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Exergoeconomic Analysis of Gas Turbines Cogeneration Systems

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Abstract: Today, these countries consider energy optimization and management as a new energy resource. With respect to the increasing energy costs, costs reduction due to exergy fuel and loss is one of the greatest objectives of researchers and craftsmen. Exergoeconomic analysis helps designers find system performance in an affordable way that significantly contribute the analysis, design and optimization of thermal system. In the present study, the effect of various values of turbine input temperature, the ratio of compressor presser and output cooling temperature of generator to the second law return as well as the system costs rate have been investigated. In cycle optimization performed by genetic algorithm, after introducing the variables of designing and determining target functions, the optimal points indicating the highest return and the lowest costs rates were specified and the effect of each designing variables on target function were presented. As the findings revealed, total cost rate at the optimal state was reduced about 14% relative to the primary state. Also, it was found that there was a relation between unit cost and operational parameters change. Moreover, as the result of increasing compressor pressure, exergy losses at combustion chamber could be decreased, leading to the cost reduction.

Key words: Cogeneration system of CHP, gas turbine, compressor pressure and temperature, exergoeconomic analysis, design

INTRODUCTION

Given to the limitations of energy resources and fossil fuels, increasing demand of electricity as well as environmental and economic limitations, optimal designing gas turbine power plant cycle is necessary both technically and economically. Today, most of power generation installations are trying to improve the efficiency (or heat rate) in existing power generation stations. Most of them are above 25 year old.

Radcenco *et al.* (1998) studied optimization of a gas turbine power plant's simple cycle from the perspective of thermodynamics with respect to irrevocability related to pressure loss and resistances existing in fluid path. Badran examined various parameters such as environment's conditions, turbine input temperature, the ratio of component's efficiency to a gas turbine power plant cycle at three different function states. He also explored the performance of the power plant at three function states as well as fuel consumption, genitive power and thermal efficiency in functional conditions. In this study, the obtained results were compared with real data of the power plant. Bram and Ruyck analyzed exergy and gas turbine cycle design and presented their suggestion to improve the cycle with reflection. This cycle was practical in terms of affordability and efficiency improvement. Ahmadi *et al.* (2012) performed multi-objective exergy analysis based on a CHP system optimization for heat and cool generation. They also performed sensitivity analysis to observe changes in each design on the system performance through exergy and energy analysis.

Literature review: Produced warm water or stem can be directly used for heating utilities. In this case, due to the extraction of two useful energies of electrical and thermal from a fuel resource, the distributed generation system is called cogeneration (CHP) system (Karimi, 2008). Further, in case of employing a part of heat produced in absorption cool systems and supplying cool, in addition to electricity and heat, it is called Trigeneration (CHCP). Designing and employing cogeneration systems with dispersed power distribution policy can cause flue consumption ruction, environmental pollutions reduction and power access and safety increase in addition to the significant decrease of the costs of power generation, distribution and transfer. However, the important point is to apply this technology, proper energy management and optimization in designing and exploiting these systems.

Cogeneration systems that are responsible to simultaneously supply electrical, heating and cooling energies, due to high complexity in energy demand and supply, require making use of appropriate and optimal design to cause fuel consumption reduction in addition to timely and sufficiently supply needed energies. To this end, many methods and approaches have been proposed to design and optimize cogeneration systems. In this regard, various studies have been conducted which are briefly referred in the following.

In their study, Sahoo (2008) designed and optimized a cogeneration system to minimize investment costs and energy consumption with micro-turbine primary driver. In this research, they designed and optimized cogeneration system by annually considering electrical, heating and cooling energies demands. Arcuri *et al.* (2007) presented an optimal design of a Trigeneration system using mixed integer programming model. In this study, Trigeneration system was considered for hospital utility with gas-burning combustion engine's primary driver through its mathematical optimization method.

Piacentino and Cradona optimized power, heat and cool cogeneration system using thermodynamic analysis for hospital utility. In their study, an optimize Trigeneration system showed desirable and reasonale results. The obtained results were consistent with the real data. The primary driver of this system is internal combustion engine that leads to heat and cool generation in addition to employing reflective converter and absorption system (Cardona and Piacentino, 2006). Cardona *et al.* (2007) also conducted a study with the purpose of optimal design of a cogeneration system for building application. In this study, using thermodynamic method, an optimal design of a cogeneration system was presented to supply heating and cooling demands simultaneously with power generation with internal combustion engine primary driver for a hospital. Notably, Piacentino and Cradona conducted other studies on cogeneration system.

Thermodynamic or exergoeconomic provides engineers with an analytical tool to achieve results which have not been obtained through ordinary thermodynamic analyses. Thermodynamic is based on the fact that exergy is the only foundation to allocate costs due to thermodynamic systems inefficiency. Generally speaking, thermodynamic science aims at minimizing costs through exergy principles.

MATERIALS AND METHODS

Thermodynamic modeling: Energy balance equations for various parts of power plant have been shown in Fig. 1.

Air compressor:

$$T_2 = T_1 \left\{ 1 + \frac{1}{\eta_{AC}} \left[\left[\frac{P_2}{p_1} \right]^{Y_0 - 1/Y_0} - 1 \right] \right\}$$

$$\dot{W}_{AC} = \dot{m}_0 C_{pp} (T_2 - T_1)$$

As shown in the following, in our analysis, air compressor has been considered as a variable of temperature function (Fig. 1):

$$C_{Pa} = 1.04841 - \left(\frac{3.8371T}{10^4} \right) + \left(\frac{9.4537T2}{10^7} \right) - \left(\frac{5.49031T^3}{10^{10}} \right) + \left(\frac{7.9298T^4}{10^{14}} \right)$$

Combustion chamber:

$$\dot{m}_a h_2 + \dot{m}_f LHV = \dot{m}s h_3 + \dot{Q}_{1,CC}$$

$$P_3 = P_2 (1 - \Delta P_{CC})$$

Combustion equation can be written as following:

$$fCH_4 + x^0_{o_1} O_2 + x^0_{N_2} N_2 + x^0_{CO_2} CO_2 + x^0_{H_2O} H_2O \rightarrow (f + x^0_{CO_2}) CO_2 + (2f + x^0 H_2O + (x^0_{H_2O} + 2f) O_2 + x^0_{O_2} N_2$$

$$f = \frac{n_{fuel}}{n_{air}}$$

Gas turbine:

$$T_4 = T_3 \left\{ 1 - \eta_{GT} \left[1 - \left[\frac{P_3}{P_4} \right]^{-1 - \gamma_\varepsilon / \gamma_\varepsilon} \right] \right\}$$

$$\dot{W}_{GT} = \dot{m}_g C_{p,g} (T_3 - T_4)$$

$$W_{net} = \dot{W}_{GT} - \dot{W}_{AC}$$

$$\dot{m}_g = \dot{m}_a + \dot{m}_f$$

As following, C_{pg} has been reconsidered as a variable of temperature function (Kurt *et al.*, 2009):

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

It should be considered that thermodynamic model has been expanded based on the following assumptions (Regulagadda *et al.*, 2010):

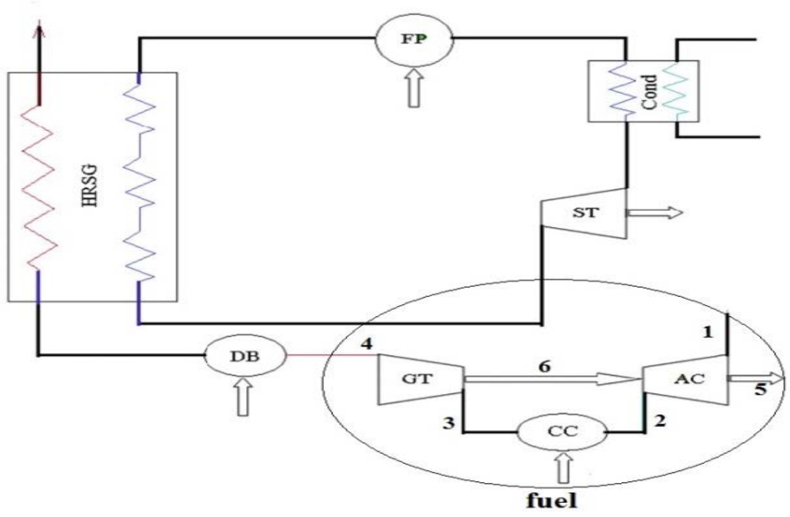

Fig. 1: Gas turbine power plant cycle

- All the processes of steady state have been considered
- The mixture of air and combustion products has been regarded as ideal gas
- The fuel injected into the combustion chamber has been regarded as ideal gas
- Thermal loss from the combustion chamber has been considered as much as 3% of the fuel low thermal value
- Dead state conditions are P0 = 1.013 bar and T0 = 293.15 k
- Cpa and Cpg have been considered as temperature-dependent

RESULTS AND DISCUSSION

Exergeoeconomic analysis

Economic model: The second law of thermodynamics mixed with economic science provides a very powerful tool for systematic study and optimization of energy systems. Such a mixture has formed the basis of a relatively new field of thermodynamics, namely exergeoeconomic. Besides this model, the economic model computes the cost of some parts including depreciation, maintenance and fuel combustion cost. In order to define a cost function which depends on considered optimization parameters, the cost of the parts should be stated as a function of thermodynamic design parameters.

Applying balance equations indicates the cost of kth part of the system such that the sum of cost rate with all existing exergy paths equals the sum of cost rate with all input exergy paths in addition to the allocated cost due to investment, operation and maintenance cost. The sum of the last terms is specified with Z_k. for each flow line in the system, a parameter called flow cost rate $\dot{C}(\$/s)$ has been defined and cost balance equation of each part can be written as following (Bejan *et al.*, 1996):

$$\sum_{e}\dot{C}_{e,k}+\dot{C}_{w,k}=\dot{C}_{q,k}+\sum_{i}\dot{C}_{e,k}+Z_k \;*$$

Cost balances are usually written such that all terms are positive. Using the equation*, the following equation can be obtained (Ahmadi and Dincer, 2011a, b):

$$\Sigma\left(c_e\dot{E}_e\right)_k+C_{w,k}=C_{q,k}\dot{E}_{q,k}+\Sigma\left(c_i\dot{E}_i\right)_k+\dot{Z}_k$$
$$\dot{C}_j=c_jE_j$$

Cost balance equations for all parts of the system form a set of non-linear algebraic equations which was solved for C_j and c_j. In this analysis, the worthy point is that the exergy of fuel and product should be determined. Both product and fuel are stated in exergy terms. Cost rate with fuel $\dot{c}_f$ and product $\dot{c}_P$ of a part is obtained by replacing exergy rate Ex_D. A combination of energy balance and exergeoeconomic balance can be obtained through the following equation:

$$\dot{E}x_{F,k}=\dot{E}x_{p,k}+\dot{E}x_{D,k}$$

Where:

$E\dot{x}_{f,k}$ = Fuel exergy rate for the kthpart
$E\dot{x}_{P,k}$ = Implies exergy rate of the kth part
$Ex_{L,k}$ and $Ex_{D,k}$ = Exergy loss rate and exergy loss of that part

For example, $Ex_{L,k}$ denotes the useful energy (exergy) which is wasted through the environment and $Ex_{D,k}$ denotes exergy loss due to irrevocability. For turbines, if the processes are assumed adiabatic, $Ex_{L,k}$ equals zero. Further, if pumps are adiabatic, equals zero. Additionally, for heaters, if it is assumed they act adiabatically, $Ex_{L,k}$ equals zero. For each flow line in the system, a parameter called flow cost rate C(D, k) has been defined as follows:

$$C_{D,k} = C_{F,K} E_{D,K}$$

Further details about exergeoeconomic analysis, cost balance equations and exergeoeconomic coefficient are explained in resources (Ameri *et al*., 2009). Generally, several methods have been suggested to state the cost of purchasing equipments based on the design parameters in equation * (Cihan *et al*., 2006). However, we employed the cost function proposed by Rowzen. To change investment cost into cost (T), it can be written:

$$Z_k = Z_k \mathrm{CRF}\phi / (N \times 3600)$$

Appendix A contains the abbreviations of each part of gas turbine power plant and economic model. N indicates the number of working hours per year and φ = 1.06 indicates maintenance and repair coefficient. Finally, to determine exergy loss cost of each part, the value of exergy loss, $Ex_{D,k}$, has been calculated through exergy balance in the previous section. Capital Recovery Factor (CRF) to the considered rate as well as the equipments shell life estimation, CRF is determined using the following equation:

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

As shown in the above equation, i indicates the considered rate and n denotes total working period of the system in a year.

Cost balance equations: To estimate exergy loss cost in each part of the power plant, cost balance equations should be firstly solved for each part; therefore, in using cost balance equation (equation *), there are usually more than one input and output path for some parts. In this investigation, the number of unknown cost parameters is more than the number of cost balance equations for that part. Complementary exergeoeconomic equations have been expanded to solve this problem. For each part, with system complementary equations, linear equations form the following:

$$[\dot{E}_k] \times [C_k] = [\dot{Z}_k]$$

Where [$\dot{E}_k$], [C_k], [$\dot{Z}_k$] introduce exergy rate matrix obtained in exergy analysis, exergetic cost vector and coefficient vectors [$\dot{Z}_k$] obtained in economic analysis, respectively:

$$\begin{pmatrix} 1 & -1 & 0 & 0 & 0 & 1 & 0 \\ 0 & 1 & -1 & 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & -1 & -1 & -1 & 0 \\ 0 & 0 & 0 & 0 & -E_6 & E_5 & 0 \\ 0 & 0 & E_4 & -E_3 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} c_1 \\ c_2 \\ c_3 \\ c_4 \\ c_5 \\ c_6 \\ c_7 \end{pmatrix} = \begin{pmatrix} -\dot{Z}_{AC} \\ -\dot{Z}_{CC} \\ -\dot{Z}_{GT} \\ 0 \\ 0 \\ 0 \\ \dot{C}_f \end{pmatrix}$$

Accordingly, solving these equations set, cost rate of each cycle line can be found. Exergeoeconomic analysis and optimization was performed for the sample turbine power plant with the capacity of 150 MW. The obtained results revealed that in cycle analysis and design, the gas turbine input temperature should be selected greater however with respect to the limitation of alloys and high price of gas turbine, this fact is allowed up to 1500°C. On the other hand, since the increase of compressor pressure leads to the decrease of exergy losses in combustion chamber, exergy losses cost is subsequently decreased.

Optimization: Now, a target function is defined as the sum of three parts; operating costs rate depends on fuel cost; capital cost rate implies investment cost and maintenance and repair cost, according to cost for exergy loss. Hence, target function shows total cost rate of the power plant (dollar/time) which is stated as following:

$$\dot{C}_T = c_f \dot{m}_f \mathrm{LHV} + \Sigma \dot{Z}_k + \Sigma \dot{C}_{D,k}$$

In this equation, c_f = 0.004 (\$/MJ) is regional fuel cost in energy unit (Valero *et al*., 1994); m_f indicates fuel mass flow rate and LHV = 50000 (kJ kg^{-1}) denotes low thermal value of methane. Since, the final value of products (net power and process stem) are constant, target function should be minimized such that the optimal value of design parameters can be obtained:

$$\dot{C}_f = c_f \dot{m}_f \mathrm{LHV}$$

Where $\dot{Z}_k$, $\dot{C}_f$ and $\dot{C}_D$ introduce the cost of purchasing each part, fuel cost and exergy loss cost, respectively.

Decision making variables: In this study, decision making variables (design parameters) were investigated as

Table 1: List of limitations

Reason of limitaions	Limitaions
Commercial access	$6 \le r_p \le 16$
Materials limitaions	$1200 \le T_3 \le 1800$
Commercial access	$0.7 \le \eta_{AC} \le 0.9$
Commercial access	$0.7 \le \eta_{GT} \le 0.92$

Table 2: Costing each of direct flows

Path numbe r	($\dot{\$}$ / s)	Path number	($\dot{\$}$ / s)
1	0	5	2.2113
2	1.5409	6	1.5409
3	5.462	7	3.9211
4	1.7097	-	-

Table 3: Fuel and product definition for various components

Component	Fuel	Product
Compressor	$\dot{E}_6$	$\dot{E}_2$-$\dot{E}_1$
Combustion chamber	$\dot{E}_7$	$\dot{E}_3$-$\dot{E}_2$
Gas turbine	$\dot{E}_3$-$\dot{E}_4$	$\dot{E}_5$-$\dot{E}_6$

following: Air compressor pressure ratio (r_{AC}), compressor isentropic return (η_{AC}), gas turbine isentropic return (η_{GT}) and gas turbine input temperature (T_3). Although, decision making variables may be different in optimization method, each of the variables isnecessarily required to be at a rational area. Table 1 presents a list of these variables and the reasons of applying them.

Genetic algorithm: During the recent years, optimization algorithms have been highly considered by researchers and craftsmen. This method can be classified into nature-inspired optimization methods. Genetic algorithm is one of the empirical or random optimization methods. Since, it has no need to analytical relations (closed mathematical formulas) but it analyzes system behavior, it can be applied for all systems (Table 2).

Genetic algorithm, in general has been composed of three main operators including selection, crossover and mutation. As an appropriate feature of genetic algorithm, it can be referred to the fact that compared to finite algorithms, it is less influenced by target function form. Accordingly, the factors such as the high number of local optimums, wide search space dimensions, non-derivation (regarding discontinuous functions) and such similar problems in implementing other algorithms cannot disturb the convergence of genetic algorithm. Fuel and product for each component have been shown in Table 3. Figure 2 presents the diagram of generation production based on target function value.

As the findings revealed, total cost rate, at the optimal state, has been decreased about 14% relative to the primary state (1.739) (Table 4). Design variables in both primary and optimized states have been presented in Table 5. The primary and optimized values of several parameters have been shown in Table 6. Also, the obtained results revealed that the values should be increased relative to compressor pressure since, the increase of compressor pressure leads to the decrease of exergy losses in combustion chamber and exergy losses cost is subsequently decreased.

Table 4: Comparing design variables

Decision variable	Case study	Optimization result
T_3(K)	1433.15	1451.57
P_2/P_1	10.644	15.798
	87.59	84.47
	90.19	89.57

Table 5: Comparing the results of primary and optimal design states

Bases	Optimum	Variation (%)
1.793	1.5251	-14.94
1.5125	1.4434	-4.74
0.2805	0.1397	-50.19

Table 6: Investment cost of each component of the power plant

System component	Capital or investment cost function
Air compressor	$Z_{AC} = (C_n m)/C_{12}-\hat{\eta}_{AC}(P_2/P_1)$ In $((P_2/P_1)$
Combustion chamber	$Z_{ac} = (C_{23} m/C_{22}-P_3-P_2)[1+EXP(C_{23}T_4-C_{24})]$
Gas turbine	$Z_{GT} = C_{32} m_g/C_{32}-\hat{\eta}_{GT})$ In $(P_3/P_4)[1+EXP(C_{33}T_3-C_{34}$

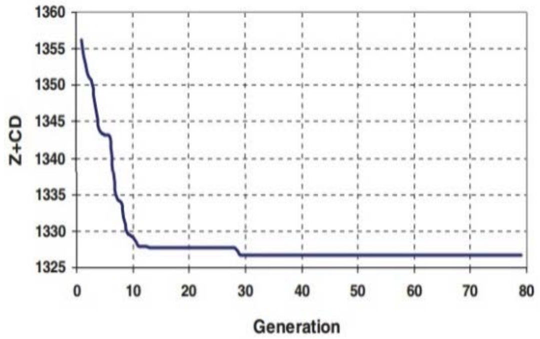

Fig. 2: The process of generation production in genetic algorithm and target function value

CONCLUSION

In addition to decreasing costs due to power transfer and distribution in network as well as decreasing heavy costs of large power plants in constructing, exploiting and marinating, employing cogeneration systems to supply energy required by residential sector causes to the decrease of fuel consumption and the increase of energy exploitation in the complex.

In the present study, for exergy analysis of the power plant, exergy of each path was computed at all states and exergy changes were determined for each main part. Deign variables were optimized such that they can present the best performance. Genetic algorithm was used for this optimization. This optimization result shows the decrease in total cost. The highest decrease pertains to capital cost rate.

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