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Allocating the Residues Cost of a Typical HTGR Directly Integrated with Steam Cycle Using Distributed Entropy Method

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Exergetic cost theory (ECT) method, is a conventional exergoeconomic analysis method. In energy systems, disposing of remaining flows of matter or energy is called residues. Distributed entropy (DE) method is an important method for allocating the residues cost. In this study, ECT method and the DE method are applied to a high-temperature gas-cooled reactor (HTGR) that is coupled with the steam cycle through the heat exchanger. Exergetic cost and exergoeconomic cost are obtained for each stream. Then residues cost distribution ratio is calculated using ECT and DE methods. The results have been compared with a model based on the disaggregation of physical exergy into its enthalpic and entropic terms which known as "H&S" model. The results show that the DE method performed similar to the H&S model, but the DE method is a rational criterion to allocate the cost of the residues. The unit product cost of HTGR turbine and steam turbine are calculated as 0.2526 cents/kWh and 1.1500 cents/kWh, respectively. The maximum product unit exergoeconomic cost value is 3.1420 cents/kWh that is corresponding to a steam cycle superheater.

Keywords: Exergoeconomic; Residues; Cost allocation; Exergetic cost theory; Distributed entropy; HTGR

Introduction

In energy systems, exergy can be defined as maximum work that can be obtained from a flow of matter or energy. By applying exergy analysis to the energy systems, the number of irreversibilities and the location of irreversibilities can be determined. The combination of exergy analysis with economic constraints is called exergoeconomic analysis. Exergoeconomic methods the grouped into two classes; the calculus methods and the algebraic methods [1, 2]. Exergetic cost theory (ECT) method [3], average cost theory (ACT) method [4], specific exergy costing method (SPECO) [5], and modified productive structural analysis (MOPSA) [6,7] are the algebraic methods. On the other hand, thermoeconomical functional analysis (TFA) [8] and engineering functional analysis (EFA) [9] belong to calculus methods. In 1999, structural theory of thermoeconomics as a common mathematical language for exergoeconomics was proposed by Erlach et al. [10]. One of the not attended concepts of energy systems is the disposal of remaining flows of matter or energy that are called residues. Many researchers have investigated the problem of allocating the residues cost, but there is no general solution. The studies about the cost of the residues in comparison with generated entropy have been performed by Lozano and Valero [3] and Frangopoulos [11]. Also, the distribution of the cost of the residues proportional to the exergy has been proposed by Torres et al. [12]. A more rational criterion for allocating the residues cost was proposed by Seyyedi et al. [13].

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This criterion, based on the distributed entropy in the components, is known as the distributed entropy (DE) method. A comparison between residues cost allocation proportional to the entropy generation, proportional to the exergy and proportional to the distributed entropy has been presented in Seyyedi et al. [13,14,15]. A similar method has also been proposed by Santos et al. [16] which is called H&S model. The basis of this method is the breakup of exergy into enthalpy and negentropy. Lourenço et al. [17] applied this method to a high-temperature gas-cooled reactor (HTGR) direct combined cycle. In this study, the ECT method and the DE method are applied to a typical HTGR that is combined with a steam cycle as used in Lourenço et al. [17]. Allocation cost evaluation results by the ECT and DE methods are comparable with the results of H&S model.

Methods and Material

Exergetic cost theory (ECT) method

In order to indicate theexergetic cost of each stream, fuel and product costs for each component, ECT method as an algebraic method applies to the energy systems. This method has been proposed by Lozano and Valero [3] who are two specialists in exergoeconomic fields. Thermoeconomic analysis distinguishes between exergy cost, formerly exergetic cost, and exergoeconomic cost. The exergy cost of a mass is the amount of exergy (kW) required to produce this mass. The unit exergy cost of a flow represents the amount of exergy needed to obtain a unit of exergy of that flow. The exergoeconomic cost takes into account the monetary cost of the consumed fuel, namely its market price ($/kWh), as well as the investment and operational cost rate of the plant ($/h), and defines the amount of money required to produce a flow. Similarly, the unit exergoeconomic cost ($/kWh) of a flow is the amount of monetary units needed to obtain a unit of exergy of the referred flow [12]. For more details, see References [3,14].

Distributed entropy (DE) method

The distributed entropy method has been proposed by Seyyedi et al. [13] and it is based on the distributed entropy in the components. In this method, the first step is constructing a fuel-product (FP) table (the mathematical representation of the thermoeconomic model) from each flow exergy to allocating the cost of the residues. In this study, the FP table means the distribution of fuel and product through the combined cycle. In the second step, the FP table is calculated by energy definition instead of the exergy concept where the new table is called FP^H table. According to $T_0 S = H - S$, an FP^S table is constructed by $FP^S = FP^H - FP$ that represents the distribution of entropy through the combined cycle [13]. The production cost of i th component is given by Torres et al. [12] and Seyyedi et al. [13]:

$$C_{P,i} = C_{F,i} + C_{R,i} + Z_i \quad (1)$$

where

$$C_{R,i} = \sum_{r \in V_D} C_{r,i} \quad (2)$$

In order to determine the values of $C_{r,i}$, it must be defined a residue cost distribution ratio ψ_{ir} such as

$$C_{r,i} = \psi_{ir} C_{r0} \quad \text{with} \quad \sum_i \psi_{ir} = 1 \quad (3)$$

Physical Model

In this study, an HTGR-steam combined cycle is used to illustrate the application of the ECT method and DE method. The HTGR is a graphite moderated helium cooled reactor with ceramic coated spherical micro fuel particles. Since the working fluid (helium) of an HTGR power cycle directly cools the core of the nuclear plant, it is called a direct cycle. Fig. (1) shows a typical HTGR direct combined cycle.

The combined cycle has two closed loops being composed of a topping helium gas cycle and a bottoming steam cycle. The tapping cycle is the core of a nuclear reactor, which provides the required energy for heating the gas helium. The two cycles are connected to each other by a heat exchanger. The outlet steam from the heat exchanger is superheated in a superheater which is fed by methane. Table (1) presents the thermodynamic properties of each stream that used to construct the FP table.

Results and Discussion

The definition of fuel and product for each component of the HTGR combined cycle are presented in Table (2).

For all calculations, a code has been developed in MATLAB. According to the thermodynamic properties of the HTGR combined cycle and the definition of the fuel and product, the amounts of fuel (F), product (P), irreversibility ($\dot{I}$), exergetic efficiency (ε), unit exergy consumption (kE) and specific exergy destruction (kI) for each component of combined cycle are shown in Table 3.

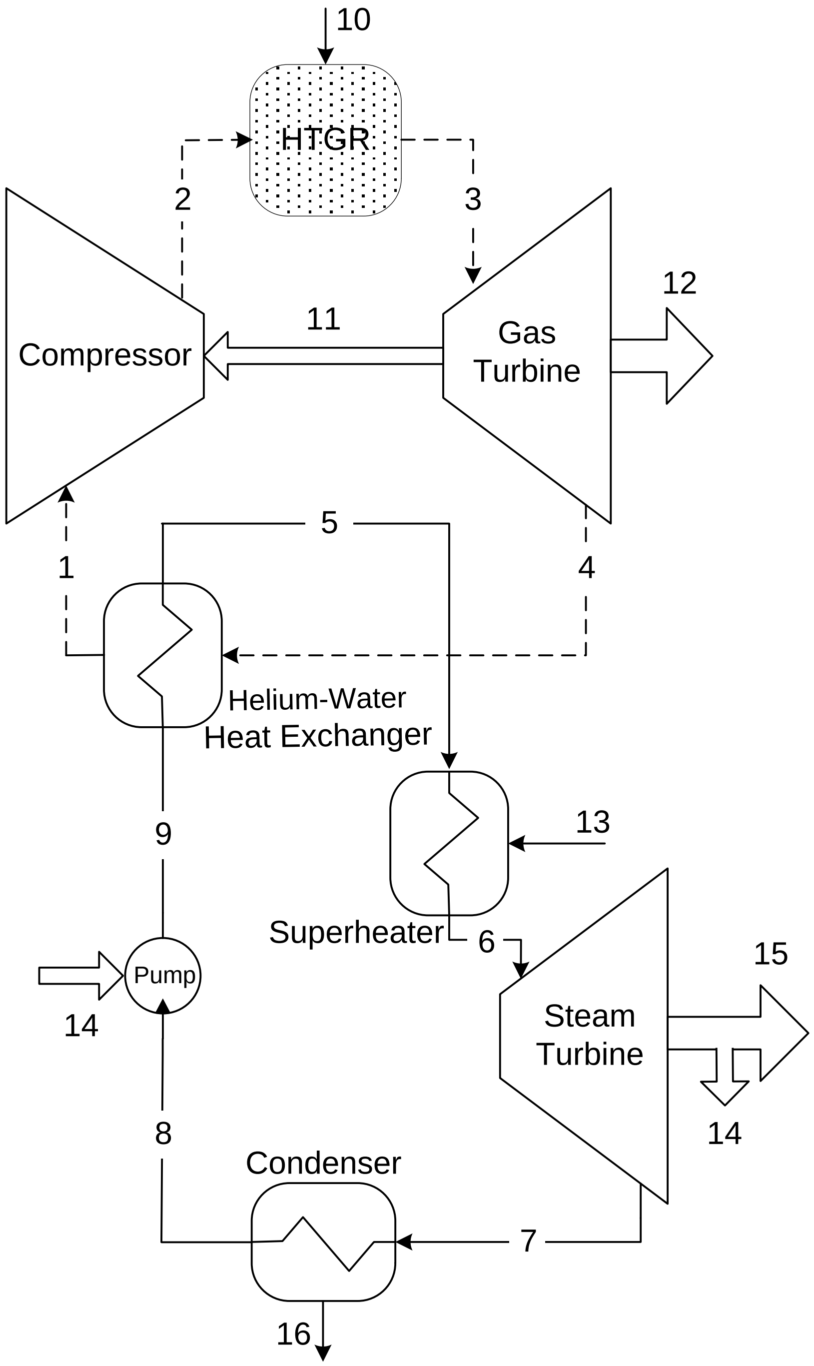

Fig. (1): Physical structure of HTGR combined cycle

Table (1): Thermodynamic properties of the combined cycle

No.	Flow description	p (kPa)	T (K)	$\dot{m}$ (kg/s)	h (kJ/kg)	s (kJ/kg ·K)	$\dot{H}$ (kW)	$\dot{E}$ (kW)
0	Environment	101.325	298					
1	Helium	1000	353.15	78.76	288.81	-3.8753	22746.68	113701.83
2	Helium	4000	643.95	78.76	1807.55	-3.6340	142362.64	227654.36
3	Helium	4000	1133.15	78.76	4346.96	-0.7004	342366.57	358805.29
4	Helium	1000	699.29	78.76	2086.06	-0.3281	164298.09	171998.75
5	Steam ($x = 1$)	8300	570.78	54.89	2753.20	5.7229	145359.70	57756.97
6	Steam	8300	703.15	54.89	3214.76	6.4594	170694.73	71044.91
7	Steam ($x = 0.9$)	7	312.16	54.89	2330.76	7.5023	122171.97	5463.20
8	Liquid ($x = 0$)	7	312.16	54.89	163.36	0.5590	3203.38	67.70
9	Liquid	8300	313.06	54.89	174.48	0.5679	3813.76	532.50
10	Nuclear fuel							200000
11	Power demanded by the Compressor							119615.96
12	Net power of gas turbine							58452.52
13	Methane (e_f = 51,848.5 kJ/kg)			0.55				28516.68
14	Power demanded by the Pump							610.38[a]
15	Net power of steam turbine							47912.38
16	Rejected Heat from condenser						118968.59[b]	5394.76[c]

[a] $\dot{W}_{\text{Pump}} = \dot{m}_{\text{Steam}} \times (h_9 - h_8) = 54.89 \times (174.48 - 163.36) = 610.38$ kW

[b] $\dot{Q}_{\text{Cond}} = \dot{m}_7 \times (h_7 - h_8) = 54.89 \times (2330.76 - 163.36) = 118968.59$ kW

[c] $\dot{E}^{Q}_{\text{Cond}} = \left(1 - \frac{T_0}{T_8}\right) \times \dot{Q}_{\text{Cond}} = \left(1 - \frac{298}{312.155}\right) \times 118968.59 = 5394.76$ kW

Columns 1 to 5 read from Lourenço et al. [16].

Table (2): Definition of fuel and product for each component

No.	Device	Fuel	Product	Type of component
1	Compressor	$\dot{E}_{11}$	$\dot{E}_2 - \dot{E}_1$	Productive
2	Reactor	$\dot{E}_{10}$	$\dot{E}_3 - \dot{E}_2$	Productive
3	Gas Turbine	$\dot{E}_3 - \dot{E}_4$	$\dot{E}_{11} + \dot{E}_{12}$	Productive
4	Heat exchanger	$\dot{E}_4 - \dot{E}_1$	$\dot{E}_5 - \dot{E}_9$	Productive
5	Superheater	$\dot{E}_{13}$	$\dot{E}_6 - \dot{E}_5$	Productive
6	Steam Turbine	$\dot{E}_6 - \dot{E}_7$	$\dot{E}_{14} + \dot{E}_{15}$	Productive
7	Pump	$\dot{E}_{14}$	$\dot{E}_9 - \dot{E}_8$	Productive
8	Condenser	$\dot{E}_7 - \dot{E}_8$	$\dot{E}_{16}$	Dissipative
	Total	$\dot{E}_{10} + \dot{E}_{13} - \dot{E}_{16}$	$\dot{E}_{12} + \dot{E}_{15}$	

Table (3): The amounts of fuel (F), product (P), irreversibility (I), exergetic efficiency (ε), unit exergy consumption (kE) and specific exergy destruction (kI) for each component of combined cycle

No.	Device	F (kW)	P (kW)	I (kW)[a]	ε[a]	kE[a]	kI[a]
1	Compressor	119615.96	113952.54	5663.43	0.9527	1.0497	0.0497
2	Reactor	200000.00	131150.93	68849.07	0.65.58	1.5250	0.5250
3	Gas Turbine	186806.54	178068.48	8738.06	0.9532	1.0491	0.0491
4	Heat exchanger	58296.92	57224.47	1072.45	0.9816	1.0187	0.0187
5	Superheater	28516.68	13287.94	15228.74	0.4660	2.1461	1.1461
6	Steam Turbine	65581.70	48522.76	17058.94	0.7399	1.3516	0.3516
7	Pump	610.38	464.80	145.58	0.7615	1.3132	0.3132
8	Condenser	5395.50	5394.76	0.74	0.9999	1.0001	0.0001
	Total*	223121.92[b]	106364.91[c]	116757.01[d]	0.4767[e]	2.0977	1.0977

**This row shows that the other values have been calculated, correctly.*

[a] $I_i = F_i - P_i$ and $\varepsilon_i = \frac{P_i}{F_i}$ and $kE = \frac{1}{\varepsilon_i} = \frac{F_i}{P_i}$ and $kI = \frac{I_i}{P_i}$

[b] $F_{\text{Total}} = \dot{E}_{10} + \dot{E}_{13} - \dot{E}_{16} = 223121.92 \text{ kW}$

[c] $P_{\text{Total}} = \dot{E}_{12} + \dot{E}_{15} = 106364.91 \text{ kW}$

[d] $I_{\text{Total}} = F_{\text{Total}} - P_{\text{Total}} = \dot{E}_{10} + \dot{E}_{13} - (\dot{E}_{12} + \dot{E}_{15} + \dot{E}_{16}) = \sum_{i=1}^{8} I_i = 116757 \text{ kW}$

[e] $\varepsilon_{\text{Total}} = 1 - \frac{I_{\text{Total}}}{\dot{E}_{10}+\dot{E}_{13}-\dot{E}_{16}} = 0.4767$

The details of the presented parameters in Table (3) have been defined in Torres et al. [12] and Seyyedi et al. [14]. The second law efficiency (exergetic efficiency) for the overall cycle is obtained as 0.4767. The maximum value of irreversibility in the HTGR combined cycle is corresponding to the gas cooled nuclear reactor. By applying the ECT method to the HTGR combined cycle under study, the exergetic cost and exergoeconomic cost of each stream were calculated. These cost values are shown in Table (4).

For these calculations, the fuel cost per energy unit (c_f) and the nuclear fuel cost per thermal exergy of the reactor (c_Q) are considered as 4 $/GJ and 0.4 $/GJ, respectively [18,19]. However, the purchase costs of components are not considered in this work. It is obvious from Table 4 that the maximum values of unit exergy cost and unit exergoeconomic cost are corresponding to stream 9 (outlet liquid from the pump) that have been estimated as 3.0106 (kW/kW) and 1.3167 (cents/kWh), respectively. Besides applying the ECT method, DE method has been applied to the HTGR direct combined cycle, too. Tables (5, 6 and 7) show FP, FP^H, and FP^S tables for combined cycle, respectively.

In order to validate the obtained values in FP, FP^H and FP^S tables illustrated in Tables (5, 6 and 7), a good comparison has been performed according to the values presented in Table (4) of Lourenço et al. [17]. Table 8 represents this comparison.

It is clear from this Table that the values of productive flow presented in Lourenço et al. [17] are in good agreement with the corresponding values of fuel or product in the Tables (5-7). For all values, the relative error is almost negligible. It should be indeed mentioned that the “H&S model” in Lourenço et al. [17] is another face of the distributed entropy method as proposed in Seyyedi et al. [13]. Residues cost distribution ratio (ψ_i) has been calculated by two important criteria. Firstly, using a distribution of the residues cost proportional to the exergy (option 1) [12] and secondly, using distributed entropy method (option 2) [13]. Table (9) represents a comparison between the obtained values of the residues cost distribution ratio (ψ_i) using both criteria.

The values of the first and second columns in Table(9) shows how the values corresponding to two criteria are obtained. These two columns are used to obtain the values in columns three and four. The last column in this Table shows the relative difference between the two options. As it has been discussed in Seyyedi et al. [13], distributed entropy method is more suitable and rational than the other method. Table (10) shows exergetic costs of components using the distributed entropy method.

Table (4): Exergetic and exergoeconomic costs for each stream

No.	Flow description	$\dot{E}$ (kW)	B (kW)	b (kW/kW)	C ($/h)	c (cent/kWh)
1	Helium	113701.83	190108.56	1.6720	273.7563	0.2408
2	Helium	27654.36	399919.62	1.7567	575.8843	0.2530
3	Helium	358805.29	599919.62	1.6720	863.8843	0.2408
4	Helium	171998.75	287580.55	1.6720	414.1160	0.2408
5	Steam $(x = 1)$	57756.97	99075.16	1 .7154	147.3710	0.2552
6	Steam	71044.91	127591.84	1.7959	558.0111	0.7854
7	Steam $(x = 0.9)$	5463.20	9811.54	1.7959	42.9099	0.7854
8	Liquid $(x = 0)$	67.70	121.59	1.7959	0.5317	0.7854
9	Liquid	532.50	1603.17	3.0106	7.0113	1.3167
10	Nuclear fuel	200000	200000	1	288.0000	0.1440
11	Power demanded by the Compressor	119615.96	209811.07	1.7540	302.1279	0.2526
12	Net power of gas turbine	58452.52	102528.00	1.7540	147.6403	0.2526
13	Methane	28516.68	28516.68	1	410.6401	1.4400
14	Power demanded by the Pump	610.38	1481.58	2.4273	6.4796	1.0616
15	Net power of steam turbine	47912.38	16298.72	2.4273	508.6217	1.0616
16	Rejected Heat from condenser	5394.76	9689.95	1.7962	42.3781	0.7855

Table (5): FP Table

	F_0	F_1	F_2	F_3	F_4	F_5	F_6	F_7	F_8	Total
P_0			200000			28516.68				228516.68
P_1				86849.36	27103.18					113952.54
P_2				99957.18	31193.75					131150.93
P_3	58452.52	119615.96								178068.48
P_4							52874.42		4350.05	57224.47
P_5							12277.82		1010.11	13287.93
P_6	47912.38							610.38		48522.76
P_7							429.46		35.33	464.79
R_8	5394.76									5394.76
		119615.96	200000	186806.54	58296.93	28516.68	65581.70	610.38	5395.49	

Table (6): FP^H Table

	F_0	F_1	F_2	F_3	F_4	F_5	F_6	F_7	F_8	Total
P_0			200000			28516.68				228516.68
P_1				66641.14	52974.83					119615.97
P_2				111427.35	88576.58					200003.93
P_3	58452.52	119615.96								178068.48
P_4							41006.30		100539.65	141545.95
P_5							7339.64		17995.39	25335.03
P_6	47912.38							610.38		48522.76
P_7							176.83		433.55	610.38
R_8	118968.59									118968.59
		119615.96	200000	178068.49	141551.41	28516.68	48522.77	610.38	118968.59	

Table (7): FP^S Table

	F_0	F_1	F_2	F_3	F_4	F_5	F_6	F_7	F_8	Total
P_0			0			0				0
P_1				-20207.95	25871.65					5663.7
P_2				11470.17	57382.83					68853
P_3	0	0								0
P_4							-11868.12		96189.6	84321.48
P_5							-4938.18		16985.28	12047.1
P_6	0							0		0
P_7							-252.63		398.22	145.59
R_8	113573.83									113573.83
				-8737.78	83254.48	0	-17058.93	0	113573.1	

Table (8): Comparison between the values fuel and product in Table (4) of Lourenço et al. [17] and present work

Table (6) in Present work		Table (5) in Present work		Table (4) in Ref. [17]		Table (7) in Present work		Table (4) in Ref. [17]	
Fuel or Product	Values	Fuel or Product	Values	Productive Flow	Values	Fuel or Product	Values	Productive Flow	Values
		F_1	119615.96	$H_{2:1}$	119613.72	P_1	5663.7	$S_{2:1}$	5665.10
		F_2	200000	$H_{3:2}$	200000	P_2	68853	$S_{3:2}$	68850.85
		P_3	178068.48	$H_{3:4}$	178064.68	$-F_3$	8737.78	$S_{3:4}$	8737.13
P_4	141545.95			$H_{4:1}$	141549.04	F_4	83254.48	$S_{4:1}$	83253.09
P_4	141545.95			$H_{5:9}$	141549.04	P_4	84321.48	$S_{5:9}$	84323.46
P_5	25335.03			$H_{6:5}$	25335.44	P_5	12047.1	$S_{6:5}$	12046.66
		P_6	48522.76	$H_{6:7}$	48523.69	$-F_6$	17058.93	$S_{6:7}$	17059.42
F_8	118968.59			$H_{7:8}$	118971.20	R_8	113573.83	$S_{7:8}$	113574.96
		F_7	610.38	$H_{9:8}$	610.42	P_7	145.59	$S_{9:8}$	145.42

Table (9): Residues cost allocation based on the distributed entropy method for combined cycle

No.	Device	Column F_8 in Table (5)	Column F_8 in Table 7	$\psi_i = \frac{E_{i,8}}{F_8}$ Ref. [12] (option 1)	$\psi_i = \frac{E^S_{i,8}}{F^S_8}$ Present work and Ref [13] (option 2)	Relative difference between two options (%)
1	Compressor	0.00	0.00	0.0000	0.0000	0.00
2	Reactor	0.00	0.00	0.0000	0.0000	0.00
3	Gas Turbine	0.00	0.00	0.0000	0.0000	0.00
4	Heat exchanger	4350.05	96189.6	0.8062	0.8469	4.8
5	Superheater	1010.11	16985.28	0.1872	0.1495	-25.22
6	Steam Turbine	0.00	0.00	0.0000	0.0000	0.00
7	Pump	35.33	398.22	0.0065	0.0035	-85.71
8	Condenser	0.00	0.00	0.0000	0.0000	0.00
	Total	5395.49	113573.1			

The minimum and maximum values of product unit exergetic cost (c_P) is corresponding to the reactor and the pump that are equal to 1.5249 (kW/kW) and 3.5324 (kW/kW), respectively. Residues cost (C_R) for the heat exchanger, superheater and pump are equal to 8890.60 kW, 1569.87 kW, and 36.85 kW, respectively, and for other components are equal to zero (corresponding to zero values of these components in column 4 of Table 9). Table (11) shows exergoeconomic costs of components using the distributed entropy method.

The minimum and maximum values of product unit exergoeconomic cost (c_P) is equal to 0.2196 (cents/kWh) and 3.1420 (cents/kWh), that are related to the reactor and superheater, respectively. In Table(11) the last column shows the product cost rate for each component. It is clear that the minimum and maximum values are 7.18 ($/h) and 558.02 ($/h) that are corresponding to the pump and steam turbine, respectively.

For better comparison, the results of product unit exergetic cost (kW/kW) and product unit exergoeconomic cost (cents/kWh) for the HTGR combined cycle, which is calculated by ECT method and DE method are presented in Fig. (2 and 3).

It is obvious from Fig. (2)that DE method is a more accurate method compared to the ECT method. However, product exergetic cost values predicted by the DE method are more conservative in comparison with the results of the ECT method. The maximum and the minimum product exergetic cost values in (kW/kW) HTGR combined cycle is related to the pump (3.5 kW/kW) and the reactor (1.4 kW/kW), respectively. In contrast, from Fig. (3) it can be seen that the combined cycle suffers from the costly superheater component. However gas-cooled reactor, as an innovated component in combined cycle under study, has an economized product unit exergoeconomic cost value.

FP^S table has interesting properties which have been extensively described in References. [13,14]. Table (12) shows the calculation results of the distributed entropy method.

In Table(13), the exergy carried out by each flow is denoted as $E_{i,j}$ that represents the product of i th component that is used as the fuel of the j th component [12]. Table (12) has been constructed using Tales (5-7). For example, in this table, a focus was made on the bold-faced values for each component. These bold-faced values represent the product of FP^S Table (P_i^S) for each component and on the other hand, are equal to the generated entropy which has been shown in the last column of this table. It is also noted that the colored bold-faced values are 96189.6 kW, 16985.28 kW, and 398.22 kW. These values correspond to the heat exchanger, superheater, and pump, respectively. The sum of three values is 113573.1 which this summation that was shown in the last row of Table (9). Therefore, for calculation of residues cost distribution ratio (ψ_i), it is enough that each of the three values is divided by the theirs summation. As mentioned before, the result was shown in Table (9). For more details, see Seyyedi et al. [13,14].

Table (10): Exergetic costs of components using the distributed entropy method

No.	Component	c_P (kW/kW)	C_F (kW)	C_R (kW)	C_P (kW)
1	Compressor	1.8412	209811.07	0	209811.07
2	Reactor	1.5249	200000.00	0	200000.00
3	Gas Turbine	1.7540	312339.07	0	312339.07
4	Heat exchanger	1.8587	97471.99	8890.60	106362.59
5	Superheater	2.2642	28516.67	1569.87	30086.55
6	Steam Turbine	2.6296	127593.70	0	127593.70
7	Pump	3.5324	1605.02	36.85	1641.87
8	Condenser	1.9458	10497.32	0	10497.32

Table (11): Exergoeconomic costs of components using the distributed entropy method

No.	Component	c_P (cents/kWh)	C_F ($/h)	C_R ($/h)	C_P ($/h)
1	Compressor	0.2651	302.13	0	302.13
2	Reactor	0.2196	288.00	0	288.00
3	Gas Turbine	0.2526	449.77	0	449.77
4	Heat exchanger	0.3132	140.36	38.88	179.24
5	Superheater	3.1420	410.64	6.87	417.51
6	Steam Turbine	1.1500	558.02	0	558.02
7	Pump	1.5449	7.02	0.16	7.18
8	Condenser	0.8510	45.91	0	45.91

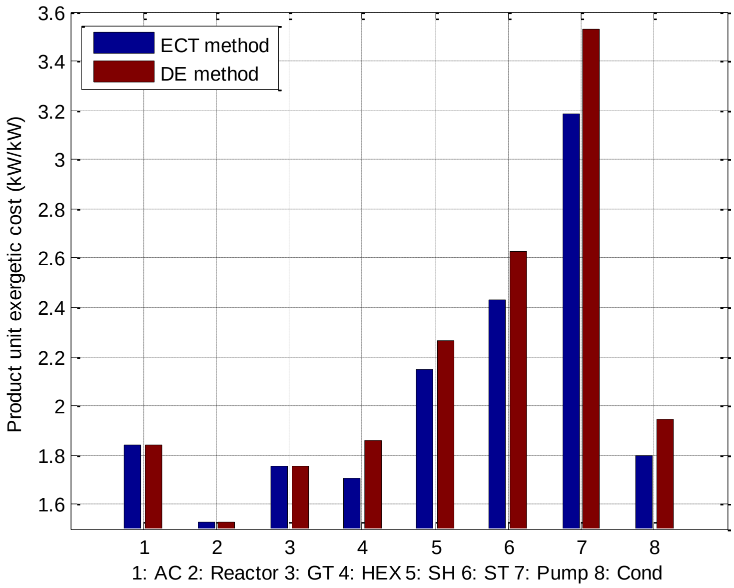

Fig. (2): Product unit exergetic cost of HTGR combined cycle

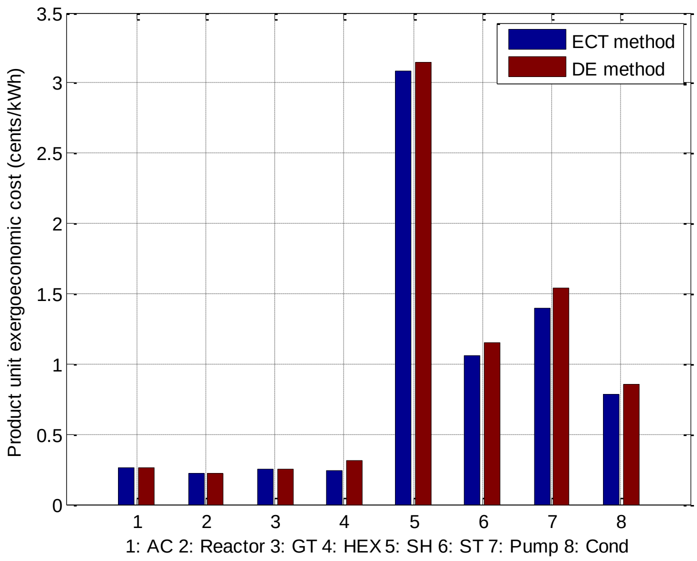

Fig. (3): Product unit exergoeconmoic cost of HTGR combined cycle

Table (12): Results of the distributed entropy method

No.	Component		$P_i^H = \sum_j \dot{E}_{i,j}^H, P_i = \sum_j \dot{E}_{i,j}$, $P_i^S = \sum_j \dot{E}_{i,j}^S$	$I = T_0\dot{S} = T_0(\dot{m}_{\text{out}}s_{\text{out}} - \dot{m}_{\text{in}}s_{\text{in}})$
1	Compressor		$\dot{E}_{1,3} + \dot{E}_{1,4} = P_1$	$T_0\dot{S} = T_0 \times \dot{m}_{\text{Helium}} \times (s_2 - s_1)$
		$\dot{E}_{1,j}^H$	$66641.14 + 52974.83 = 119615.97$	$T_0\dot{S} = 298 \times 78.76 \times (-3.6340 + 3.8753) = \mathbf{5663.4}$
		$\dot{E}_{1,j}$	$86849.36 + 27103.18 = 113952.54$	
		$\dot{E}_{1,j}^S$	$-20207.95 + 25871.65 = \mathbf{5663.7}$	
2	Reactor		$\dot{E}_{2,3} + \dot{E}_{2,4} = P_2$	$T_0\dot{S} = T_0 \times \dot{m}_{\text{Helium}} \times (s_3 - s_2)$
		$\dot{E}_{2,j}^H$	$111427.35 + 88576.58 = 200003.93$	$T_0\dot{S} = 298 \times 78.76 \times (-0.7004 + 3.6340) = \mathbf{68853}$
		$\dot{E}_{2,j}$	$99957.18 + 31193.75 = 131150.93$	
		$\dot{E}_{2,j}^S$	$11470.17 + 57382.83 = \mathbf{68853}$	
3	Gas Turbine		$\dot{E}_{3,0} + \dot{E}_{3,1} = P_3$	$T_0\dot{S} = T_0 \times \dot{m}_{\text{Helium}} \times (s_4 - s_3)$
		$\dot{E}_{3,j}^H$	$58452.52 + 119615.96 = 178068.48$	$T_0\dot{S} = 298 \times 78.76 \times (-0.3281 + 0.7004) = 8738.06$
		$\dot{E}_{3,j}$	$58452.52 + 119615.96 = 178068.48$	
		$\dot{E}_{3,j}^S$	$0 + 0 = 0$	
4	Heat exchanger		$\dot{E}_{4,6} + \dot{E}_{4,8} = P_4$	$T_0\dot{S} = T_0 \times \dot{m}_{\text{Helium}} \times (s_1 - s_4)$
		$\dot{E}_{4,j}^H$	$41006.30 + 100539.65 = 141545.95$	$T_0\dot{S} = 298 \times 78.76 \times (-3.8753 + 0.3281) = -83254.49$
		$\dot{E}_{4,j}$	$52874.42 + 4350.05 = 57224.47$	
		$\dot{E}_{4,j}^S$	$-11868.12 + \mathbf{96189.6} = \mathbf{84321.48}$	$T_0\dot{S} = T_0 \times \dot{m}_{\text{Steam}} \times (s_5 - s_9)$
				$T_0\dot{S} = 298 \times 54.89 \times (5.7229 - 0.5679) = \mathbf{84321.47}$
				$\dot{I} = 84321.47 - 83254.49 = 1066.98 \approx 1072.45$
5	Superheater		$\dot{E}_{5,6} + \dot{E}_{5,8} = P_5$	$T_0\dot{S} = T_0 \times \dot{m}_{\text{Steam}} \times (s_6 - s_5)$
		$\dot{E}_{5,j}^H$	$7339.64 + 17995.39 = 25335.03$	$T_0\dot{S} = 298 \times 54.89 \times (6.4594 - 5.7229) = \mathbf{12047.1}$
		$\dot{E}_{5,j}$	$12277.82 + 1010.11 = 13287.93$	
		$\dot{E}_{5,j}^S$	$-4938.18 + \mathbf{16985.28} = \mathbf{12047.1}$	
6	Steam Turbine		$\dot{E}_{6,0} + \dot{E}_{6,7} = P_6$	$T_0\dot{S} = T_0 \times \dot{m}_{\text{Steam}} \times (s_7 - s_6)$
		$\dot{E}_{6,j}^H$	$47912.38 + 610.38 = 48522.76$	$T_0\dot{S} = 298 \times 54.89 \times (7.5023 - 6.4594) = \mathbf{17058.94}$
		$\dot{E}_{6,j}$	$47912.38 + 610.38 = 48522.76$	
		$\dot{E}_{6,j}^S$	$0 + 0 = 0$	
7	Pump		$\dot{E}_{7,6} + \dot{E}_{7,8} = P_7$	$T_0\dot{S} = T_0 \times \dot{m}_{\text{Steam}} \times (s_9 - s_8)$
		$\dot{E}_{7,j}^H$	$176.83 + 433.55 = 610.38$	

		$\dot{E}_{7,j}$	$429.46 + 35.33 = 464.79$	$T_0\dot{S} = 298 \times 54.89 \times (0.5679 - 0.5590)$
		$\dot{E}^S_{7,j}$	$-252.63 + \mathbf{398.22} = \mathbf{145.59}$	$= \mathbf{145.58}$
8	Condenser		$\dot{E}_{8,0} = R_8$	$T_0\dot{S} = T_0 \times \dot{m}_{\text{Steam}} \times (s_7 - s_8)$
		$\dot{E}^H_{8,j}$	$118968.59 = 118968.59$	
		$\dot{E}_{8,j}$	$5394.76 = 5394.76$	$T_0\dot{S} = 298 \times 54.89 \times (7.5023 - 0.5590)$
		$\dot{E}^S_{8,j}$	$113573.83 = \mathbf{113573.83}$	$= \mathbf{113573.09}$

Table (13): Product unit exergetic cost (kW/kW) and product unit exergoeconomic cost (cents/kWh)

No.	Component	c_P (kW/kW) ECT method	c_P (kW/kW) DE	Error (%)	c_P (cents/kWh) ECT method	c_P (cents/kWh) DE method	Error (%)
1	Compressor	1.8412	1.8412	0.0000	0.2651	0.2651	0 .0000
2	Reactor	1.5250	1.5250	0.0000	0.2196	0.2196	0
3	Gas Turbine	1.7540	1.7540	0.0000	0.2526	0.2526	0.0000
4	Heat exchanger	1.7033	1.8587	8.3588	0.2453	0.3132	21.6926
5	Superheater	2.1461	2.2642	5.2179	3.0903	3.1420	1.6445
6	Steam Turbine	2.4273	2.6296	7.6911	1.0616	1.1500	7.6911
7	Pump	3.1876	3.5324	9.7627	1.3941	1.5449	9.7627
8	Condenser	1.7962	1.9458	7.6911	0.7855	0.8510	7.6911

Conclusion

In this work, the ECT method and the DE method were applied to a typical high-temperature gas-cooled reactor that directly coupled with a steam cycle through a superheater. Exergetic and exergoeconomic costs for each stream has been calculated. Also, fuel and product cost for each component has been obtained. Residues cost distribution ratio has been calculated by two important criteria and were compared with each other. The results show that criterion based on the distributed entropy is more rational than the other criterion. FP^S table that has been used in distributed entropy method has interesting properties that have been extensively described. Also, the method was compared with the H&S model. These two methods are similar. The unit product cost of gas turbine and steam turbine are calculated as 0.2526 cents/kWh and 1.1500 cents/kWh, respectively. Also, the maximum product unit exergoeconomic cost value is 3.1420 cents/kWh that is corresponding to superheater.

Symbols

c exergoeconomic cost (cents/kWh)
C exergoeconomic cost rate ($/h)
B exergetic cost (kW)

Greek letters

ε **exergetic efficiency**
ψ **residue cost distribution ratio**

b unit exegetic cost (kW/kW)

$\dot{E}$ exergy of a flow (kW)
F fuel exergy of a component (kW)
h specific enthalpy (kJ/kg)
$\dot{H}$ enthalpy of a flow (kW)

I irreversibility of a component (kW)
kI specific exergy destruction
$\dot{m}$ mass flow rate (kg/s)
n number of components
p pressure (bar)
P product exergy of a component (kW)

$\dot{Q}$ heat flow rate (kW)
s specific entropy (kJ/kg .k)
T temperature (K)
$\dot{W}$ workflow rate (kW)
$\dot{Z}$ Capital cost rate of a component ($/h)
$\mathbf{V_D}$ set of dissipative components

Subscripts
0 **Environment**
r **Index for dissipative components**
F **related to fuel**
P **related to product**
R **related to residue**

Superscripts
E **related to exergy**
H **related to energy, heat, and enthalpy**
S **related to entropy**

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