Thermodynamic and Thermo Economic Optimization of Combined Cycle Power Plant

Masoud Taghavi , Mohsen Abdollahi, and Gholamreza Salehi

***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.**

Index Terms—Component, combined cycle power plant, thermodynamic analysis, thermo economic optimization, exergy.

I. INTRODUCTION

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 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 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] Analysis Exergy system is usually closely associated with It is economical, therefore thermo economic analysis is good tools 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 Combined cycle power plants is done such as Al- Muslim and Dince that energy analysis and Exergy steam power plant and or pre heating for states of Various boiler temperatures and pressures and has been established. [4] Also, Ahmadiet *et al*. [5] has analyzed the thermodynamic and thermo economic of dual pressure Neka Combined Cycle Power Plant. Also, Barzegar [6] has analyzed the combined cycle power plant from Exergy and exergo economic. Ahmadiet *et al*. [2] the purpose of Exergy is the maximum work available of system from current state to thermodynamic equilibrium state with the surrounding environment. [3] analysis Exergy system is usually closely associated with It is economical, therefore thermo economic analysis is good tools 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 Combined cycle power plants is done such as Al- Muslim and Dince that energy analysis and Exergy steam power plant and or pre heating for states of Various boiler temperatures and pressures and has been established. [4] Also, Ahmadiet. al. [5] has analyzed the thermodynamic and thermo economic of dual pressure Neka Combined Cycle Power Plant. Also, Barzegar [6] has analyzed the combined cycle power plant from Exergy and Agzrzhv economic. Ahmadiet. 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 Journal used of thermo economic optimization method that those Optimizing the design parameters to the pressure ratio Compressor, compressor efficiency, inlet temperature to the gas turbine and Steam and condenser pressure and 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. Optimizations in the form of optimization algorithms to minimize the goal function are performed. In this paper, Shiraz combined cycle power plant first analyzed from the thermodynamic analysis and then optimized in the while of Exergy analysis with the help of genetic algorithm and with modeling in EES software in the thermo economic method.

II. FARS COMBINED CYCLE POWER PLANT

Combined cycle power plant in Fars that schematic cycle of that has shown in Figure 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.

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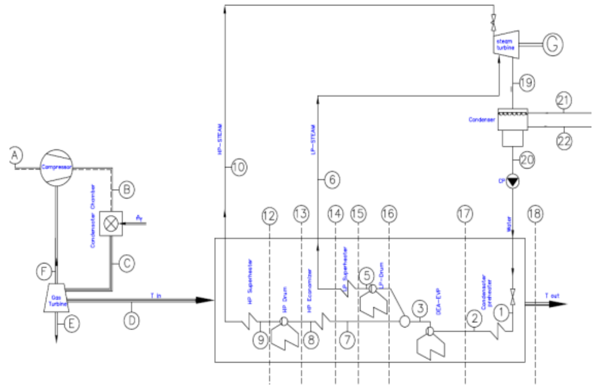


Fig. 1. schematic flow diagram of combined cycle power plant in Fars

III. THERMO-DYNAMIC ANALYSIS

In this section with regard of the form (1) the law of energy conservation and Enthalpy quantity, temperature and flow pressure during the entire cycle is computed.

A. Air Compressor

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

Compressorwork is given from follow relation:

$$W_{com} = M_a C_{pa} (T_B - T_A) \tag{2}$$

Which the value of Cpa is related to temperature and calculated from follow relation:

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

B. Combustion Chamber (cc)

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

$$\dot{M}_g = \dot{M}_a + \dot{m}_f \tag{5}$$

In the above relation LHV is the fuel heating value, that here is natural gas, and η_{cc} is the Efficiency of the combustion chamber;

$$\frac{P_C}{P_B} = 1 - \Delta p_{cc} \tag{6}$$

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

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

Equilibrium of reaction equation is as follow:

$$y_{CO_2} = (\lambda \times x_1 + x_{CO_2} - y_{CO}) \tag{8}$$

$$y_{N_2} = x_{N_2} - y_{NO} \tag{9}$$

$$y_{H_2O} = x_{H_2O} + \lambda \times \frac{y_1}{2} \tag{10}$$

$$y_{O_2} = x_{o_2} - \lambda \times x_1 - \lambda \times \frac{y_1}{4} - \frac{y_{CO}}{2} - \frac{y_{NO}}{2} \tag{11}$$

$$y_{Ar} = x_{Ar} \tag{12}$$

$$\lambda = \frac{n_{fuel}}{n_{air}} \tag{13}$$

C. Gas Turbine

$$T_D = T_C \times \left(1 - \eta_{gt} \times \left(1 - (rc)^{\frac{1-\gamma}{\gamma}}\right)\right) \tag{14}$$

This in the above relation ngt is turbine isentropic efficiency.

$$W_{GT} = \dot{M}_g C_{pg} (T_C - T_D) \tag{15}$$

where C_{pg} is taken as a tempreture variable function as follow:

$$C_{pg}(T) = 0.991615 - \left(\frac{6.99703T}{10^5}\right) + \left(\frac{2.7129T^2}{10^7}\right) - \left(\frac{1.22442T^3}{10^{10}}\right) \tag{16}$$

Thus, for work output of the turbine we have:

$$\dot{W}_{net} = \dot{W}_{GT} - \dot{W}_{com} \tag{17}$$

D. Modeling of Recovery Heat Boiler

Recovery boiler or HRSG Consists of several parts which continue with Modeling of these sectors:
High pressure super heater:

$$\dot{M}_g C_p (T_D - T_{12}) = \dot{M}_{s,HP} (h_{10} - h_9) \tag{18}$$

In the above relation $\dot{M}_{s,HP}$ is flow rate inlet steam to high Pressure turbine.

High pressure evaporator:

$$\dot{M}_g C_p (T_{12} - T_{13}) = \dot{M}_{s,HP} (h_9 - h_8) \tag{19}$$

High pressure economizer:

$$\dot{M}_g C_p (T_{13} - T_{14}) = \dot{M}_{s,HP} (h_8 - h_7) \tag{20}$$

Low pressure super heater:

$$\dot{M}_g C_p (T_{14} - T_{15}) = \dot{M}_{s,LP} (h_6 - h_5) \tag{21}$$

Low pressure evaporator:

$$\dot{M}_g C_p (T_{15} - T_{16}) = \dot{M}_{s,LP} (h_5 - h_4) \tag{22}$$

Deaerator:

$$\dot{M}_g C_p (T_{16} - T_{17}) = \dot{M}_{s,LP} (h_3 - h_2) \tag{23}$$

Pre heater:

$$\dot{M}_g C_p (T_{17} - T_{18}) = \dot{M}_{s,LP} (h_2 - h_1) \tag{24}$$

E. Steam turbine

$$(\dot{M}_{s,HP} h_{10} + \dot{M}_{s,LP} h_6 - \dot{M}_s h_{19}) = \dot{W}_{ST,i} \tag{25}$$

That we have:

$$\dot{M}_{s,HP} + \dot{M}_{s,LP} = \dot{M}_s \tag{26}$$

And we have for the steam turbine efficiency:

$$\eta_T = \frac{\dot{W}_{act}}{\dot{W}_{is}} \tag{27}$$

F. Condenser

$$\dot{W}_{p1} = \frac{\dot{M}_s(h_1 - h_{20})}{\eta_p} \tag{28}$$

G. Pump

$$\dot{M}_s(h_{19} - h_{20}) = \dot{M}_{cooling}\,(h_{22} - h_{21}) \times \eta_{cond} \tag{29}$$

$$\dot{W}_{BFP,HP} = \frac{\dot{M}_{s,HP}(h_{out} - h_{in})}{\eta_p} \tag{30}$$

$$\dot{W}_{BFP,LP} = \frac{\dot{M}_{s,LP}(h_{out} - h_{in})}{\eta_p} \tag{31}$$

Calculate the thermal efficiency:
Thermal efficiency of gas Cycle:

$$\eta_{gas,cycle} = \frac{\dot{W}_{GT} - \dot{W}_{com}}{\dot{Q}_{CC}} \tag{32}$$

Steam turbine cycle efficiency:

$$\eta_{steam,cycle} = \frac{\dot{W}_{ST} - \dot{W}_{pump}}{\dot{Q}_{HRSG}} \tag{33}$$

Efficiency of combined cycle power plant:

$$\eta_{CCPP} = \frac{\dot{W}_{ST} + \dot{W}_{GT} - \dot{W}_{com} - \dot{W}_{pump}}{\dot{Q}_{in,CCPP}} \tag{34}$$

In the above equation, $\dot{Q}_{in,CCPP}$ is the heat transfer in enclosures Combustion and heat consumption in auxiliary boiler (if used).

$$\dot{Q}_{HRSG} = \dot{M}_{w_{lp}} \times (h_6 - h_5) + \dot{M}_{w_{hp}} \times (h_{10} - h_9) \tag{35}$$

IV. Exergy Analysis

In this paper, for doing Exergy analysis, values Exergy of all parts of the process is calculated. For Calculating Exergy it is necessary to be measured to the state that here are the environmental conditions. For the environmental conditions, temperature 25 °C and 1 atmosphere pressure is considered. Knowing the conditions and calculate Enthalpy and entropy currents with using of thermodynamic analysis, the values Exergy of each follows is given from follow relation:

$$e = (h - h_0) - T_0(S - S_0) \tag{36}$$

With writing this equation for determined all points, the values Exergy are calculated. Also, having of input and output Exergy amount of each power plant components, the degradation rate of Exergy in each destination with using of be calculated. relationship are shown in Table I can be calculated.

TABLE I: The Exergy Destruction Rate and Exergy Efficiency Equation for Plant Components

Component	**Exergy Destruction**	**Exergy Efficiency**
HRSG	$\sum_{i,HRSG}\dot{E} - \sum_{o,HRSG}\dot{E}$	$\frac{E_{10} + \dot{E}_6 - E_1}{E_{11} - E_{18}}$
Steam Turbine	$\sum_{i,T}\dot{E} - \sum_{e,T}\dot{E} - \dot{W}$	$\frac{\dot{W}_t}{(\dot{E}_{i,T} - \dot{E}_{e,T})}$
Pump	$\dot{E}_{i,p} + \dot{W}_P$	$\frac{(\dot{E}_{i,p} - \dot{E}_{o,p})}{\dot{W}_P}$
Compressor	$E_A - E_B - E_{W,AC}$	$\frac{E_2 - E_1}{W_{AC}}$
Combustion Chamber	$E_B + E_{f,cc} - E_C$	$\frac{E_C}{E_B + E_{f,cc}}$
Gas Turbine	$E_C - E_D - W_{GT}$	$\frac{W_{GT}}{E_C - E_D}$
Duct Burner	$E_D - E_{11} + E_{f,DB}$	$\frac{E_{11}}{E_D + E_{f,DB}}$
Condenser	$\sum_{i,C}\dot{E} - \sum_{e,C}\dot{E}$	$1 - \frac{E_{D,Cond}}{\sum_{in,Cond} E}$

V. Thermo Economic Analysis

Thermo economic is the combination of analysis Exergy and economics. Exergy analysis is able to estimate the destruction Exergy and for This work, the program should be prepared that analyzed an entire cycle thermodynamic ally and after complete solving of equations mass conservation and energy and determination of properties of all defined nodesin the cycle estimated destructions Exergy that this is done separately, in this way that after Writing the equations of mass conservation and energy for all plant components, the equations is solved using numerical iteration. But because this area is known it has not been getting. After estimating Exergy destruction, the next important thing is to know the cost of these losses. In the while of discussing Thermo economic, it is necessary to Differentiate between Exergy cost (*$ / kj*) and the cost rate (*$ / sec*).

A. Exergy Costing:

For a thermodynamic system some mass flows and energy in the inlet and outlet with exchanging work and heat with the environment can be considered. According to the mass flows and Energy, 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 value of a flow, it is normal that the cost of these currents 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:

$$\dot{C}_i = c_i \times \dot{E}_i = c_i(\dot{m}_i \times e_i) \tag{37}$$

$$\dot{C}_e = c_e \times \dot{E}_e = c_e(\dot{m}_e \times e_e) \tag{38}$$

$$\dot{C}_w = c_w \times \dot{W} \tag{39}$$

$$\dot{C}_q = c_q \times \dot{Q} \tag{40}$$

where e_i is system input Exergy per mass unit at kilo joule per kilo gram and e_e is system output Exergy per mass unit at kilo joule per kilo gram. Also $\dot{m}$ is mass flow rate at kilogram per second 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:

$$\sum \dot{C}_{e,k} + \dot{C}_{w,k} = \dot{C}_{q,k} + \sum \dot{C}_{i,k} + \dot{Z}_k \tag{41}$$

The left side of equation represents output costs of component k and its right side represents input costs rate.

In the above equation, $\dot{Z}_k$ is the cost related to the initial investment and maintenance, that equipment price based on their capacity is obtained as a determined function, by using of the reliable references [10], [11], and they placed in the equations. Different methods is proposed to calculate $\dot{Z}_k$, But what is used here, is the method that Ahmadi *et. al*. [5] has proposed and this is as follow:

$$\dot{Z}_k = Z_k \times CRF \times \frac{\varphi}{N \times 3600} \tag{42}$$

$$CRF2 = i \times \frac{1+i}{\{(1+i)^n - 1\}} \tag{43}$$

CRF is Capital Recovery Factor.

While Zk is price per dollar, N is annual operation at seconds or hours, i is the bank interest rates and n is the number of the operation years.

VI. Results

A. Thermo Economic Analysis and Optimization:

According to pervious subject, Fars power plant cycle in EES software is fully simulated. Then with considering the optimized parameters in Table II, the value of these parameters are provided in both current and optimal states, And also definition of objective function that it is total cost including equipment Purchase costs, fuel costs and maintenance costs, and it has thermo economic optimized by using genetic algorithm optimization. With regard to the genetic algorithm is able to optimize problems simultaneously and based on several variables, in this work the results of the optimization of objective function calculated based on variables of Table II, and they are presented in Table III. Also, since in a power plant cycle in addition of total cost, the amount of power production is very interesting, one of the important works that done in this article.

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. In figures 3 and 4, respectively, the effect of rc and air flow on the power production and the effect of rc and air flow rate on consumed cost has shown. With regard to mentioned figures, a suitable range of parameters such as rc and air flow rate can be obtained.

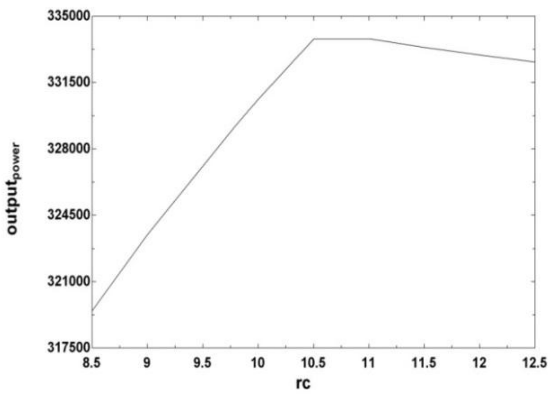
Thus, with regard to determined objectives that they are increasing of output power and reduce of total cost, the values of each parameters calculated to achieve the optimal operating conditions.

TABLE II: Optimization Parameter in the Current and Optimal States

parameter	Initial value	Value in the optimal state
Compression ratio of compressor	12.5	11.97
Input temperature to gas turbine (K)	1474	1500
Input temperature to high pressure steam turbine (K)	783.	787.4
Condenser pressure (KP)	9.81	11.28
Input steam pressure into high pressure steam (KP)	8453	8346
Input temperature to low pressure steam turbine (K)	502	536.5
Input pressure into low pressure steam (KP)	660	626.6
Compressor air flow rate (Kg/S)	820	1000
Fuel flow rate(Kg/S)	20	15.06

TABLE III: Comparison of the Exergy Flow Value for the Initial and New Optimal States (*in $/year*)

Point	Initial state	Optimal state
C1	29599	12589
C10	155.8	115.3
C19	1298	1024
C20	17169	10373
C6	231	194.3
Cb	5.48	5.73
Cc	7.7	5.25
Cd	57. 52	30.97



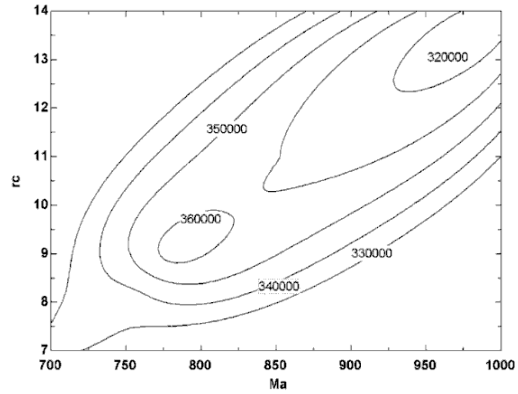


Fig. 2. Output power contour in terms of compression ratio and air flow rate

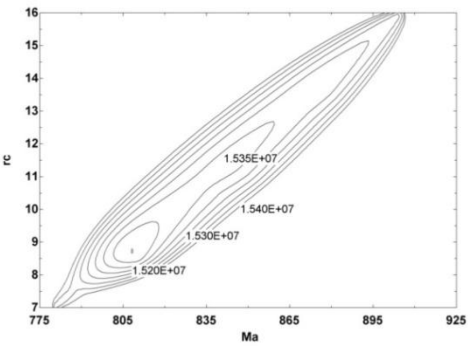


Fig. 3. Output power in terms of compression ratio and the place of maximum

VII. Conclusion

In this paper, with studying the first and second law of thermodynamics for Fars combined cycle power plant attempted to Thermodynamic analysis and Exergy that its result is determination of Exergy for different points of cycle by simultaneous equations. Now the mentioned cycle is Thermo economic analyzed, by help of these results and writing cost Balance for individual components, which finally has Thermo economic optimized with the Exergy flow rates for different parts of the cycle. That its result is Finding of Important design parameters including compression ratio and air flow rate of compressor for minimize the total cost and maximize the total power output. This work has been done the first time for Shiraz Combined Cycle Power Plant.

VIII. Nomenclature

BFP*:* Boiler Feed Pump
HRSG: Recovery boiler
HRSG: Recovery boiler
CCPP: Combined Cycle Power Plant
ST: steam turbine
Cond: condenser
ED: Exergy destruction
C: Cost
Z: Equipment Price
e: Exergy unit mass
E: Exergy
com: compressor
gt: gas turbine
g: exhaust gas
f: Fuel
cc: combustion chamber
$w_{net:}$ work output
hp: High pressure
lp: low pressure
s: Steam

References

[1] M. Ameri, P. Ahmadi, and S. Khanmohammadi, "Exergy analysis of a 420MW combined cycle power plant," *Int J. Energy Res*, vol. 32, pp. 175-83, 2008.

[2] A. R. Azimian, "Thermo economic analysis of power plant cycles," Isfahan University of Technology, 1382

[3] H. Kurt, Z. Recebli, E. Gredik, "Performance analysis of open cycle gas turbines," *Int J. Energy Res,* vol. 33, no. 2, 2009, pp. 285-94.

[4] I. Dincer, H. Al-Muslim, "Thermodynamic analysis of reheats cycle steam power plants," *Int J. Energy Res,* vol. 25, pp. 727-739, 2001.

[5] P. Ahmadi and I. Dincer, "Thermodynamic analysis and thermo economic optimization of a dual pressure combined cycle power plant with a supplementary firing unit," Department of Mechanical Engineering, Faculty of Engineering and Applied Science, University of Ontario, North, Oshawa, Canada, 2011.

[6] H. B. Avval, P. Ahmadi, A. R. Ghaffarizadeh, M. H. Saidi, "Thermo economicenvironmentalmultiobjective optimization of a gas turbine power plant with preheater using evolutionary algorithm," *Int J. Energy Res*, 2010.

[7] M. Ameri, P. Ahmadi, A. Hamidi, "Energy, exergy and exergo economic analysis of a steam power plant (a case study)," *Int J. Energy Res,* vol. 33, 2009, pp. 499-512.

[8] P. Ahmadi, I. Dincer, "Exergo environmental analysis and optimization of a cogeneration plant system using multimodal genetic algorithm (MGA)," *Energy*, vol. 35, no. 12, 2011, pp. 5161-5172.

[9] M. Amidpour, M. H. K. Manesh, "Multi-objective thermo economic optimization of coupling MSF desalination with PWR nuclear power plant through evolutionary algorithms," Energy System Department, Laboratory, K. N. Toosi University of Technology, Tehran, Iran, 2009

[10] M. S. Peters and K. D. Timmerhaus, *Plant Design and Economics for Chemical Engineers*, Fourth Edition, University of Colorado, McGraw-Hill, Inc.

[11] J. Lyons, C. W. White, "Process Equipment Cost Estimation Final Report," U.S. Department of Energy National Energy Technology Laboratory, Morgantown, January 2002

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