Comparison between the Distributed Entropy Method and Average Cost Theory Method in Exergoeconomic Analysis of Energy Systems

Seyyed Masoud Seyyedi

Abstract – Residues are disposal remaining flows of matter or energy that are produced by energy systems. Residues cost allocation is a complex problem. One of the most important criteria for residues cost allocation is distributed entropy method. In this method, the fuel-product (FP) table (a mathematical representation of the thermoeconomic model) is used as input data. Average cost theory (ACT) method is one of the most important conventional exergoeconomic methods that can be applied to energy systems. In this paper, distributed entropy method and ACT method are applied to a combined cycle and a cogeneration system. Fuel and product costs for each component are obtained and compared with each other. Specific cost of product for each component is calculated, too.

Keywords: Exergoeconomic, Residues, Cost allocation, Average cost theory

1. Introduction

For an energy system (such as power plant) mass and energy balances must be written. Energy balance is known as first law of thermodynamics. Exergy can be defined as maximum work that can be obtained from a flow of matter or energy. Exergy analysis is applied to energy systems to determine amount and location of irreversibilities. Combination of exergy analysis with economic constraints is called exergoeconomic analysis. Exergoeconomic methods can be grouped in two classes: the algebraic methods and the calculus methods [1, 2]. Some of the algebraic methods are: exergetic cost theory (ECT) [3], average cost theory (ACT) [4], specific cost exergy costing method (SPECO) [5] and modified productive structural analysis (MOPSA) [6, 7]. On the other hand, thermoeconomical functional analysis (TFA) [8, 9] and engineering functional analysis (EFA) [10] belong to calculus methods. Also, structural theory of thermoeconomics as a common mathematical language for exergoeconomics was proposed by Erlach et al. [11]. In energy systems, disposal remaining flows of matter or energy are appeared which are called residues. Problem of residues cost allocation has been investigated by many researchers but there is not a general solution for it. Distribution of the cost of the residues proportional to the entropy generation or negentropy has been performed by Lozano and Valero [12] and Frangopoulos [13]. Also, distribution of the cost of the residues proportional to the exergy has been proposed by Torres et al. [14]. A more rational criterion for residues cost allocation has been proposed by Seyyedi et al. [15], that it is based on the distributed entropy in the components. This is called the distributed entropy 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 Ref. [15].

In this paper, the average cost theory (ACT) method and the distributed entropy method are applied to a combined cycle and to a cogeneration system. The aim of this work is comparison between the values of fuel and product costs for each component of the energy systems. Also, specific cost of product for each component is evaluated. The results indicate the importance of good criterion for residues cost allocation.

2. Average cost theory (ACT) method

Average cost Theory (ACT) method [4] is a good, simple and strong conventional approach for determination of fuel and product costs of each component in an energy system such as power plant. In this method, it must be written n cost balance equation (one cost balance equation for each component and n is the number of components) and m-n auxiliary cost equation (m is the number of streams). Then liner equations system must be solved to determine the cost of each stream. Then, fuel and product costs can be calculated by definition of fuel and product for each component.

Corresponding Author :Department of Mechanical Engineering , Aliabad Katoul Branch, Islamic Azad University, Aliabad Katoul , Iran
Email: s.masoud_seyedi@yahoo.com

Received 2019.05.06 ; Accepted 2019.11.22

3. Distributed entropy method

This method has been proposed by Seyyedi et al. [15] that it is based on the distributed entropy in the components. In this method, firstly the fuel-product (FP) table (a mathematical representation of the thermoeconomic model) must be constructed. The second step is construction of FPH and FPS tables. For more details see Ref. [15, 16]. The product cost of the ith component, in a general form, is given by [14, 15]:

$$C_{P,i} = C_{F,i} + C_{R,i} + Z_i \tag{1}$$

where

$$C_{R,i} - \sum_{r \in V_D} C_{r,i} \tag{2}$$

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

$$C_{r,i} - \psi_{ir} C_{r0} \quad \text{with} \quad \sum_i \psi_{ir} - 1 \tag{3}$$

4. Case 1: combined cycle

Fig. 1 shows the physical model of the combined cycle and Table 1 represents the thermodynamic properties of the combined cycle. Table 2 represents the definition of fuel and products for each component. The amounts of fuel (F), product (P), irreversibility (I), exergetic efficiency (Ɛ) and specific exergy destruction (kI) for each component can be seen in Table 3.

4.1. Application ACT to the combined cycle

Here, the ACT method is applied to the combined cycle which is shown in Fig. 1. Cost balance and auxiliary equations for each component are shown in Table 4. Equations in Table 4 can be written in the matrix form. The system of 21 equations and 21 unknowns can be solved to obtain the cost of streams 1–21 for combined cycle. Table 5 represents exergy rate $\dot{E}$ (kW), cost of stream $\dot{C}$ (€/h) and unit exergy cost of stream c (€/GJ) for each stream of the combined cycle. Unit exergy cost of fuel (cF) and unit exergy cost of product (cP) for each component are defined as follows:

c_F=C˙_F/F and c_P=C˙_P/P (4)

Table 6 shows unit exergy cost of fuel cF (€/GJ), unit exergy cost of product cP (€/GJ), exergy cost of fuel CF (€/h), exergy cost of product CP (€/h) and the capital cost rate Z (€/h), for each component.

4.2. Application distributed entropy method to the combined cycle

Table 7 shows FPS table for the combined cycle. For more details see Ref. [15]. Table 8 shows how the values of this criterion are obtained. Table 9 shows exergoeconomic costs of components that have been calculated by this method.

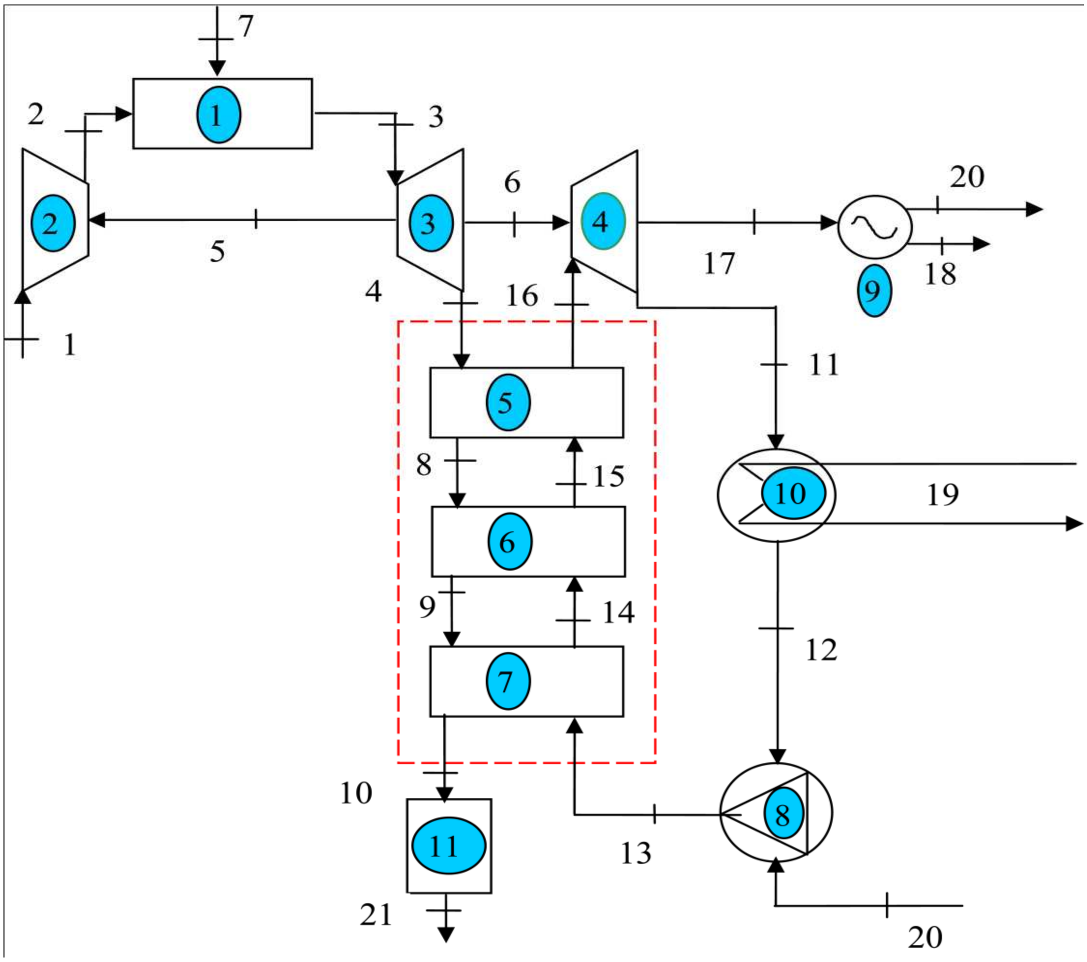

Fig .1: Physical structure of simple combined cycle

Table 1: Thermodynamic properties of the combined cycle

No.	*Flow description*	*p (bar)*	*T (°C)*	*(kg/s)*	*s (kJ/kg · K)*	*h (kJ/kg)*	*(kW)*	**(kW)**
0	Environment	1.013	20.00					
1	Air inlet compressor	1.013	25.00	309.930	0.0170	5.02	1555.85	13.12
2	Air outlet compressor	9.100	331.23	309.930	0.0963	312.47	96843.83	88091.52
3	Gas inlet turbine	9.009	870.00	314.055	0.9585	994.50	312327.70	224086.23
4	Gas inlet superheater	1.044	444.17	314.055	1.0383	496.28	155859.22	60266.99
5	Power compressor						95288.91	95288.91
6	Power gas turbine						61180.17	61180.17
7	Fuel combustor	1.013	25.00	4.125	0.0000	53306.00	219887.25	219880.32
8	Gas inlet boiler	1.033	406.09	314.055	0.9774	451.73	141868.07	51931.62
9	Gas inlet economizer	1.023	262.22	314.055	0.7018	283.39	89000.05	24425.76
10	Gas outlet economizer	1.013	184.20	314.055	0.5204	192.11	60333.11	12450.16
11	Outlet LP turbine	0.065	37.64	30.904	7.1956	2225.88	68788.59	3723.19
12	Outlet condenser	0.065	37.67	30.904	0.5408	157.64	4871.71	64.66
13	Steam inlet economizer	40.804	37.91	30.904	0.5441	162.77	5030.24	193.36
14	Steam inlet evaporator	40.400	251.00	30.904	2.8007	1090.41	33698.03	8426.93
15	Steam inlet superheater	40.400	251.00	30.904	6.0681	2801.08	86564.58	31708.09
16	Steam inlet HP turbine	40.000	417.13	30.904	6.8281	3253.80	100555.44	38817.60
17	Power steam turbine						31766.76	31766.76
18	Electric power						90000.00	90000.00
19	Condense heat						63916.89[a]	3633.28[b]
20	Power extraction pump						158.53[c]	158.53

[a] $Q_{Condenser} = \dot{m}_{12}(h_{11} - h_{12}) = 30.904 \times (2225.88 - 157.64) = 63916.89 \text{ kW}$

[b] $\dot{E}^{Q}_{Condenser} = (1 - \frac{T_0}{T_{12}})\dot{Q}_{Condenser} = (1 - \frac{293.15K}{310.82K}) \times 63916.89 = 3633.28 \text{ kW}$

[c] $\dot{W}_{Pump} = \dot{m}_{12}(h_{13} - h_{12}) = 30.904 \times (162.77 - 157.64) = 158.53 \text{ kW}$

Table 2: Definition of fuel and product for each component

No.	*Device*	*Fuel*	*Product*	*Fuel cost*	*Product cost*	**Type of component**
1	Combustor	$\dot{E}_7$	$\dot{E}_3-\dot{E}_2$	$\dot{C}_7$	$\dot{C}_3-\dot{C}_2$	Productive
2	Compressor	$\dot{E}_5$	$\dot{E}_2-\dot{E}_1$	$\dot{C}_5$	$\dot{C}_2-\dot{C}_1$	Productive
3	Gas Turbine	$\dot{E}_3-\dot{E}_4$	$\dot{E}_5+\dot{E}_6$	$\dot{C}_3-\dot{C}_4$	$\dot{C}_5+\dot{C}_6$	Productive
4	Steam Turbine	$\dot{E}_{16}-\dot{E}_{11}$	$\dot{E}_7$	$\dot{C}_{16}-\dot{C}_{11}$	$\dot{C}_7$	Productive
5	Superheater	$\dot{E}_4-\dot{E}_8$	$\dot{E}_{16}-\dot{E}_{15}$	$\dot{C}_4-\dot{C}_8$	$\dot{C}_{16}-\dot{C}_{15}$	Productive
6	Evaporator	$\dot{E}_8-\dot{E}_9$	$\dot{E}_{15}-\dot{E}_{14}$	$\dot{C}_8-\dot{C}_9$	$\dot{C}_{15}-\dot{C}_{14}$	Productive
7	Economizer	$\dot{E}_9-\dot{E}_{10}$	$\dot{E}_{14}-\dot{E}_{13}$	$\dot{C}_9-\dot{C}_{10}$	$\dot{C}_{14}-\dot{C}_{13}$	Productive
8	Pump	$\dot{E}_{20}$	$\dot{E}_{13}-\dot{E}_{12}$	$\dot{C}_{20}$	$\dot{C}_{13}-\dot{C}_{12}$	Productive
9	Generator	$\dot{E}_6+\dot{E}_{17}$	$\dot{E}_{18}+\dot{E}_{20}$	$\dot{C}_6+\dot{C}_{17}$	$\dot{C}_{18}+\dot{C}_{20}$	Productive
10	Condenser	$\dot{E}_{11}-\dot{E}_{12}$	$\dot{E}_{19}$	$\dot{C}_{11}-\dot{C}_{12}$	$\dot{C}_{19}$	Dissipative
11	Stack	$\dot{E}_{10}$	$\dot{E}_{21}$	$\dot{C}_{10}$	$\dot{C}_{21}$	Dissipative

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

No.	*Device*	*F (kW)*	*P (kW)*	*I (kW)*[a]	ε^a	**kI**[a]
1	Combustor	219880.32	135994.71	83885.61	0.6185	0.6168
2	Compressor	95288.91	88078.40	7210.51	0.9243	0.0819
3	Gas Turbine	163819.24	156469.08	7350.16	0.9551	0.0470
4	Steam Turbine	35094.41	31766.76	3327.65	0.9052	0.1047
5	Superheater	8335.37	7109.51	1225.86	0.8529	0.1724
6	Evaporator	27505.56	23281.16	4224.40	0.8464	0.1814
7	Economizer	11975.60	8233.57	3742.03	0.6875	0.4545
8	Pump	158.53	128.70	29.83	0.8118	0.2318
9	Generator	92946.93	90158.53	2788.40	0.9700	0.0309
10	Condenser	3658.53	3633.28	25.25	0.9931	0.0069
11	Stack	12450.16	12450.16	0	1.0000	0.0000
	Total	219880.32	90000	113809.7[b]	0.4415[c]	—

[a] $I_i = F_i - P_i \quad \text{and} \quad \varepsilon_i = \dfrac{P_i}{F_i} \quad \text{and} \quad \text{kI}_i = \dfrac{I_i}{P_i}$

[b] $I_{Total} = \dot{E}_1 + \dot{E}_7 - (\dot{E}_{18} + \dot{E}_{19} + \dot{E}_{21}) = \sum_{i=1}^{11} I_i = 113809.7\,\text{kW}$

[c] $\varepsilon_{Total} = 1 - \dfrac{I_{Total}}{(\dot{E}_1 + \dot{E}_7 - \dot{E}_{19} - \dot{E}_{21})} = 0.4415$

Table 4: Cost balance equations and auxiliary exergoeconomic equations based on the ACT method

No.	*Component*	*Cost balance equation*[a]	*Auxiliary exergoeconomic equations based on the ACT method*
1	Combustor	$\dot{C}_2 + \dot{C}_7 + \dot{Z}_{CC} = \dot{C}_3$	C ̇_7=c_fuel×E ̇_7 where c_fuel=4.378 €/GJ
2	Compressor	$\dot{C}_1 + \dot{C}_5 + \dot{Z}_{AC} - \dot{C}_2$	$\dot{C}_1 - 0$
3	Gas Turbine	$\dot{C}_3 + \dot{Z}_{GT} = \dot{C}_4 + \dot{C}_5 + \dot{C}_6$	$c_3 = c_4 \Rightarrow \frac{\dot{C}_3}{\dot{E}_3} =$ and $c_5 = c_6 \Rightarrow \frac{\dot{C}_5}{\dot{E}_5} =$
4	Steam Turbine	$\dot{C}_{16} + \dot{Z}_{ST} = \dot{C}_{11} + \dot{C}_{17}$	$c_{11} = c_{16} \Rightarrow \frac{\dot{C}_{11}}{\dot{E}_{11}} = \frac{\dot{C}_{16}}{\dot{E}_{16}}$
5	Superheater	$\dot{C}_4 + \dot{C}_{15} + \dot{Z}_{Sup} = \dot{C}_8 + \dot{C}_{16}$	$c_4 = c_8 \Rightarrow \frac{\dot{C}_4}{\dot{E}_4} = \frac{\dot{C}_8}{\dot{E}_8}$
6	Evaporator	$\dot{C}_8 + \dot{C}_{14} + \dot{Z}_{Eva} = \dot{C}_9 + \dot{C}_{15}$	$c_8 = c_9 \Rightarrow \frac{\dot{C}_8}{\dot{E}_8} = \frac{\dot{C}_9}{\dot{E}_9}$
7	Economizer	$\dot{C}_9 + \dot{C}_{13} + \dot{Z}_{Eco} = \dot{C}_{10} + \dot{C}_{14}$	$c_9 = c_{10} \Rightarrow \frac{\dot{C}_9}{\dot{E}_9} = \frac{\dot{C}_{10}}{\dot{E}_{10}}$
8	Pump	$\dot{C}_{12} + \dot{C}_{20} + \dot{Z}_{Pump} - \dot{C}_{13}$	-
9	Generator	$\dot{C}_6 + \dot{C}_{17} + \dot{Z}_{Gen} = \dot{C}_{18} + \dot{C}_{20}$	$c_{18} = c_{20} \Rightarrow \frac{\dot{C}_{18}}{\dot{E}_{18}} = \frac{\dot{C}_{20}}{\dot{E}_{20}}$
10	Condenser	$\dot{C}_{11} + \dot{Z}_{Cond} = \dot{C}_{12} + \dot{C}_{19}$	$c_{11} = c_{12} \Rightarrow \frac{\dot{C}_{11}}{\dot{E}_{11}} = \frac{\dot{C}_{12}}{\dot{E}_{12}}$
11	Stack	$\dot{C}_{10} + \dot{Z}_{Stack} = \dot{C}_{21}$	-

a. In this system the number of components and streams are 11 and 21 respectively. Therefore, there are 11 equations; so we need 21 – 11 = 10 auxiliary equations.

Table 5: Exergy rate, cost of stream and unit exergy cost of stream for each stream of combined cycle using ACT method

No.	*Flow description*	$\dot{E}$ (kW)	$\dot{C}$ (€/h)	**c (€/GJ)**[a]
1	Air inlet compressor	13.12	0	0
2	Air outlet compressor	88091.52	3741.7	11.7987
3	Gas inlet turbine	224086.23	7208.2	8.9353
4	Gas inlet superheater	60266.99	1938.6	8.9353
5	Power compressor	95288.91	3385.5	9.8692
6	Power gas turbine	61180.17	2173.7	9.8692
7	Fuel combustor	219880.32	3465.5	4.3780
8	Gas inlet evaporator	51931.62	1670.5	8.9353
9	Gas inlet economizer	24425.76	785.7	8.9353
10	Gas outlet economizer	12450.16	400.5	8.9353
11	Outlet LP turbine	3723.19	159.8	11.9219
12	Outlet condenser	64.66	2.8	11.9219
13	Steam inlet economizer	193.36	9.6	13.7991
14	Steam inlet evaporator	8426.93	430.3	14.1829
15	Steam inlet superheater	31708.09	1384.3	12.1269
16	Steam inlet HP turbine	38817.60	1666.0	11.9219
17	Power steam turbine	31766.76	1627.0	14.2274
18	Electric power	90000.00	3803.9	11.7404
19	Condense heat	3633.28	162.3	12.4054
20	Power extraction pump	158.53	6.7	11.7404

a: $1\ kWh = 3.6\ MJ = 3.6 \times 10^{-}$

Table 6: Exergoeconomic costs of components using ACT method

No.	*Device*	c_F (¢/kWh)	C_F (€/h)	c_p (¢/kWh)	*Z* (€/h)	C_P **(€/h)**
1	Combustor	1.5761	3465.5	2.5490	0.98	3466.5
2	Compressor	3.5529	3385.5	4.2482	356.19	3741.7
3	Gas Turbine	3.2167	5269.6	3.5529	289.63	5559.2
4	Steam Turbine	4.2919	1506.2	5.1219	120.83	1627.0
5	Superheater	3.2167	268.12	3.9628	13.61	281.73
6	Evaporator	3.2167	884.78	4.0978	69.23	954.01
7	Economizer	3.2167	385.22	5.1091	35.44	420.66
8	Pump	4.2266	6.70	5.3072	0.13	6.83
9	Generator	4.0891	3800.7	4.2266	9.88	3810.6
10	Condenser	4.2919	157.02	4.4659	5.24	162.26
11	Stack	3.2167	400.49	3.2167	0.00	400.49

Table 7: $FP^{\langle S\rangle}$ table for the combined cycle

	$\mathbf{F}_0^S$	$\mathbf{F}_1^S$	$\mathbf{F}_2^S$	$\mathbf{F}_3^S$	$\mathbf{F}_4^S$	$\mathbf{F}_5^S$	$\mathbf{F}_6^S$	$\mathbf{F}_7^S$	$\mathbf{F}_8^S$	$\mathbf{F}_9^S$	$\mathbf{F}_{10}^S$	$\mathbf{F}_{11}^S$	**Total**
$\mathbf{P}_0^S$		7	1543										1550
$\mathbf{P}_1^S$				8530		4591	19787	12512				34074	79494
$\mathbf{P}_2^S$				−16650		994	5319	4043				13516	7222
$\mathbf{P}_3^S$			0							0			0
$\mathbf{P}_4^S$										0			0
$\mathbf{P}_5^S$					−1798						8679		6881
$\mathbf{P}_6^S$					−3533						33112		29579
$\mathbf{P}_7^S$					2064						18373		20437
$\mathbf{P}_8^S$					−64						94		30
$\mathbf{P}_9^S$	0								0				0
$\mathbf{R}_{10}^S$	57584												57584
$\mathbf{R}_{11}^S$	47883												47883
		7	1543	−8120	−3331	5585	25106	16555	0	0	60258	47590	

Table 8: Allocation of the cost of residues based on the distributed entropy for combined cycle

No.	*Device*	$\psi_i^G = \frac{E^S_{i,11}}{F^S_{11}}$	$\psi_i^H = \frac{E^S_{i,10}}{F^S_{10}}$
1	Combustor	0.7160	0.0000
2	Compressor	0.2840	0.0000
3	Gas Turbine	0.0000	0.0000
4	Steam Turbine	0.0000	0.0000
5	Superheater	0.0000	0.1440
6	Evaporator	0.0000	0.5495
7	Economizer	0.0000	0.3049
8	Pump	0.0000	0.0016
9	Generator	0.0000	0.0000

Table 9: Exergoeconomic costs of components using distributed entropy method

No.	*Device*	*c_P (¢/kWh)*	*C_F (€/h)*	*C_R (€/h)*	*Z (€/h)*	**C_P (€/h)**
1	Combustor	2.7836	3465.92	318.69	0.98	3785.59
2	Compressor	4.7976	3743.06	126.41	356.19	4225.66
3	Gas Turbine	3.9281	5856.66	0.00	289.63	6146.29
4	Steam Turbine	6.1753	1840.83	0.00	120.83	1961.66
5	Superheater	4.7823	298.00	28.39	13.61	340.00
6	Evaporator	4.9864	983.36	108.33	69.23	1160.92
7	Economizer	6.3605	428.13	60.11	35.44	523.68
8	Pump	6.2937	7.69	0.32	0.13	8.14
9	Generator	4.8523	4364.89	0.00	9.88	4374.77
10	Condenser	5.4248	191.90	0.00	5.24	197.14
11	Stack	3.5750	445.10	0.00	0.00	445.10

5. Case 2: cogeneration system

Fig. 2 shows a schematic of cogeneration system which delivers 34 MW of electricity and 18 kg/s of saturated steam at 20 bar. The system consists of a combustion chamber (CC), an air compressor (AC), a gas turbine (GT), a heat recovery steam generator (HRSG) and a stack. The assumptions are similar to the CGAM problem [17]. Table 10 represents the thermodynamic properties of the cogeneration system. Table 11 represents the definition of fuel and products for each component. The values of fuel (F), product (P), irreversibility (I), exergetic efficiency (e) and specific exergy destruction (kI) for each component can be seen in Table 12.

5.1. Application ACT to the cogeneration system

Here, the ACT method is applied to the combined cycle which is shown in Fig. 2. Cost balance and auxiliary equations for each component are shown in Table 13. Equations in Table 13 can be written in the matrix form. The system of 11 equations and 11 unknowns can be solved to obtain the cost of streams 1–11 for cogeneration system. Table 14 represents exergy rate $\dot{E}$ (k, cost of stream $\dot{C}$ ($/h) and unit exergy cost of stream c (cent/kWh) for each stream of the cogeneration system. Table 15 shows unit exergy cost of fuel cF (cent/kWh), unit exergy cost of product cP (cent/kWh), exergy cost of fuel CF ($/h), exergy cost of product CP ($/h) and the capital cost rate Z ($/h), for each component. It should be mentioned that equations for calculating the purchased-equipment costs (PEC) for the components of the cogeneration system are in Appendix B of Ref. [4] and also Refs. [17, 18].

5.2. Application distributed entropy method to the cogeneration system

Table 16 shows FPS table for the cogeneration system. For more details see Ref. [16]. Table 17 shows how the values of this criterion are obtained. Table 18 shows exergoeconomic costs of components that have been calculated by this method.

6. Results and discussion

Some results are presented in previous sections. Figs. 3 and 4 represent the specific cost of product and product cost for each component of combined cycle using ACT method and distributed entropy method, respectively. As it is seen, the all values corresponding to distributed entropy method are more than those of ACT method. It is result of cost allocation of residues to all components that are responsible for production of residues. Fig. 3 shows that the maximum and minimum values are corresponding to economizer and combustion chamber, respectively. Fig. 4 represents the maximum and minimum values are corresponding to gas turbine and pump, respectively.

Figs. 5 and 6 represent the specific cost of product and product cost for each component of cogeneration system using ACT method and distributed entropy method, respectively. As it is seen, the all values corresponding to distributed entropy method are more than those of ACT method. It is result of cost allocation of residues to all components that are responsible for production of residues. Fig. 5 shows that the maximum and minimum values are corresponding to heat recovery steam generator (HRSG) and combustion chamber, respectively. Fig. 6 represents the maximum and minimum values are corresponding to gas turbine and stack, respectively.

Furthermore, from comparison of Figs. 3 and 5, it can be seen that the specific cost of product for gas turbine using distributed entropy method is 3.9281 (cent/kWh) and 2.8631 (cent/kWh) for and combined cycle and cogeneration system, respectively. In the other hand, the value corresponding to combined cycle is 37% more than that of cogeneration system.

In final, it should be mentioned that application of ACT method is simpler than the distributed entropy method, but the last method is more correct and more rational because of cost allocation of residues to all components that are responsible for production of them. Also, the second method, have more advantages than the former. Some advantages have been extensively described in Refs. [15, 16].

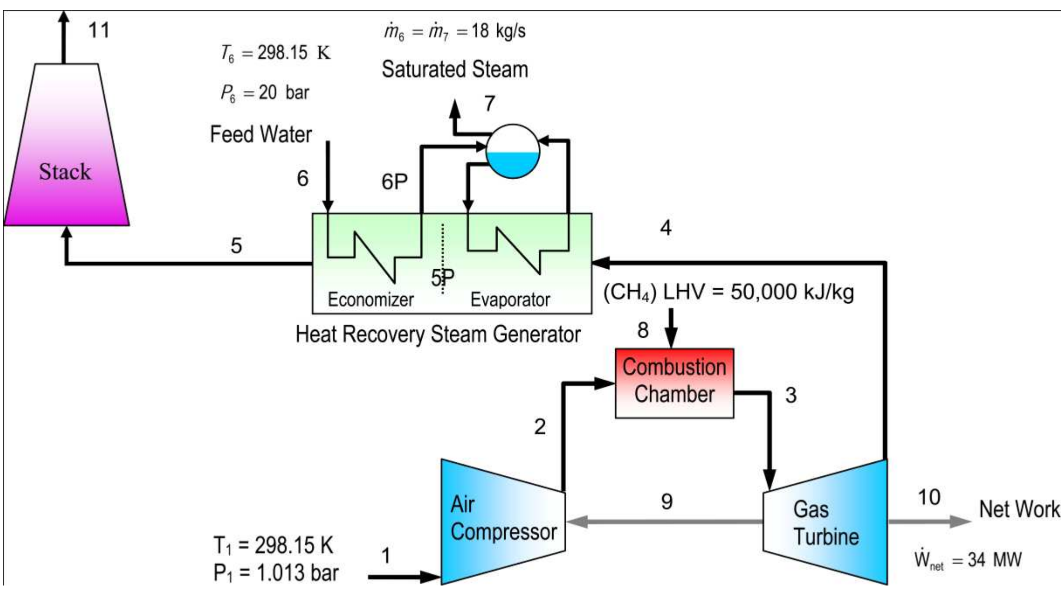

Fig.2: Physical structure of cogeneration system

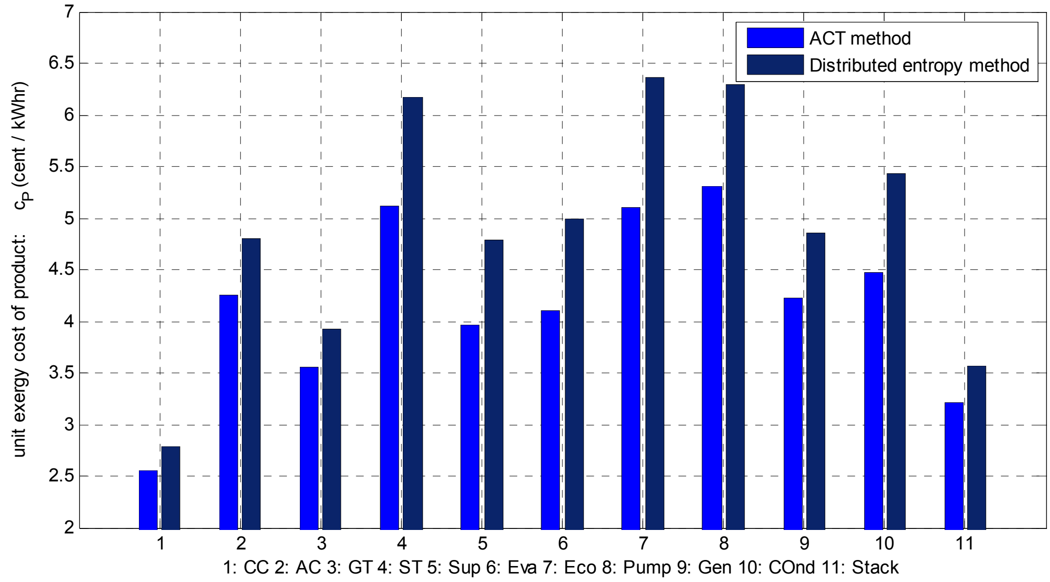

Fig. 3: Specific cost of product for each component of combined cycle

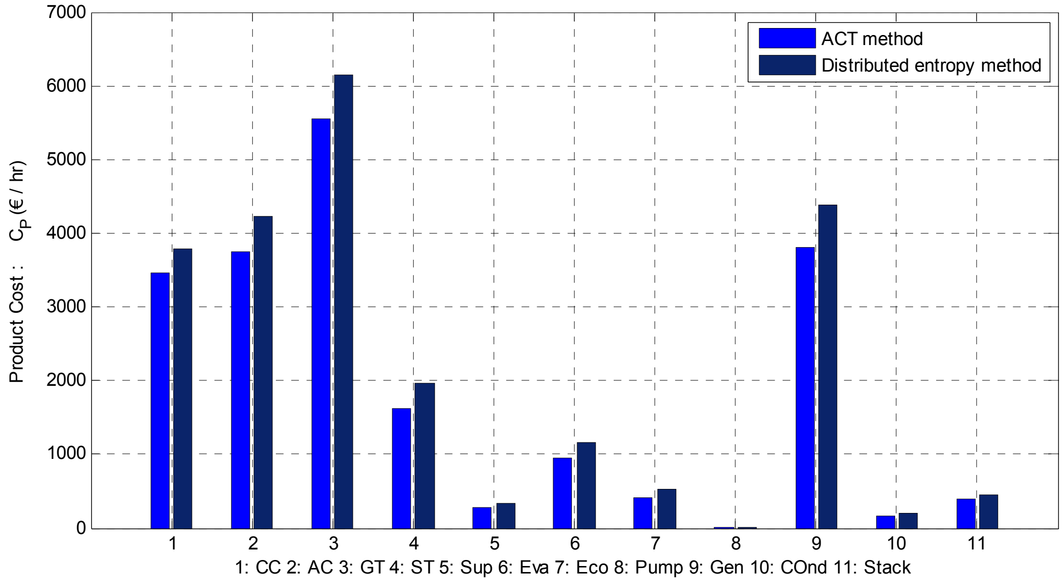

Fig. 4: Product cost for each component of combined cycle

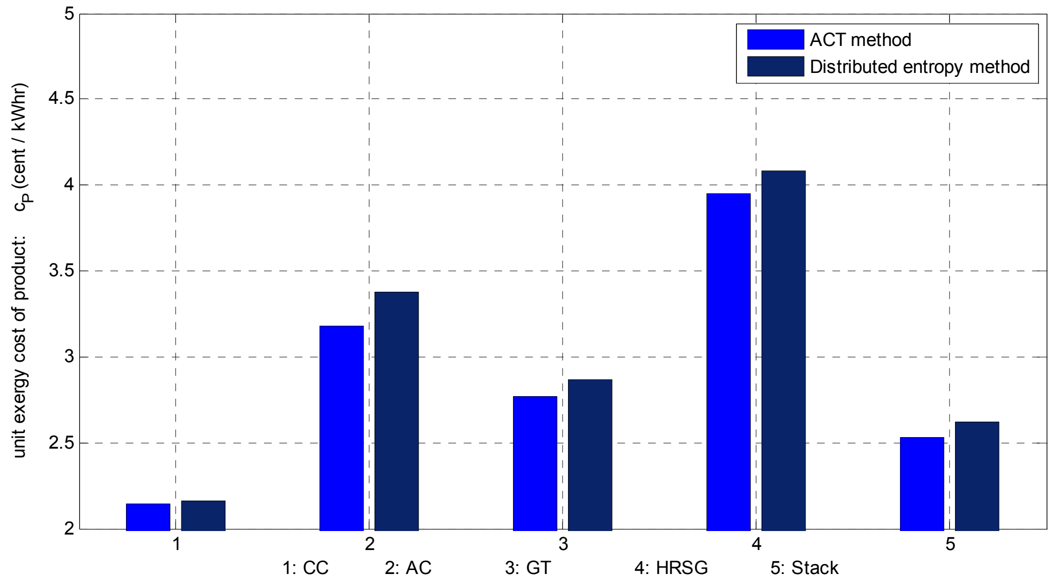

Fig. 5: Specific cost of product for each component of cogeneration system

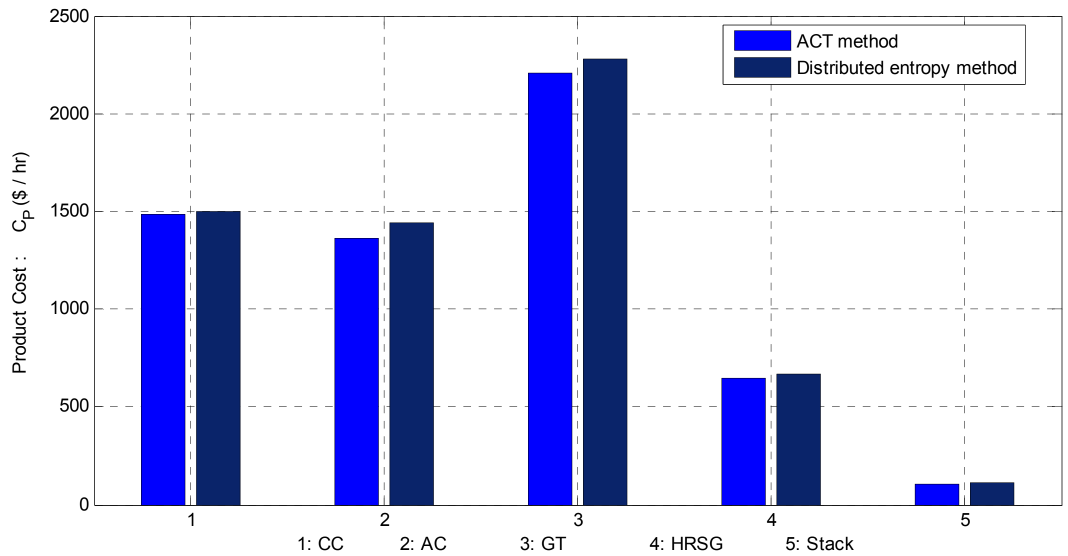

Fig. 6: Product cost for each component of cogeneration system

Table 10: Thermodynamic properties of the cogeneration system corresponding to optimum conditions

No.	*Flow description*	*P (bar)*	*T (K)*	*m'(kg/s)*	*s (kJ/kg · K)*	*h (kJ/kg)*	*H'(kW)*	***E'* (kW)**
0	Environment	1.013	298.15					
1	Air inlet compressor	1.013	298.15	101.4513	0.0000	0.00	0.00	0.00
2	Air outlet compressor	17.973	746.72	101.4513	0.0964	450.36	45689.78	42774.88
3	Gas inlet turbine	17.074	1477.60	103.4317	1.0535	1380.00	142731.61	112078.64
4	Gas inlet evaporator	1.066	819.09	103.4317	1.1675	609.50	63041.83	28873.44
5	Gas outlet economizer	1.013	418.98	103.4317	0.3981	141.37	14621.83	4182.52
6	Water inlet economizer	20	298.15	18.0000	0.3674	109.00	1962.00	79.20
7	Steam outlet evaporator	20	485.60	18.0000	6.3409	2798.00	50364.00	16470.26
8	Fuel combustion chamber	1.013	298.15	1.9804	0.0000	50000.00	99022.27	102686.10
9	Power air compressor						45689.78	45689.78
10	Power gas turbine						34000.00	34000.00
11	Gas outlet stack	1.013	418.98	103.4317	0.3981	141.37	14621.83	4182.52

Table 11: Definition of fuel and product for each component of cogeneration system

No.	*Device*	*Fuel*	*Product*	*Fuel cost*	*Product cost*	**Type of component**
1	Combustion Chamber	$\dot{E}_8$	$\dot{E}_3 - \dot{E}_2$	$\dot{C}_8$	$\dot{C}_3 - \dot{C}_2$	Productive
2	Air Compressor	$\dot{E}_9$	$\dot{E}_2 - \dot{E}_1$	$\dot{C}_9$	$\dot{C}_2 - \dot{C}_1$	Productive
3	Gas Turbine	$\dot{E}_3 - \dot{E}$	$\dot{E}_9 + \dot{E}$	$\dot{C}_3 - \dot{C}_4$	$\dot{C}_9 + \dot{C}_{10}$	Productive
4	Heat Recovery Steam Generator	$\dot{E}_4 - \dot{E}$	$\dot{E}_7 - \dot{E}_6$	$\dot{C}_4 - \dot{C}_5$	$\dot{C}_7 - \dot{C}_6$	Productive
5	Stack	$\dot{E}_5$	$\dot{E}_{11}$	$\dot{C}_5$	$\dot{C}_{11}$	Dissipative

Table 12: Fuel (F), product (P), irreversibility (I), exergetic efficiency (ε) and specific exergy destruction (kI) for each component of cogeneration system

No.	*Device*	*F (kW)*	*P (kW)*	*I (kW)*	*ε*	**kI**
1	Combustion Chamber	102686.10	69303.76	33382.34	0.6749	0.4817
2	Air Compressor	45689.78	42774.88	2914.90	0.9362	0.0681
3	Gas Turbine	83205.20	79689.78	3515.42	0.9578	0.0441
4	Heat Recovery Steam Generator	24690.91	16391.06	8299.86	0.6638	0.5064
5	Stack	4182.52	4182.52	0.00	1.0000	0.0000

Table 13: Cost balance equations and auxiliary exergoeconomic equations based on the ACT method

No.	*Component*	*Cost balance equation*	*Auxiliary exergoeconomic equations based on the ACT method*
1	CC	$\dot{C}_2 + \dot{C}_8 + \dot{Z}_{CC} = \dot{C}_3$	C˙_7=c_fuel×E˙_8 where c_fuel=4 $/GJ
2	AC	$\dot{C}_1 + \dot{C}_9 + \dot{Z}_{AC} = \dot{C}_2$	$\dot{C}_1 = 0$
3	GT	$\dot{C}_3 + \dot{Z}_{GT} = \dot{C}_4 + \dot{C}_9 + \dot{C}_{10}$	$c_3 = c_4 \Rightarrow \frac{\dot{C}_3}{\dot{E}_3} =$ and $c_9 = c_{10} \Rightarrow \frac{\dot{C}_9}{\dot{E}_9} =$
4	HRSG	$\dot{C}_4 + \dot{C}_6 + \dot{Z}_{HRSG} = \dot{C}_5 + \dot{C}_7$	$c_4 = c_5 \Rightarrow \frac{\dot{C}_4}{\dot{E}_4} =$ and $\dot{C}_6$:
5	Stack	$\dot{C}_5 + \dot{Z}_{Stack} = \dot{C}_{11}$	-

a. In this system the number of components and streams are 5 and 11 respectively. Therefore, there are 11 equations; so we need 11 – 5 = 6 auxiliary equations.

Table 14: Exergy rate, cost of stream and unit exergy cost of stream for each stream of combined cycle using ACT method

No.	*Flow description*	$\dot{E}$ (kW)	$\dot{C}$ ($/h)	c (cent/kWh)
1	Air inlet compressor	0.00	0	0
2	Air outlet compressor	42774.88	1359.0	3.1772
3	Gas inlet turbine	112078.64	2840.8	2.5347
4	Gas inlet evaporator	28873.44	731.8	2.5347
5	Gas outlet economizer	4182.52	106.0	2.5347
6	Water inlet economizer	79.20	0	0
7	Steam outlet evaporator	16470.26	647.4	3.9305
8	Fuel combustion chamber	102686.10	1478.7	1.4400
9	Power air compressor	45689.78	1266.0	2.7708
10	Power gas turbine	34000.00	942.1	2.7708
11	Gas outlet stack	4182.52	106.0	2.5347

Table 15: Exergoeconomic costs of components for the cogeneration system using ACT method

No.	*Device*	c_F (¢/kWh)	C_F ($/h)	c_P (¢/kWh)	*Z* ($/h)	C_P ($/h)
1	Combustion Chamber	1.44	1478.7	2.14	3.09	1481.8
2	Air Compressor	2.77	1266.0	3.18	93.09	1359.0
3	Gas Turbine	2.53	2109.0	2.77	99.04	2208.0
4	Heat Recovery Steam Generator	2.53	625.84	3.95	21.53	647.36
5	Stack	2.53	106.01	2.53	0.00	106.01

Table 16: $FP^{\langle S \rangle}$ table for the cogeneration system

	$\mathbf{F}_0^S$	$\mathbf{F}_1^S$	$\mathbf{F}_2^S$	$\mathbf{F}_3^S$	$\mathbf{F}_4^S$	$\mathbf{F}_5^S$	**Total**
$\mathbf{P}_0^S$		−3664					-3664
$\mathbf{P}_1^S$				2730	17652	7355	27737
$\mathbf{P}_2^S$				−6246	6077	3085	2916
$\mathbf{P}_3^S$	0		0				0
$\mathbf{P}_4^S$	32011						32011
$\mathbf{R}_5^S$	10439						10439
		−3664	0	−3516	23729	10440	

Table 17: Allocation of the cost of residues based on the distributed entropy for cogeneration system

No.	*Device*	$\psi_i = \frac{E_{i,5}^S}{F_5^S}$
1	Combustion Chamber	0.7045
2	Air Compressor	0.2955
3	Gas Turbine	0.0000
4	Heat Recovery Steam Generator	0.0000

Table 18: Exergoeconomic costs of components for cogeneration system using distributed entropy method

No.	*Device*	c_p *(¢/kWh)*	C_F *($/h)*	C_R *($/h)*	*Z ($/h)*	C_P **($/h)**
1	Combustion Chamber	2.1598	1425.92	67.84	3.09	1496.85
2	Air Compressor	3.3737	1308.15	41.87	93.09	1443.11
3	Gas Turbine	2.8631	2182.57	0.00	99.04	2281.61
4	Heat Recovery Steam Generator	4.0827	647.67	0.00	21.53	669.20
5	Stack	2.6231	109.71	0.00	0.00	109.71

Nomenclature

c	unit exergoeconomic cost (¢/kWh)	**Greek letters**	
$\dot{C}$	exergoeconomic cost (€/h) or ($/h)	ε	exergetic efficiency
$\dot{E}$	exergy of a flow (kW)	ψ	residue cost distribution ratio
F	fuel exergy of a component (kW)	**Subscripts**	
h	specific enthalpy (kJ/kg)	0	Environment
$\dot{H}$	enthalpy of a flow (kW)	r	Index for dissipative components
I	irreversibility of a component (kW)	F	related to fuel
kI	specific exergy destruction	P	related to product
$\dot{m}$	mass flow rate (kg/s)	R	related to residue
n	number of components	**Superscripts**	
p	pressure (bar)	E	related to exergy
P	product exergy of a component (kW)	H	related to energy, heat and enthalpy
$\dot{Q}$	heat flow rate (kW)	G	related to gas
s	specific entropy (kJ/kg .k)	S	related to entropy
T	temperature (°C)		
$\dot{W}$	work flow rate (kW)		
$\dot{Z}$	Capital cost rate of a component (€/h) or ($/h)		
V_D	set of dissipative components		

7. Conclusions

In this paper, two methods for cost allocation have been compared. These methods are average cost theory (ACT) and distributed entropy methods that have been applied to a combined cycle and a cogeneration cycle. Fuel and product costs for each component were calculated and compared with each other. The specific cost of product for each component was obtained, too. The results indicate for importance of a good criterion for cost allocation of residues. The distributed entropy method is a more correct and more rational than the ACT method.

References

[1] El-Sayed YM, Gaggioli RA. A critical review of second law costing methods – I: background and algebraic procedures. ASME J Energy Resour Technol 1989;111:1–7.

[2] Gaggioli RA, El-Sayed YM. A critical review of second law costing methods – II: calculus procedures.

ASME J Energy Resour Technol 1989;111:8–15.

[3] Lozano MA, Valero A. Theory of the exergetic cost. Energy Int J 1993;18(9):939‐40.

[4] Bejan A, Tsatsaronis G, Moran M. Thermal design and optimization. New York: Wiley; 1996.

[5] Lazzaretto A, Tsatsaronis G. On the calculation of efficiencies and costs in thermal systems. In: Aceves SM et al. editors. Proceedings of the ASME advanced energy systems division ‐ 1999, AES-vol. 39. New York: ASME; 1999. p. 421‐30.

[6] Kim SM, Oh SD, Kwon YH, Kwak HY. Exergoeconomic analysis of thermal systems. Energy 1998;23(5):393‐406.

[7] Kwon YH, Kwak HY, Oh SD. Exergoeconomic analysis of gas turbine cogeneration systems. Energy Int J 2001;1(1):31‐40.

[8] Frangopoulos CA. Thermoeconomic functional analysis: a method for optimal design or improvement of complex thermal systems. Ph.D. Thesis, Georgia Institute of Technology, Georgia; 1983.

[9] Frangopoulos CA. Thermoeconomic functional analysis and optimization. Energy 1987;12(7):563‐71.

[10] von Spakovsky MR. A practical generalized analysis approach to the optimal thermoeconomic design and improvement of real-world thermal systems. Ph.D. Thesis, Georgia Institute of Technology, Georgia; 1986.

[11] Erlach B, Serra L, Valero A. Structural theory as standard for thermoeconomic. Energy Convers Manage 1999;40:1627‐49.

[12] Lozano MA, Valero A. Thermoeconomic analysis of a gas turbine cogeneration system. ASME book no. H00874, AES, vol. 30, WAM; 1993. p. 312-20.

[13] Frangopoulos CA. Thermoeconomic functional analysis. from Encyclopedia of Life Support System (EOLSS), developed under the auspices of the UNESCO. In: Frangopoulos CA, editor. Exergy, energy system analysis and optimization. Oxford: EOLSS Publishers; 2004. See also: <http://www.eolss.net>.

[14] Torres C, Valero A, Rangel V, Zaleta A. On the cost formation process of the residues. Energy 2008; 33: 144-52.

[15] Seyyedi S.M., Ajam H., Farahat S. A new criterion for the allocation of residues cost in exergoeconomic analysis of energy systems, Energy 2010; 35: 3474-82.

[16] Seyyedi S.M., Exergoeconomic Analysis of a Cogeneration System and Proposal for a New Approach for Optimization Based on the Structural Method, Ph.D. Thesis in Mechanical engineering, the University of Sistan & Baluchestan, 2010.

[17] Valero A, Lozano MA, Serra L, Tsatsaronis G, Pisa J, Frangopoulos CA, et al. CGAM problem: definition and conventional solution. Energy 1994;19(3): 279‐86.

[18] Seyyedi S.M., Ajam H., Farahat S. A new approach for optimization of thermal power plant based on the exergoeconomic analysis and structural optimization method: Application to the CGAM problem. Energy Conversion and Management 2010; 51: 2202‐11.