SPECIFIC EXERGY COSTING ANALYSIS AND OPTIMIZATION OF CCPP POWER PLANT

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ABSTRACT

There are different methodologies for calculating exergy costs and efficiencies for combined cycle power plant. In current work modified specific exergy costing (SPECO) are applied. Based on SPECO approach the cost and exergy stable equations are worked out and the exergoeconomic analysis are performed. Exergy and energy examinations regarding triple pressure integrated cycle power plant are applied to decide the exergoeconomic variables for whole system and the elements, auxiliary equations and cost balance equations are developed. Exergoeconomic optimization by simple method for six operating parameters of the bottoming cycle is conducted. A comparison between the result of exergoeconomic optimization and initial case shows that the reduction in total cost per hour by this method is 31.5%. The result shows an improvement in the thermodynamic performance and exergoeconomic parameters by applying new optimum operating parameters

KEYWORDS: *Exergy, Exergoeconomic optimization & SPECO*

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1. INTRODUCTION

Due to the rise on fossil fuel prices, the environmental effect during their use and the external energetic dependency on instable nations, it turns highly crucial to recognize the procedure that degenerate energy and sources. In the design of integrated cycle power plant or any thermal system the first essential and interested subjective was optimization. Therefore, knowing optimum conditions of power plant or any other thermal system is very important.

“Exergoeconomic (Thermoeconomic) is the branch of engineering that combines exergy analysis with economic constraints to provide the system designer with information not available through conventional energetic analysis and economic evaluation” Sahoo [1]. The objectives of Themoeconomic studies are, understanding the flow of cost and cost formation in the system, based on the calculations of every product-created cost by a structure Tsatsaronis and Moran [2], Much researcher has been studied the exergoeconomic performance of thermal system.

Sahoo [1] studied an exergoeconomic study by the developmental programming of a cogeneration structure; he concluded that the optimum condition gives product cost lower by 9.9% than that of the core instance. This result obtained with increased investment cost for 10%. Abusoglu and Kanoglu [3] investigate an exergoeconomic study and maximum effective of integrated heat and power systems, considering different optimization methods. Baghernejad and Yaghoubi [7] considered an Integrated Solar combined cycle system (ISCCS), employing genetic algorithm; he provided a review for exergoeconomic analysis and optimization of (ISCCS).

2. SYSTEM DESCRIPTION

The main components of the structure in the research are depicted in figure 1. The integrated cycle power unit mainly consists of high temperature recuperation steam initiator steam turbine condenser and gas turbine.

Figure 1: A Schematic Diagram of the Triple Pressure Combined Cycle Power Plant.

3. EXERGoeCONOMIC ANALYSIS

Incorporations of economic laws into thermodynamic analysis or precisely exergy analysis, at a degree of technique component, in accordance to give data for engineers to cost- effectively model is that branch of engineering called exergoeconomic.

Current study implies, the SPECO (specific exergy costing) technique is employed. This method combines exergetic and economic properties; The base factors of this method are, cost per unit exergy, specific exergies, exergy efficiency and auxiliary equations (cost equations) for element of combined cycle. This method includes three main processes:

Quantifying the Energy and Exergy Streams

As a first step in this method is energy and exergy analysis, this analysis performed based on energy and exergy conservation equations, beside the exergy balance to every element of the system [5].

$$\sum \dot{m}_i = \sum \dot{m}_e \quad (1)$$

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

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

where $\dot{m}_i$ and $\dot{m}_e$ are the mass inlet and outlet, $\dot{E}_D$ is the exergy elimination value in the system element, $\dot{E}_Q$ is the exergy rate corresponding to high temperature transfer rate, i.e. $\dot{E}_Q = (1 - T_o/T_i) \dot{Q}_i$, and $\dot{E}_W$ is the exergy rate of the mechanical power, i.e. $\dot{E}_W = \dot{W}$. $\dot{Q}$ refer to the heat rate and $\dot{W}$ to the work rate, while T_o is the average temperature. The equation applied to the physical exergy is [6]:

$$e^{PH} = (h - h_o) + T_o (s - s_o) \quad (4)$$

Total exergy of each stream equal to the product of specific exergy and its corresponding mass flow rate. Applying continuity equations, initial and subsequent rules of thermodynamics, and exergy efficiency equation Eq.5, the exergy destruction $\dot{E}_D$ could easily acquired. Table 1 Indicates the equations of every element of the method

$$\varepsilon = \frac{\sum \Delta \dot{E}_{out}}{\sum \Delta \dot{E}_{in}} \quad \varepsilon = 1 - \frac{I_r}{\sum \dot{E}_{in}} \quad (5)$$

Where I_r is the irreversibility.

Table 1: The Exergy Destruction Rate and Exergy Efficiency for the Main Components of the System

Component	Exergy Destruction	Exergy Efficiency
Steam turbine	$\dot{E}_{D,ST} = \dot{E}_{22} + \dot{E}_{15} + \dot{E}_8 - \dot{E}_{24} - \dot{E}_{26} - \dot{E}_{ST}$	$\varepsilon_{ST} = \frac{\dot{E}_{ST}}{\dot{E}_{16} + \dot{E}_{23} + \dot{E}_9 - \dot{E}_{26} - \dot{E}_{24}}$
HRSG	$\dot{E}_{D,HRSG} = \dot{E}_{4g} + \dot{E}_{24} + \dot{E}_{18} + \dot{E}_{10} + \dot{E}_2 - \dot{E}_{22} - \dot{E}_{15} - \dot{E}_8 - \dot{E}_5 - \dot{E}_{11g}$	$\varepsilon_{HRSG} = 1 - \frac{\dot{E}_{D,HRSG}}{\dot{E}_{4g}}$
Condenser	$\dot{E}_{D,Con} = \dot{E}_{26} - \dot{E}_1$	$\varepsilon_{Con} = 1 - \frac{\dot{E}_1}{\dot{E}_{26}}$
Total	$\dot{E}_{D,TOT} = \dot{E}_{D,HRSG} + \dot{E}_{D,ST} + \dot{E}_{D,Con}$	$\varepsilon_{TOT} = 1 - \frac{\dot{E}_{D,TOT} + \dot{E}_{11g}}{\dot{E}_{4g}}$

Definition of Fuel and Product for Every Element of Thermal System

The fuel is a necessary resource to produce the output by system or component and this input is not necessary to be a real fuel like coal, oil, natural gas. The invention is the outcome or wanted result that the method generated or component. Product and fuel are in term of exergy [7].

Table 2 gives the exergy equations of fuels $\dot{E}_F$ and generates $\dot{E}_P$ for each component of the method.

Table 2: The Definitions of the Exergy of Fuel, Exergy of Product

Component		Fuel Exergy Rate $\dot{E}_F$	Production Exergy Rate $\dot{E}_P$
HRSG	Section1	$\dot{E}_{4g} - \dot{E}_{5g}$	$\dot{E}_{22} - \dot{E}_{21} + \dot{E}_{15} - \dot{E}_{14}$
	Section2	$\dot{E}_{5g} - \dot{E}_{6g}$	$\dot{E}_{21} - \dot{E}_{20}$

	Section3	$\dot{E}_{6g} - \dot{E}_{7g}$	$\dot{E}_{20} - \dot{E}_{19} + \dot{E}_{13} - \dot{E}_{12}$
	Section4	$\dot{E}_{7g} - \dot{E}_{8g}$	$\dot{E}_{12} - \dot{E}_{11}$
	Section5	$\dot{E}_{8g} - \dot{E}_{9g}$	$\dot{E}_8 - \dot{E}_7 + \dot{E}_{11} - \dot{E}_{10} + \dot{E}_{19} - \dot{E}_{18}$
	Section6	$\dot{E}_{9g} - \dot{E}_{10g}$	$\dot{E}_7 - \dot{E}_6$
	Section7	$\dot{E}_{10g} - \dot{E}_{11g}$	$\dot{E}_4 - \dot{E}_3$
Steam turbine pressure level	High	$\dot{E}_{23} - \dot{E}_{24}$	$P_{ST,HP}$
	Intermediate	$\dot{E}_{16} - \dot{E}_{17}$	$P_{ST,IP}$
	low	$\dot{E}_{25} - \dot{E}_{26}$	$P_{ST,LP}$
Condenser		$\dot{E}_{26} - \dot{E}_1$	$\dot{E}_{w2} - \dot{E}_{w1}$
Feed water tank		$P_{pump,HP} + P_{pump,LP}$	$\dot{E}_{18} + \dot{E}_{10} - \dot{E}_5$
Condenser pump		$P_{pump,CON}$	$\dot{E}_2 - \dot{E}_1$

4. COST BALANCE

Cost balance equation Eq.6 implied to each component (k^{th} element) of this system. Eq.6 shows the equality between summation of input exergy cost value as well output exergy cost value plus the capital investment cost rate with all costs for maintenance and operating $\dot{Z}_k$ [7].

$$\sum_e \dot{C}_{e,k} + \dot{C}_{w,k} = \dot{C}_{q,k} + \sum_i \dot{C}_{i,k} + \dot{Z}_k \quad (6)$$

$$\dot{C}_j = c_j \dot{E}_j \quad (7)$$

Where, $\dot{C}$ (\$/s) is the flow cost rate, subscripts e and i are the entering as well exiting streams for k^{th} component. There are several methods for calculating $\dot{Z}_k$ in terms of model parameters, in this work Eq. 8 is applied for transforming the capital investment to cost per time unit.

$$\dot{Z}_k = \frac{Z_k CRF \phi}{3600N} \quad (8)$$

where Z_k is the purchase cost function of k^{th} component in dollar [5], CRF is the capital recovery factor, N , ϕ are number of operating hours in year and maintenance factor respectively.

The investment recuperation factor CRF is a basis of the interest rate as well estimated component lifetime, it was determined using eq. 9, [10]:

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1} \quad (9)$$

where i is the interest rate and n is the total operating period of the method in certain period.

Table 3: Exergetic Cost Balances and Auxiliary Equations for the Bottoming Cycle Power Plant

Component	Exergetic Cost Rate Balance Main	Additional Equations
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	Equation	P rule	F rule
HRSG Section 1	$\dot{C}_{4g} + \dot{C}_{21} - \dot{C}_{22} - \dot{C}_{5g} + \dot{C}_{14}$ $-\dot{C}_{15} = -\dot{Z}_{su,HP} - \dot{Z}_{RH}$	$\frac{\dot{C}_{15} - \dot{C}_{14}}{\dot{E}_{15} - \dot{E}_{14}} = c_{p1}$ $\frac{\dot{C}_{22} - \dot{C}_{21}}{\dot{E}_{22} - \dot{E}_{21}} = c_{p1}$	$\frac{\dot{C}_{4g}}{\dot{E}_{4g}} = \frac{\dot{C}_{5g}}{\dot{E}_{5g}}$
HRSG Section 2	$\dot{C}_{5g} + \dot{C}_{20} - \dot{C}_{21} - \dot{C}_{6g} = -\dot{Z}_{ev,HP}$		$\frac{\dot{C}_{5g}}{\dot{E}_{5g}} = \frac{\dot{C}_{6g}}{\dot{E}_{6g}}$
HRSG Section3	$\dot{C}_{6g} + \dot{C}_{19} - \dot{C}_{20} - \dot{C}_{7g} + \dot{C}_{12}$ $-\dot{C}_{13} = -\dot{Z}_{ec2,HP} - \dot{Z}_{su,IH}$	$\frac{\dot{C}_{20} - \dot{C}_{19}}{\dot{E}_{20} - \dot{E}_{19}} = c_{p2}$ $\frac{\dot{C}_{13} - \dot{C}_{12}}{\dot{E}_{13} - \dot{E}_{12}} = c_{p2}$	$\frac{\dot{C}_{6g}}{\dot{E}_{6g}} = \frac{\dot{C}_{7g}}{\dot{E}_{7g}}$
HRSG Section 4	$\dot{C}_{7g} + \dot{C}_{11} - \dot{C}_{12} - \dot{C}_{8g} = -\dot{Z}_{ev,IP}$		$\frac{\dot{C}_{7g}}{\dot{E}_{7g}} = \frac{\dot{C}_{8g}}{\dot{E}_{8g}}$
HRSG Section 5	$\dot{C}_{8g} + \dot{C}_{18} - \dot{C}_{19} - \dot{C}_{9g} + \dot{C}_{10} - \dot{C}_{11}$ $+ \dot{C}_7 - \dot{C}_8 = -\dot{Z}_{ec1,HP} - \dot{Z}_{ec,IP} - \dot{Z}_{su,LP}$	$\frac{\dot{C}_{19} - \dot{C}_{18}}{\dot{E}_{19} - \dot{E}_{18}} = c_{p3}$ $\frac{\dot{C}_{11} - \dot{C}_{10}}{\dot{E}_{11} - \dot{E}_{10}} = c_{p3}$ $\frac{\dot{C}_8 - \dot{C}_7}{\dot{E}_8 - \dot{E}_7} = c_{p3}$	$\frac{\dot{C}_{8g}}{\dot{E}_{8g}} = \frac{\dot{C}_{9g}}{\dot{E}_{9g}}$
HRSG Section 6	$\dot{C}_{9g} + \dot{C}_6 - \dot{C}_7 - \dot{C}_{10g} = -\dot{Z}_{ev,LP}$		$\frac{\dot{C}_{9g}}{\dot{E}_{9g}} = \frac{\dot{C}_{10g}}{\dot{E}_{10g}}$
HRSG Section 7	$\dot{C}_{10g} + \dot{C}_2 - \dot{C}_4 - \dot{C}_{11g} = -\dot{Z}_{ec,LP}$		$\frac{\dot{C}_{10g}}{\dot{E}_{10g}} = \frac{\dot{C}_{11g}}{\dot{E}_{11g}}$
High pressure steam turbine	$\dot{C}_{22} - \dot{C}_{24} - \dot{C}_{ST,HP} = -\dot{Z}_{ST,HP}$		$\frac{\dot{C}_{23}}{\dot{E}_{23}} = \frac{\dot{C}_{24}}{\dot{E}_{24}}$
Intermediate pressure steam turbine	$\dot{C}_{15} - \dot{C}_{17} - \dot{C}_{ST,IP} = -\dot{Z}_{ST,IP}$		$\frac{\dot{C}_{16}}{\dot{E}_{16}} = \frac{\dot{C}_{17}}{\dot{E}_{17}}$
Low pressure steam turbine	$\dot{C}_{25} - \dot{C}_{26} - \dot{C}_{ST,LP} = -\dot{Z}_{ST,LP}$		$c_{25} = c_{26}$
Condenser	$\dot{C}_{26} + \dot{C}_{w1} - \dot{C}_1 - \dot{C}_{w2} = -\dot{Z}_{CON}$		$\frac{\dot{C}_{26}}{\dot{E}_{26}} = \frac{\dot{C}_1}{\dot{E}_1}$
Mixing of stream 2 & 43	$\dot{C}_2 + \dot{C}_{43} = \dot{C}_3$		
Feed water tank	$\dot{C}_5 + \dot{C}_{pump,IP} + \dot{C}_{pump,HP}$ $-\dot{C}_{10} - \dot{C}_{18} = -\dot{Z}_{FWT}$	$\frac{\dot{C}_{10}}{\dot{E}_{10}} = \frac{\dot{C}_{18}}{\dot{E}_{18}}$	
Splitting of streams 43 & 45	$\dot{C}_4 = \dot{C}_{43} + \dot{C}_{45}$	$\frac{\dot{C}_{43}}{\dot{E}_{43}} = \frac{\dot{C}_{45}}{\dot{E}_{45}}$	
Fed water pump	$\dot{C}_1 + \dot{C}_{pump,CON} - \dot{C}_2 = -\dot{Z}_{pump}$		
Mixing of streams 13 & 14	$\dot{C}_{24} + \dot{C}_{13} = \dot{C}_{14}$		
Splitting of streams 5 & 6	$\dot{C}_{45} = \dot{C}_5 + \dot{C}_6$		$\frac{\dot{C}_5}{\dot{E}_5} = \frac{\dot{C}_6}{\dot{E}_6}$
Mixing of stream 8 & 17	$\dot{C}_8 + \dot{C}_{17} = \dot{C}_{25}$		

The costs of the unknown streams were determined by figuring out the method of linear equations in table 3.

The parameters in table 4 have significant impact over exergoeconomic analysis of integrated cycle power unit. These parameter are the exergy destruction cost rate ($\dot{C}_D$), the fuel ($c_{F,k}$) average cost per unit exergy, the product ($c_{P,k}$) average cost per unit exergy, the relative cost difference (r_k) and the exergoeconomic factor (f_k). The parameters are computed in a following manner [8]:

Table 4: Exergoeconomic Parameter

$c_{F,k}$	$c_{P,k}$	$\dot{C}_{D,k}$	r_k	f_k
$c_{F,k} = \frac{\dot{C}_{F,k}}{\dot{E}_{F,k}}$	$c_{P,k} = \frac{\dot{C}_{P,k}}{\dot{E}_{P,k}}$	$\dot{C}_{D,k} = c_{F,k} \dot{E}_{D,k}$	$r_k = \frac{c_{P,k} - c_{F,k}}{c_{F,k}}$	$f_k = \frac{\dot{Z}_k}{\dot{Z}_k + \dot{C}_{D,k} + \dot{C}_{L,k}}$

The relative cost difference r_k reports the variability among these particular product and fuel cost of every element. Such variability is because of a cost rate of exergy elimination ($\dot{C}_{D,k}$) and the cost rate related with the capital cost ($\dot{Z}_k$) [8]. The exergoeconomic element f_k was the criterion that indicates the parallel significance of a element cost to the cost of exergy elimination and depletion related with the element

5. EXERGoeCONOMIC OPTIMIZATION

Commonly, a thermal power plant has two contradictory objectives:- one being decreased and other is increased, costs to be decreased, while, thermal and exergy productivity should increased. The aim of optimization is for fulfill all goals. Cost purpose was limited because of economic constrains, while the efficiencies are regulated by thermodynamic requirements. Hence, a major purpose must choose particularly where a result of maximization fulfills all contradictory prerequisites [7].

In this, work the objective function defined by Eq. 10 [9], which is the total specific unit cost of product $c_{P,TOT}$.

$$c_{P,TOT} = \frac{\sum_{k=1}^{nk} \dot{Z}_k + \sum_{k=1}^{NF} c_{F,k} \dot{E}_{F,k}}{\sum_{k=1}^{NP} \dot{E}_{P,k}} \quad (10)$$

Where is, nk , NF and NP amount of system elements, number of system fuel, stream as well number of system product stream respectively.

The exergoeconomic performance of integrated cycle power unit relies upon following decision variables: (i) pinch point degree in the evaporators, (ii) force drum for a low, intermediate, as well high-pressure level. Hence, the maximization issue could conveyed as a purpose of six determination variables minimize $c_{P,TOT}$ ($PPL, PPI, PPH, LP, IP, HP$). In this work constrains are; the higher margin of the high load drum $HP \leq 180$ bar, an exhaust gas temperature T_{11g} lower limit $T_{11g} \geq 93$ °C and pinch point temperature lower limit $PP \geq 4$ °C.

6. RESULT AND DISCUSSIONS

The influence of performing criterions on the factor exergy cost of the net generated power $C_{P,TOT}$ as well the results of optimization are presented in Figs. (2-7). **Error! Reference source not found.** shows the lower limit of $PPL = 14\text{ }^{\circ}\text{C}$ because the constrain of the exhaust gas temperature T_{11g} . **Error! Reference source not found.** shows the lower limit of $PPI = 4\text{ }^{\circ}\text{C}$ because of the pinch point constrain, **Error! Reference source not found.** shows the optimal value of the high pressure pinch point $PPH = 17\text{ }^{\circ}\text{C}$. The results shown in Figs. 6-7 represent the optimum performance condition at pressure drum of $IP = 37\text{ bar}$ and $HP = 175\text{ bar}$. There is a constrain regarding low pressure drum (exhaust gas temperature T_{11g}), therefore, the upper limit of $LP = 4\text{ bar}$. In **Error! Reference source not found.**,

The major significant element of an exergoeconomic outlook is HRSG, because it have a largest $\dot{Z}_k + \dot{C}_D$ and low exergoeconomic factor f_k , that is an sign of the respective importance of exergy elimination and capital investment costs. The subsequent largest value of $\dot{Z}_k + \dot{C}_D$ connects to steam turbine. **Error! Reference source not found.** indicates the outcome of maximization, exergoeconomic criterions of the primary elements of the bottoming cycle for the optimum case. As it is shown, the value of $\dot{Z}_k + \dot{C}_D$ and the exergoeconomic factor of all elements has increased after optimization proposing that by reducing the exergy destruction cost and raising exergetic potentiality of the tool via higher investment costs, the total cost can be saved.

Figure 1: Low Pressure Pinch Point PPL vs. Objective Function.

Figure 2: Intermediate Pressure Pinch Point PPI vs. Objective Function.

Table 5: Exergoeconomic Parameters of the System for the Initial Case

	$\dot{E}_{F,k}$ [kW]	$\dot{E}_{P,k}$ [kW]	$\dot{E}_{D,k}$ [kW]	$\dot{C}_{D,k}$ [\$/h]	$\dot{Z}_k$ [\$/h]	$\dot{Z}_k + \dot{C}_{D,k}$ [\$h]	ϵ_k [%]	f_k [%]
HRSG	186365	161663	24702	1483.92	677.11	2161.03	86.745	31.333
Condenser	10909	3839	7070	430.34	95.41	525.75	96.929	12.563
FWT	1938	1391	547	41.12	23.68	64.8	71.784	36.538
Steam turbine	149356	134544	14812	904.18	925.1	1829.28	90.083	50.572
Total	186365	134544	49997	3003.4	1852.4	4855.84	73.173	38.148

Table 6: Exergoeconomic Parameters of the System for the Optimum Case

	$\dot{E}_{F,k}$ [kW]	$\dot{E}_{P,k}$ [kW]	$\dot{E}_{D,k}$ [kW]	$\dot{C}_{D,k}$ [\$/h]	$\dot{Z}_k$ [\$/h]	$\dot{Z}_k + \dot{C}_{D,k}$ [\$h]	ϵ_k [%]	f_k [%]
HRSG	186515	165637	20878	549.42	881.37	1430.79	88.806	61.6
Condenser	10756	3785	6971	199.31	94.06	293.37	96.929	23.422
FWT	2942	2110	832	32.24	32.83	65.07	71.723	50.458
Steam turbine	154431	139202	15229	434.61	954.81	1389.42	90.138	68.72
Total	186515	139202	46551	1225	2097.2	3322.2	75.042	63.127

Table 7: Comparison Between the Initial Case and Optimized Case

	Pinch point [°C]			Pressure drum [bar]			Objective function $C_{P,TOT}$ [\$/kJ]	CCGT efficiency η_{CCGT} [%]	CCGT gross power P [MW]
	PPL	PPI	PPH	LP	IP	HP			
Indicial case	13	13	13	5	36	140	0.09847	57.67	420.5
Optimum case	14	4	17	4	37	175	0.05144	58.178	424.2

The comparative results of the initial case and the maximum instance were provided in **Error! Reference source not found..** It is noticed that the capability raises for 1%, net output power increase for 1% and the unit exergy cost of the total generated power reduced (objective function) for 47.76%. In the maximized system the exergy elimination reduces

for, HRSG 18% and whole system for 7% condenser 1%, and the total cost rate for system ($\dot{Z} + \dot{C}_D$) increase from 4855 \$/h to 3322 \$/h

7. CONCLUSIONS

In this research, a comprehensive thermodynamic model of the CCGT was conducted. Additionally, a simple optimization method has applied for obtaining the favourable design parameters of the system taking into account limitations. The main purpose in this study involves exergy, economic parameters and performance. A maximization procedure has been carried out with six determination variables.

In the maximization process, the two objectives, minimization of the total cost rate (economic) and maximization of exergetic capability (thermodynamics) were included.

The findings indicates that the exergy elimination cost per hour is reduced by 59.2%, the total cost per hour ($\dot{Z} + \dot{C}_D$) is decreased by 31.5%, when the capital cost per hour $\dot{Z}$ is increased by 21.46% . In addition, the exergetic efficiency was increased by 2.5%.

NOMENCLATURE

c	cost per exergy unit (\$/kJ)	ST	steam turbine
$\dot{C}$	cost rate (\$/s)	T	temperature (C, K)
e	specific exergy (kJ/kg)	Z	capital cost of a component (\$)
$\dot{E}$	exergy rate (kW)	$\dot{Z}$	capital cost rate (\$/s)
f	exergoeconomic factor	<i>Greek letters</i>	
FWT	Feed water tank	η	isentropic efficiency
h	specific enthalpy (kJ/kg)	ε	exergy efficiency
HP	High pressure drum	<i>Subscripts</i>	
I	irreversibility	0	dead (environmental) state
IP	Intermediate pressure drum	1,2,3..	cycle locations
LP	Low pressure drum	Con	condenser
$\dot{m}$	mass flow rate (kg/s)	$CCGT$	Combine cycle gas turbine
PPH	High pressure pinch point temperature (K)	D	destruction
PPI	intermediate pressure pinch point temperature (K)	F	fuel
PPL	Low pressure pinch point temperature (K)	HP	high pressure
$\dot{Q}$	heat transfer rate (kW)	IP	Intermediate pressure
r	relative cost difference	LP	Low pressure
s	specific entropy (kJ/kg K)	P	product
SPECO	specific exergy costing	PH	physical

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