Thermodynamic Analysis and Thermo-economic Optimization of a Combined Cycle Power Plant

M. Abdollahi, M.S. Student, Dept. of Energy Conversion, The Faculty of Mech. Eng., TIAU
M. layeghi, Ass. Prof., Dept. of Energy Conversion, The Faculty of Mech. Eng., KIAU
M.H. Hamedi, Prof., Dept. of Energy Conversion, The Faculty of Mech. Eng., TIAU
Email: azad_ezat@yahoo.com

Abstract: Combined Cycle Power Plant is the most effective among all the plants because in addition of high efficiency and power, it has other benefits such as fast Installation and flexibility. In this paper, fars combined cycle power plant consists of gas and steam parts has been analyzed and optimized through technical and economical aspect with EES software. The evaluation criterion in the optimization operation is the objective function of total costs that includes the costs related to the current costs (thermodynamic sector) and investment costs (economic sector). In this method using of exergy balance equations in the various components, value of Exergy flow in system lines and value of exergy destruction in each component of the cycle is determined. In the next stage with balancing the cost of exergy in each component of system, set of equations of exergy cost has determined that with solving it, exergy unit price in flow lines, exergy destruction cost in different components of the system and other variables needing for analyze exergy – economic has obtained.

Keywords: Combined cycle power plant, Thermodynamic Analysis, Thermo-Economic Optimization, Exergy.

تحلیل ترمودینامیکی و بهینه‌سازی حرارتی– اقتصادی یک سیکل ترکیبی قدرت

محسن عبداللهی – دانشجوی کارشناسی ارشد تبدیل انرژی، دانشکده مهندسی مکانیک، دانشگاه آزاد اسلامی واحد تاکستان

محمد لایقی – استادیار گروه تبدیل انرژی، دانشکده مهندسی مکانیک، دانشگاه آزاد اسلامی واحد تاکستان

محمدحسین حامدی – استاد گروه تبدیل انرژی، دانشکده مهندسی مکانیک، دانشگاه آزاد اسلامی واحد تاکستان

چکیده: این مقاله رویکد نظری طراحی یک مبدل حرارتی لوله‌گرمائی را توصیف می‌کند. تحلیل براساس رویکرد NTU– ضریب تأثیر قراردارد که منتج به تعیین مشخصه‌های حرارتی مبدل حرارتی می‌گردد. در این مطالعه تغییرات ضریب تأثیر کلی مبدل حرارتی لوله‌گرمائی برحسب نسبت ظرفیت‌های حرارتی (C_e/C_c) ارائه می‌شود و تعداد بهینه ردیف لوله‌های‌گرمائی برای حداکثر عملکرد حرارتی مبدل تعیین می‌شود.

واژه‌های کلیدی: نانوسیال، شبیه‌سازی عددی، کانال عمودی، جابجایی آزاد و اجباری.

1. Introduction

Power Plant is the most effective among all the plants because in addition of high efficiency and power, it has other benefits such as fast Installation and flexibility. In this kind of power plants optimal design of cycle is very effective to reduce the cost of fossil fuels consumed [1]. The most important thing about the combined cycle power plant (CCPP) is that we will be able to obtain the most power of the output steam plant cycle from the determined output of gas plant cycle. Whereas that combined cycle has greater efficiency to the Rankin and Brighton cycle it has more regarded for the production of power and for less pollution has widely spread in the world. Exergy analysis of a thermodynamic system lead to estimate value of destruction of the system exergy, and efficiency Set was calculated [2]. The purpose of exergy is the maximum work available of system from current state to thermodynamic equilibrium state with the surrounding environment [3]. System exergy analysis is usually closely associated with its economical; therefore thermo-economic analysis is a convenient tool that makes it possible to calculate the cost of products and the cost of destruction exergy and entropy production can be estimated [2]. Many works in conjunction with the analysis of power thermo economic of CCPPs is done; Al-Muslim and Dince have done an energy and exergy analysis of a steam power plant and evaluated preheating states at various boiler temperatures and pressures [4]. Ahmadi et. al. has done the thermo-economic analysis of the dual pressure Neka CCPP [5]. Barzegar has analyzed the CCPP from exergy and exergo-economic [6].

Ahmadi et. al. Optimization of thermodynamic cycles do in different ways Such as pinch, Exergy, Exergy pinch and thermo economic that in Each of these methods different variables Can be considered as design parameters. This study used of thermo economic optimization method that those optimizing the design parameters to the pressure ratio and efficiency of compressor, inlet temperature to the gas turbine and steam and condenser pressure. This optimization performed based on the clear goal function. The function can be the cost of whole plant, including equipment purchase costs, consumption fuel costs and the cost of repairs.

In this study, Shiraz CCPP first analyzed from the thermodynamic analysis and then optimized while of exergy analysis with the help of genetic algorithm and with modeling in EES software in the thermo economic method.

2. Description of Fars CCPP

The CCPP installed in Fars that its schematic of that has shown in Fig. (1) includes of six gas units steam which each one has power 121.3 MW, and three steam units, each with 98.2 MW. It should be noted that power plant cycle steam turbine in Fars are dual pressure.

3. Thermodynamic Analysis

In this section with regard to Fig. (1) the law of energy conservation derived for each component of the cycle, based on the enthalpy quantity, temperature and flow pressure.

3.1. Air Compressor

Compressor outlet temperature in terms of inlet temperature and adiabatic efficiency is defined as:

$$T_B = T_A \left[1 + \frac{1}{\eta_{com}} \left(r_c^{\frac{\gamma-1}{\gamma}} - 1 \right) \right] \tag{1}$$

Compressor work is given from follow relation:

$$W_{com} = \left(MC_p \right)_a \left(T_B - T_A \right) \tag{2}$$

The value of C_{pa} is related to temperature and calculated from follow relation:

$$C_{pa}(T)=$$
$$1.04841-3.8371\times10^{-4}T+9.4537\times10^{-7}T^2 \quad (3)$$
$$-5.4931\times10^{-10}T^3+7.9298\times10^{-14}T^4$$

3.2. Combustion Chamber (CC)

Energy Balance:

$$\dot{M}_a h_B + \dot{m}_f . LHV = \dot{M}_g h_C +$$
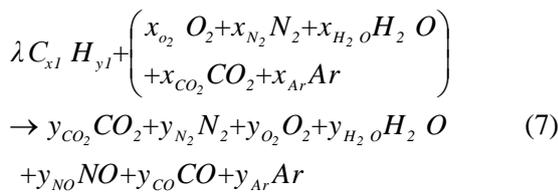$$(1-\eta_{CC})\dot{m}_f . LHV \quad (4)$$

Mass Balance:

$$\dot{M}_g = \dot{M}_a + \dot{m}_f \quad (5)$$

Where LHV is the fuel heating value, that here is natural gas, and η_{CC} is the thermal efficiency of the combustion chamber and:

$$\frac{P_C}{P_B} = 1 - \Delta p_{CC} \quad (6)$$

The combustion chemical reaction is carried out in the chamber as follow:

$$\lambda C_{x1}H_{y1}+\begin{pmatrix} x_{o_2}\,O_2+x_{N_2}N_2+x_{H_2O}H_2O \\ +x_{CO_2}CO_2+x_{Ar}Ar \end{pmatrix}$$
$$\rightarrow y_{CO_2}CO_2+y_{N_2}N_2+y_{O_2}O_2+y_{H_2O}H_2O \quad (7)$$
$$+y_{NO}NO+y_{CO}CO+y_{Ar}Ar$$

Equilibrium of reaction equation is as follow:

$$\begin{cases} y_{CO_2} = (\lambda x_1 + x_{CO_2} - y_{CO}) \\ y_{N_2} = x_{N_2} - y_{NO} \\ y_{H_2O} = x_{H_2O} + \lambda\dfrac{y_1}{2} \\ y_{O_2} = x_{O_2} - \lambda x_1 - \frac{1}{4}\lambda y_1 - \frac{1}{2}y_{CO} - \frac{1}{2}y_{NO} \\ y_{Ar} = x_{Ar} \\ \lambda = \dfrac{n_{fyel}}{n_{Air}} \end{cases} \quad (8)$$

3.3. Gas Turbine

Turbine outlet temperature in terms of inlet temperature and adiabatic efficiency is defined as:

$$T_D = T_C\left[1-\frac{1}{\eta_{GT}}\left(1-r_c^{\frac{\gamma-1}{\gamma}}\right)\right] \quad (9)$$

Where, η_{GT} is the turbine isentropic efficiency.

Turbine work is given from follow relation:

$$W_{GT} = (MC_p)_g (T_C - T_D) \quad (10)$$

The heat capacity of gases, C_{pg} is assumed as a temperature dependent variable as follow:

$$C_{pg}(T)=0.991615-6.99703\times10^{-5}T$$
$$+2.7129\times10^{-7}T^2 \quad (11)$$
$$-1.22442\times10^{-10}T^3$$

Thus, the net work of the power plant is:

$$\dot{W}_{net} = \dot{W}_{GT} - \dot{W}_{com} \quad (12)$$

3.4. Recovery Heat Steam Generator

Recovery Heat Steam Generator (HRSG) consists of several parts, each part models as below:

3.4.1. High pressure super heater

$$\dot{M}_g C_p (T_D - T_{12}) = \dot{M}_{s,HP}(H_{10} - h_9) \quad (13)$$

Where $M_{S,HP}$ is mass flow rate of steam to high pressure turbine.

3.4.2. High pressure evaporator

$$\dot{M}_g C_p (T_{12} - T_{13}) = \dot{M}_{s,HP}(H_9 - h_8) \quad (14)$$

3.4.3. High pressure economizer

$$\dot{M}_g C_p \left(T_{13} - T_{14} \right) = \dot{M}_{s,HP} \left(H_8 - h_7 \right) \quad (15)$$

3.4.4. Low pressure super heater

$$\dot{M}_g C_p \left(T_{14} - T_{15} \right) = \dot{M}_{s,LP} \left(H_6 - h_5 \right) \quad (16)$$

3.4.5. Low pressure evaporator

$$\dot{M}_g C_p \left(T_{15} - T_{16} \right) = \dot{M}_{s,LP} \left(H_5 - h_4 \right) \quad (17)$$

3.4.6. Deaerotor

$$\dot{M}_g C_p \left(T_{16} - T_{17} \right) = \dot{M}_{s,LP} \left(H_3 - h_2 \right) \quad (18)$$

3.4.7. Pre-heater

$$\dot{M}_g C_p \left(T_{17} - T_{18} \right) = \dot{M}_{s,LP} \left(H_2 - h_1 \right) \quad (19)$$

3.5. Steam turbine

$$\dot{M}_{S,HP} h_{10} + \dot{M}_{S,LP} h_6 - \dot{M}_S h_{19} = \dot{W}_{ST,i} \quad (20)$$

Where:

$$\dot{M}_{S,HP} + \dot{M}_{S,LP} = \dot{M}_S \quad (21)$$

and the steam turbine efficiency is:

$$\eta_{ST} = \frac{\dot{W}_{act}}{\dot{W}_{IS}} \quad (22)$$

3.6. Condenser

$$\dot{M}_S \left(h_{19} - h_{20} \right) = M_{cooling} \left(h_{22} - h_{21} \right) \quad (23)$$

3.7. Pump

$$\dot{W}_{p1} = \dot{M}_S \left(h_1 - h_{20} \right) \quad (24)$$
$$\dot{W}_{BFP,HP} = \dot{M}_{S,HP} \left(h_{out} - h_{in} \right) \quad (25)$$
$$\dot{W}_{BFP,LP} = \dot{M}_{S,LP} \left(h_{out} - h_{in} \right) \quad (26)$$

3.8. Thermal efficiency

Thermal efficiency of gas cycle is:

$$\eta_{gas,cycle} = \frac{\dot{W}_{GT} - \dot{W}_{com}}{\dot{Q}_{CC}} \quad (27)$$

Steam cycle efficiency is:

$$\eta_{steam,cycle} = \frac{\dot{W}_{ST} - \dot{W}_{pump}}{\dot{Q}_{HRSG}} \quad (28)$$

Efficiency of combined cycle power plant is:

$$\eta_{CCPP} = \frac{\left(\dot{W}_{ST} + \dot{W}_{GT} \right) - \left(\dot{W}_{pump} + \dot{W}_{com} \right)}{\dot{Q}_{in,CCPP}} \quad (29)$$

Where, $Q_{in,ccpp}$ is the heat transfer entering the cycle from enclosures, combustion and heat consumed in auxiliary boiler (if used).

$$\dot{Q}_{HRSG} = \dot{M}_{wlp} \left(h_6 - h_5 \right) + \dot{M}_{whp} \left(h_{10} - h_9 \right) \quad (30)$$

4. Exergy analysis

In this study, to make an exergy analysis, the exergy values of all parts of the cycle are calculated, individually. It is necessary to note that exergy values measured relative to the reference state that is at the environment conditions (temperature 25°C and 1 atm in pressure). Knowing the conditions at each state of the cycle, enthalpy and entropy currents are calculated by using the thermodynamic relations that mentioned in Sec. (3), and finally, the values exergy of each is determined from below:

$$e = \left(h - h_o \right) - T_o \left(S - S_o \right) \quad (31)$$

Knowing of input and output exergy amount of each power plant components, the

degradation rate of exergy in each destination can be calculated by using the equations tabulated in Table (2).

5. Thermo-economic analysis

Thermo-economic is the combination of exergy analysis and economics. An exergy analysis is able to estimate the destruction exergy and for the cycle studied here, a computer program have been prepared that analyzed an entire cycle thermodynamically. It should determine the properties of all defined nodes in the cycle after complete solution of the conservation equations and estimate the destructions exergy. After estimating exergy destruction, the next important step is to know the cost of these losses. In the while of discussing thermo-economic, it is necessary to distinguish between exergy cost ($ / kj) and the cost rate ($ / sec).

6. Exergy costing

For a thermodynamic system some mass and energy flows in the inlet and outlet with exchanging work and heat transfer with the surroundings can be considered. According to the mass and energy flows, there are exergy flows into and out of system and also at the same time there is irreversibility in exergy destruction system. Since exergy represents a thermodynamic property of a flow, it is obvious that the cost of these flows related to exergy transfer rate. This section of thermo-economic, called exergy costing. Depending on the source, the costs have shown with i (for input) or e (for output) and also w for work and q for heat transfer, that means:

$$
\begin{aligned}
\dot{C}_i &= c_i \times \dot{E}_i = c_i\left(\dot{m}_i \times e_i\right) \\
\dot{C}_e &= c_e \times \dot{E}_e = c_e\left(\dot{m}_e \times e_e\right) \\
\dot{C}_w &= c_w \times \dot{W} \\
\dot{C}_q &= c_q \times \dot{Q}
\end{aligned}
\tag{32}
$$

Where e_i is system input exergy per mass unit at kJ/kg and e_e is system output exergy per

mass unit at kJ/kg. Also $\dot{m}$ is mass flow rate in kg/s and c_q, c_w, c_i, c_e are the average costs per exergy unit.

For a component k in the system, a cost rate equilibrium equation cycle is as the following:

$$
\sum \dot{C}_{e,k} + \dot{C}_{w,k} = \dot{C}_{q,k} + \sum \dot{C}_{i,k} + \dot{Z}_k
\tag{33}
$$

The left side of Eq. (33) represents the output costs of component k and the right side represents input costs rate., $\dot{z}_k$ is the cost related to the initial investment and maintenance, the equipment price based on its capacity and obtained by the procedure mentioned in [10, 11. Different methods are proposed to calculate $\dot{z}_k$, but here, we used the method of Ahmadi et. al has proposed and this is as follow[5]:

$$
\begin{aligned}
\dot{Z}_k &= Z_k \times CRF \times \frac{\varphi}{N \times 3600} \\
CRF &= i \times \frac{1+i}{\left\{(1+i)^n - 1\right\}}
\end{aligned}
\tag{33}
$$

Where, Z_k is price in $, N is annual operation in seconds or hours, i is the bank interest rate, n is the number of the operation years, and CRF is the capital recovery factor.

7. Results

According to pervious Sec., Fars power plant cycle in EES software is fully simulated. Then with the optimized parameters as shown in Table 3, the values of these parameters are provided in both current and optimal cases. By definition the objective function, that is the total cost including equipment purchase costs, fuel costs and maintenance costs, the thermo-economic of the cycle optimized by using genetic algorithm. As the GA is able to optimize problems simultaneously based on several variables, in this work the optimization of objective function performed based on the variables of Table 2, and the result is presented

in Table 3. Also, since in a power plant cycle in addition of total cost , the rate of power production is very interesting, one of the important task that done in this study is the selection of suitable compression ratio for compressor and suitable air flow rate in order to achieve maximum power production and the least consumed cost. Figures (3) and (4) show, the effects of r_c and air flow rate on the power production and consumed cost, respectively. With regard to mentioned values of parameters in Table (2), a suitable range of these parameters such as r_c and air flow rate can be obtained.

Thus, with regard to determined objectives that they cause an increase in output power and a reduction in total cost, the optimal values of each parameter can be calculated.

8. Conclusion

In this study, by applying the first and second laws of thermodynamics for Fars CCPP attempted to make a thermodynamic and exergy analysis for the cycle which it follows by determination of exergy for different states of the cycle. After that, a thermo-economic analysis of the cycle is made, and it optimised by writing the cost balance equations for individual components. The thermo-economic optimization yield the optimized values of the important design parameters including compression ratio and air flow rate of compressor. This work has been done for the first time on Shiraz CCPP.

Acknowledgments

9. References

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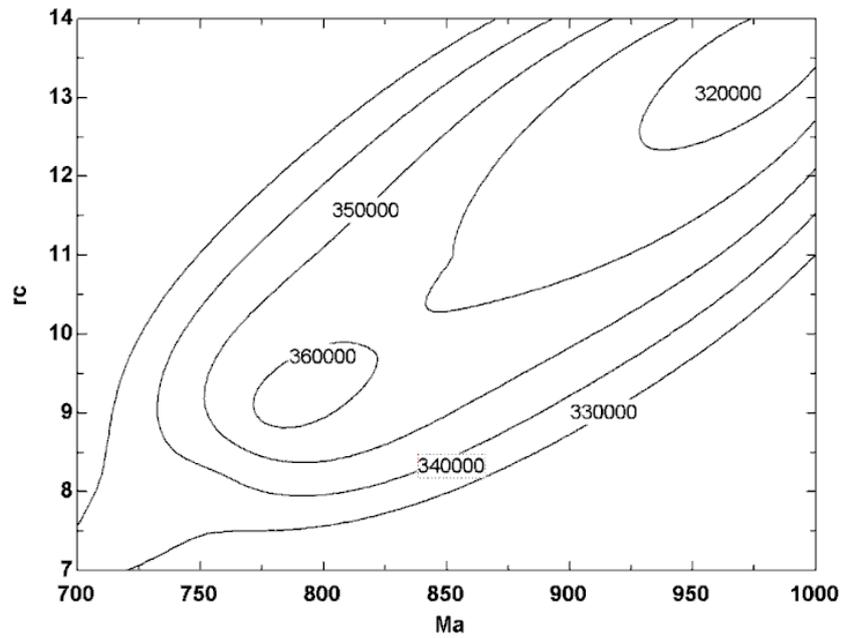
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Fig. (1): Schematic flow diagram of combined cycle power plant in fars

Fig. (2): Output power in terms of compression ratio and the place of maximum

Fig. (3): Output power contour in terms of compression ratio and air flow rate
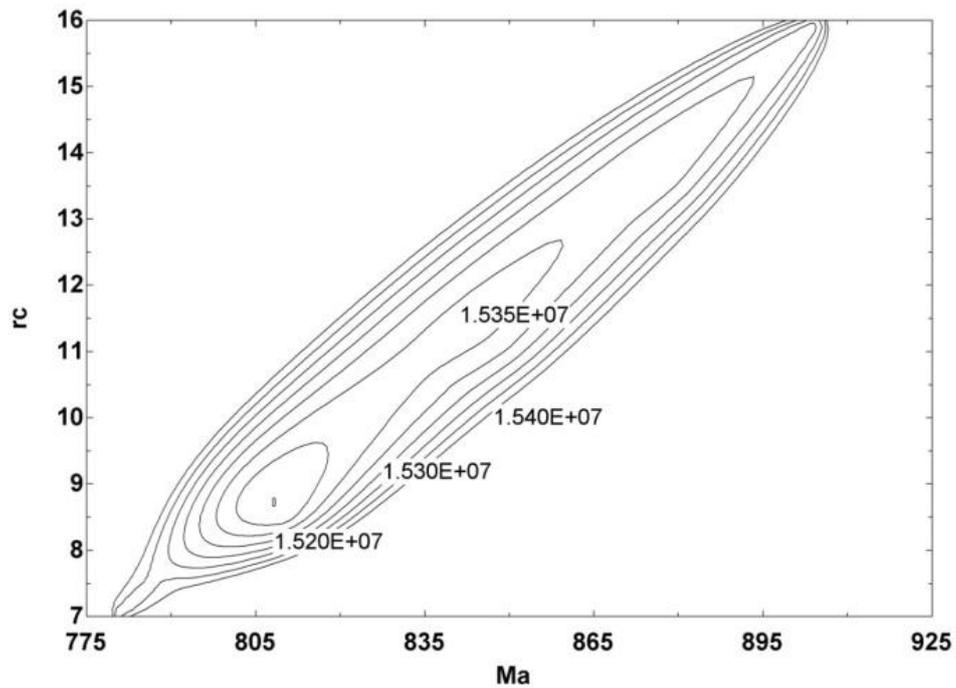
Fig. (4): Total cost Contour in terms of compression ratio and air rate

Table 1: Abbreviation of the cycle components

Component name	Symbol	Exergy Destruction	Exergy Efficiency
Boiler feed pump	BFP	$\dot{E}_{D,P} = \dot{E}_{i,p} + \dot{W}_P$	$\eta_{e,p} = \dfrac{(\dot{E}_{i,p} - \dot{E}_{o,p})}{\dot{W}_P}$
Recovery boiler	HRSG	$\dot{E}_{D,HRSG} = \sum_{i,HRSG} \dot{E} - \sum_{o,HRSG} \dot{E}$	$\eta_{HRSG} = \dfrac{E_{10} + \dot{E}_6 - E_1}{E_{11} - E_{18}}$
Duct burner	db	$E_{D,DB} = E_D - E_{11} + E_{f,DB}$	$\eta_{DB} = \dfrac{E_{11}}{E_D + E_{f,DB}}$
Steam turbine	ST	$\dot{E}_{D,T} = \sum_{i,T} \dot{E} - \sum_{e,T} \dot{E} - \dot{W}$	$\eta_{e,s} = \dfrac{\dot{W}_t}{(\dot{E}_{i,T} - \dot{E}_{e,T})}$
Condenser	Cond	$\dot{E}_{D,C} = \sum_{i,C} \dot{E} - \sum_{e,C} \dot{E}$	$\eta_{Cond} = 1 - \dfrac{E_{D,Cond}}{\sum_{in,Cond} E}$
Exergy destruction	ED		
Cost	C		
Equipment price	Z		
Exergy unit mass	e		
Exergy	E		
Compressor	com	$E_{D,AC} = E_A - E_B - E_{W,AC}$	$\eta_{AC} = \dfrac{E_2 - E_1}{W_{AC}}$
Gas turbine	gt	$E_{D,GT} = E_C - E_D - W_{GT}$	$\eta_{GT} = \dfrac{W_{GT}}{E_C - E_D}$
Air	a		
Exhaust gas	g		
Fuel	f		
Combustion chamber	cc	$E_{D,CC} = E_B + E_{f,cc} - E_C$	$\eta_{CC} = \dfrac{E_C}{E_B + E_{f,cc}}$
Work output	Wnet		
High pressure	HP		
Low pressure	LP		
Steam	S		