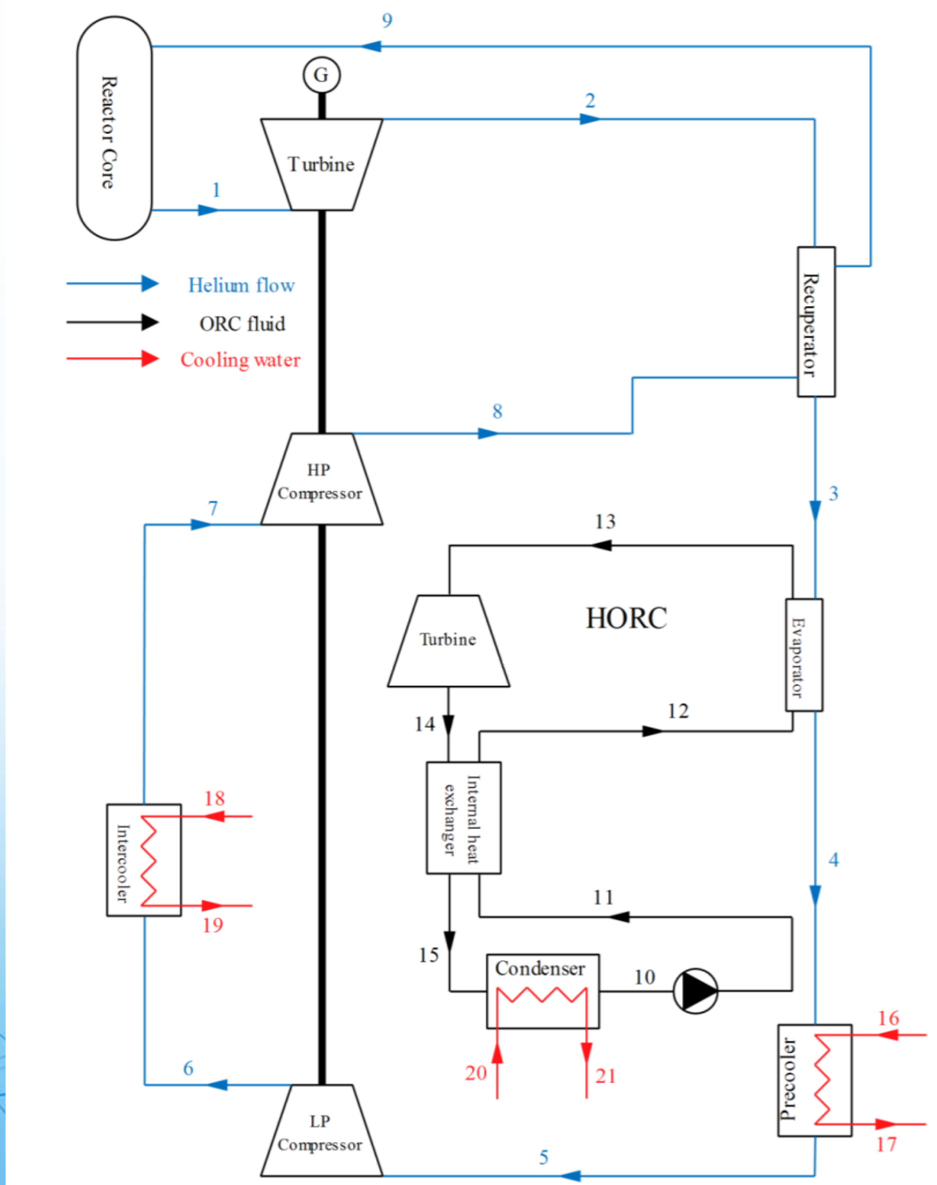
and Regenerative Organic Rankine Cycle (RORC).

Also a parametric study is performed to reveal the effects of some important parameters on the exergoeconomic performance of the combined cycles.

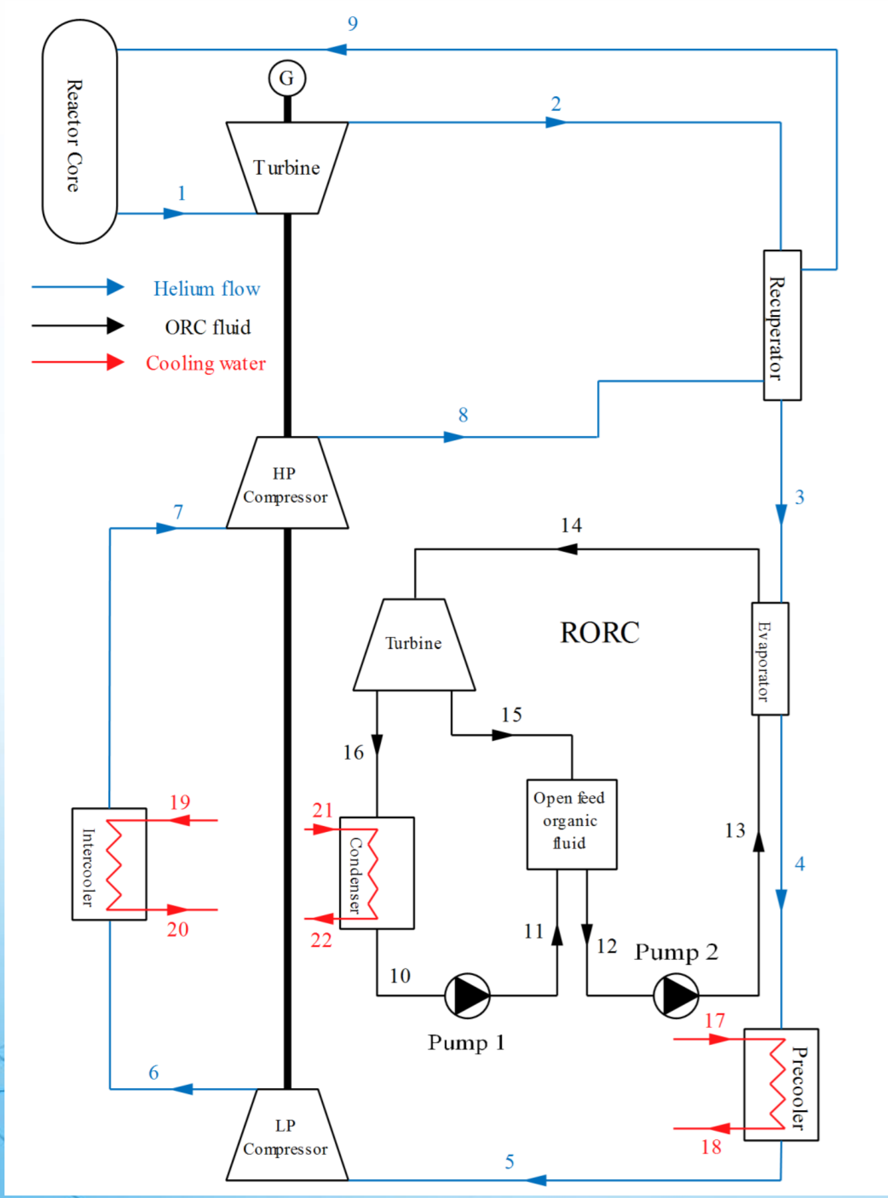
2) Configurations of GT-MHR/ORC Combined Cycles



Turbine-Modular Helium Reactor/Simple Organic Rankine Cycle (GT-MHR/SORC)



Turbine-Modular Helium Reactor/ORC with internal heat exchanger (GT-MHR/HORC)



Turbine-Modular Helium Reactor/Regenerative Organic Rankine Cycle (GT-MHR/RORC)

3) Exergoeconomic Analysis

3-1) Identification and Analysis of Energy and Exergy Streams

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

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

$$\dot{E} = \dot{E}_{ph} + \dot{E}_{ch}$$

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

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

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

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

3-2) 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.

3-3) 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 ($\dot{Z}_k$).

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 :

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

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

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.

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:

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

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

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

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

4) Results and Discussion

4-1) Exergoeconomic Analysis

Table 2. Cost of streams in the combined cycles

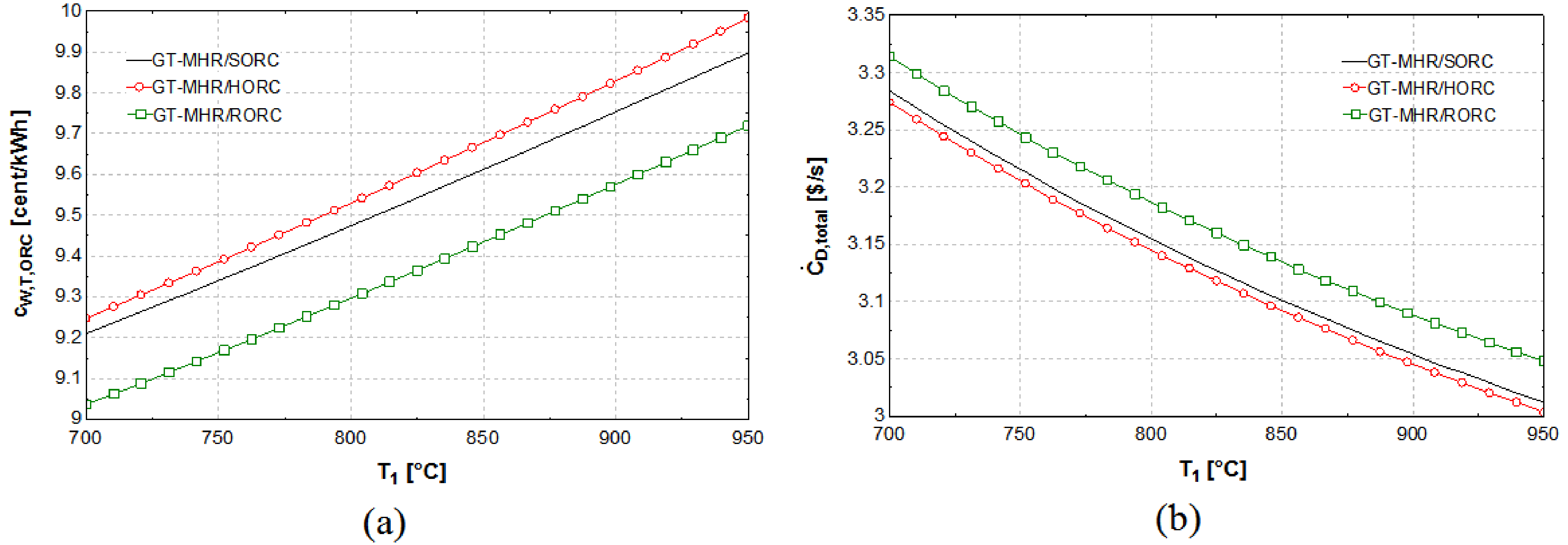
State no.	GT-MHR/SORC		GT-MHR/HORC		GT-MHR/RORC	
	$\dot{C}$ ($/s)	c ($/GJ)	$\dot{C}$ ($/s)	c ($/GJ)	$\dot{C}$ ($/s)	c ($/GJ)
1	17.17	11.83	17.15	11.83	17.20	11.83
2	10.55	11.83	10.53	11.83	10.59	11.83
3	7.428	11.83	7.419	11.83	7.444	11.83
4	7.016	11.83	7.015	11.83	7.046	11.83
5	6.936	11.83	6.927	11.83	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. Important exergy and exergoeconomic parameters of the combined cycles

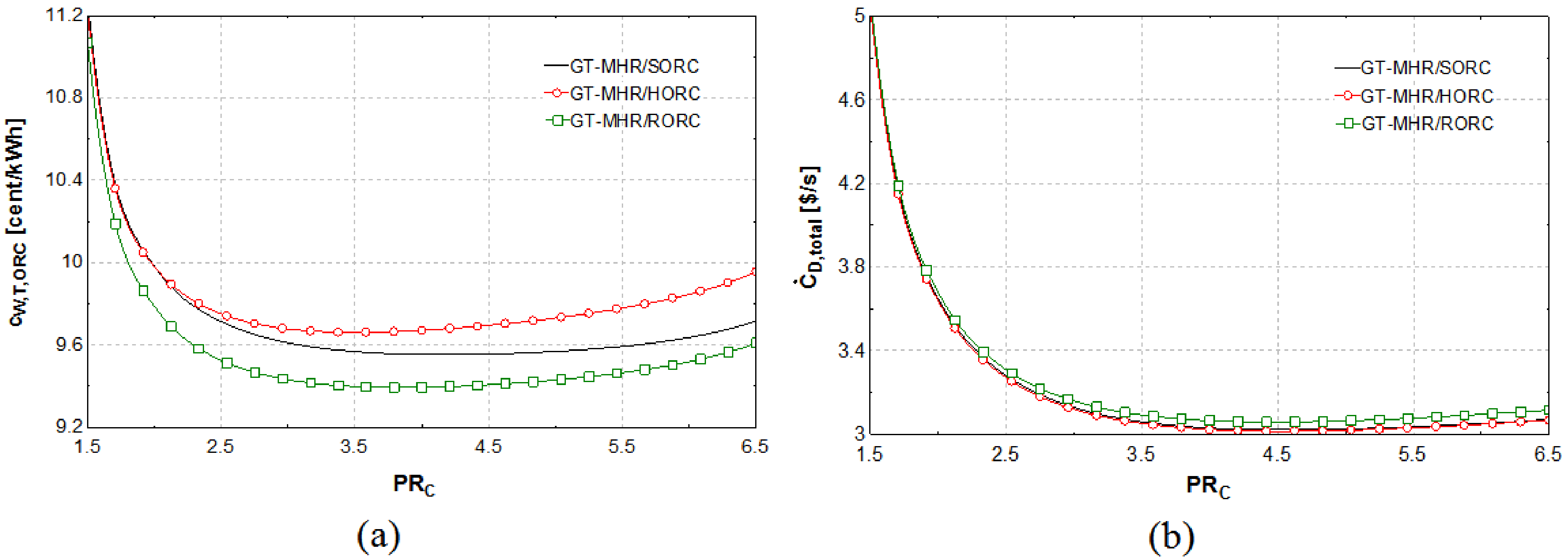
Component	GT-MHR/SORC				GT-MHR/HORC				GT-MHR/RORC			
	$\dot{E}_D$ (kW)	ε (%)	$\dot{C}_D$ ($/s)	f (%)	$\dot{E}_D$ (kW)	ε (%)	$\dot{C}_D$ ($/s)	f (%)	$\dot{E}_D$ (kW)	ε (%)	$\dot{C}_D$ ($/s)	f (%)
Reactor core	198088	87.99	1.874	45.51	198122	87.98	1.874	45.52	197980	88.02	1.874	45.51
Turbine	14868	97.34	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

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.

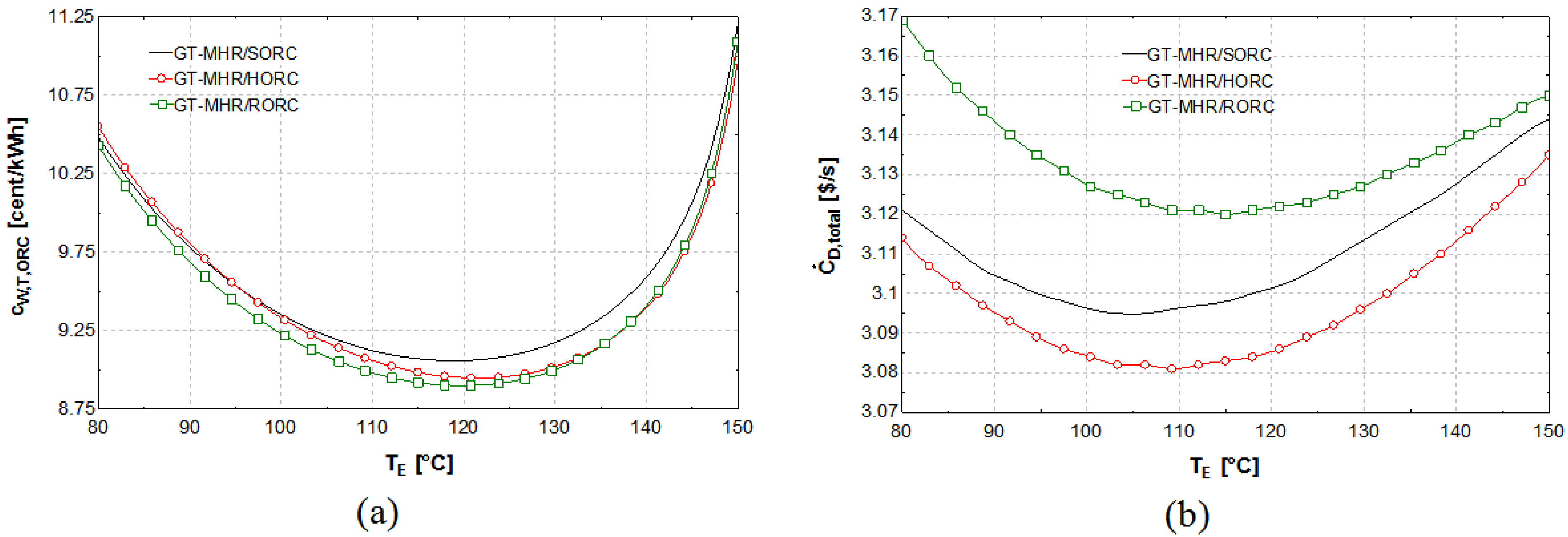
4-2) Parametric Study



Effects of turbine inlet temperature (T_1) on the (a) unit cost of electricity produced by the ORC turbine $c_{W,T,ORC}$ and (b) total exergy destruction cost rate $\dot{C}_{D,total}$



Effects of compressor pressure ratio (PR_C) on the (a) unit cost of electricity produced by the ORC turbine $c_{W,T,ORC}$ and (b) total exergy destruction cost rate $\dot{C}_{D,total}$



Effects of evaporator temperature (T_E) on the (a) unit cost of electricity produced by the ORC turbine $c_{W,T,ORC}$ and (b) total exergy destruction cost rate $\dot{C}_{D,total}$

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.

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.

Thanks

for

your attention