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Thermodynamic modelling, energy and exergoeconomic analysis and optimization of Mahshar gas turbine power plant

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Abstract: The objective of this paper is to optimize the gas turbine cycle through exergy and exergoeconomic. The optimization procedure is an evolutionary algorithm (i.e. Genetic Algorithm). The optimization program is developed in Matlab Software programming. Therefore; like each optimization problem, the design Parameters of the plant, were chosen as: compressor pressure ratio (r_C), compressor isentropic efficiency (η_C), gas turbine isentropic efficiency (η_{GT}), combustion chamber inlet temperature (T_3), and turbine inlet temperature (T_5). In order to optimally find the design parameters a thermoeconomic approach has been followed. An objective function, representing the total cost of the plant in terms of dollar per second, was defined as the sum of the operating cost, related to the fuel consumption. Finally, the optimal values of decision variables were obtained by minimizing the objective function using Evolutionary algorithm such as Genetic Algorithm. At the end of this paper the variation of decision variable and exergy destruction of each component were estimated by the variation of fuel cost.

Keywords: Exergy, optimization, Decision variable, Genetic Algorithm, Exergy destruction

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1 INTRODUCTION

Gas turbine power plant is one of the most important power generation units that are used. The combined cycles (CC) use the exhaust heat from the gas turbine engine to increase the power plant output and boost the overall efficiency to more than 50%. will not be accepted for process if they are not prepared in accordance with the required format.

The power generation industry uses a large amount of the primary energy demand in the European Union and power generation from gas turbine and combined heat & power systems are an important and growing part of it. Therefore, there is a continuing need for improved energy efficiency, coupled with a pressing need to reduce toxic and noxious emissions. Gas turbines have three application areas: First one is open cycle gas turbines, which produces only power, second one is cogeneration systems in which heat and power are produced together and the third one is combined cycle systems in which gas turbines and steam turbines are used together. Although the thermal efficiency of the open cycle gas turbine systems is very low, they are preferred to supply peak loads since they can be brought up to operation fast and their costs are considerably lower than that of the other systems [1–4].

Badran [2] discussed the effect of the major parameters, such as pressure ratio (P_R), compressor and turbine inlet temperatures (TIT), turbine and compressor efficiency, combustion efficiency, specific fuel consumption and cost of power generation on the thermal efficiency. The values of these parameters can be calculated using same basic cycle equations and assuming constant values for the thermodynamic properties. Nowadays, developing techniques for designing efficient and cost-effective energy systems is one of the foremost challenges energy engineers face. In a world with finite natural resources and increasing energy demand by developing countries, it becomes increasingly important to understand the mechanisms which degrade energy and resources and to develop systematic approaches for improving the design of energy systems and reducing the impact on the environment. The second law of thermodynamics combined with economics represents a very powerful tool for the systematic study and optimization of energy systems. This combination forms the basis of the relatively new field of thermoeconomics [5].

Exergy analysis based on the first and second thermodynamic laws is a significant tool to analyze the energy systems. It also reveals the inefficient thermodynamic processes. Recently, exergy analysis has become a key issue in providing a better understanding of the processes, to quantify sources of destruction is well-known that the exergy can be used to determine the location, type and true magnitude of exergy loss (or destruction). Thus, it can play an important role in developing strategies and in providing guidelines for more effective use of energy in the existing power plants [7]. Moreover, another important issue for improving the existing system is the origin of the exergy loss. Hence, a clear picture, instead of only the magnitude of exergy loss in each section, is required. Exergy analysis is very important in power generation systems. A lot of researchers like Dincer [6], Kotas [8], Fischer [9], Ameri [10], Cihan [11] and Habib [12] have carried out the exergy analysis for power plants. On the other hand, Exergoeconomic is going to be more popular than exergy analysis because it combines the thermodynamic & economic with each other. First introduction of exergoeconomic was introduced in a paper at a conference which was held in 1994.

In 1990, a group of concerned specialists in the field [13-16] decided to compare their methodologies by solving a predefined and simple problem of optimization: the CGAM problem, which was named after the first initials of the participating investigators. The objective of the CGAM problem is to show how the methodologies are applied, what concepts are used and what numbers are obtained in a simple and specific problem. In the final analysis, the aim of the CGAM problem is the unification of thermoeconomic methodologies. This comparison is not a competition among methodologies. Each methodology has specific fields of applications for which it provides proven and efficient solutions. The CGAM problem refers to a cogeneration plant which delivers 30 MW of electricity and 14 kg/s of saturated steam at 20 bar. The structure of the cogeneration plant is shown in Fig. 2. The installation consists of a gas turbine followed by an air preheater that uses part of the thermal energy of the gases leaving the turbine, and a heat-recovery steam generator in which the required steam is produced. The environmental conditions are defined as To = 298.15K a.nd P, = 1.013 bar. The fuel for the total plant is natural gas (taken as methane) with a lower heating value (LHV) equal to50000 kJ/kg. In the present work, like CGAM problem, firs each part of the gas turbine power plant is modelled and the each part of the objective function is expressed based on the thermodynamic modelling and decision variables. For having a good insight of this study, exergy analysis is performed to this problem and exergy destruction of each part of Mahshar (i.e. The north part of Iran) gas turbine power plant is estimated and those components which have the greatest exergy destruction are selected and some suggestions are given in order to have a cycle which has the less exergy destruction and high efficiency. For verification of the developed simulation code, modelling part is compared with the actual amount of a running gas turbine power plant in Iran. A modified in-house developed version of Genetic Algorithm which guaranteed, the quick convergence of results in smaller generation numbers was applied. The variations of optimum design values with number of generation when convergence reached are shown. The effect of variation of fuel cost on the amount of design parameters is shown.

2 EXERGY ANALYSIS

Exergy is composed of two important parts. The first one is the physical exergy and the second one is the chemical exergy. In this study, the kinetic and potential parts of exergy were assumed to be negligible. The chemical exergy was associated with the departure of the chemical composition of a system from its chemical equilibrium. The chemical exergy was an important part of exergy in combustion process [8]. For analyzing the thermal systems, one should consider the first and second laws of thermodynamic together. The first law is used for energy balance for each part in HRSG and the second law was used for finding the exergy destruction from the following relation [17].

If one applies the first and second laws of thermodynamics, one can find the formula for exergy balance as the following [17]:

$$\dot{E}_Q + \sum_i \dot{m}_i e_i = \sum_e \dot{m}_e e_e + \dot{E}_W + \dot{E}_D \qquad (1)$$

Where subscripts i and e refer to streams entering and leaving the control volume, respectively. The exergy rate of a stream of substance (neglecting the potential and kinetic components) can be written in the form:

In this equation, (e) is the total specific exergy and is the exergy destruction.

$$\dot{E}_Q = \left(1 - \frac{T_\circ}{T_i}\right)\dot{Q}_i \qquad (2)$$

$$\dot{E}_W = \dot{W} \qquad (3)$$

$$e_{ph} = (h - h_\circ) - T_\circ(S - S_\circ) \qquad (4)$$

Where T is the absolute temperature (K) and subscripts (i) and (o) refer to inlet and ambient conditions respectively.

$$\dot{E} = \dot{E}_{ph} + \dot{E}_{ch} \qquad (5)$$

Where $\dot{E} = \dot{m}e$ The mixture chemical exergy is defined as follows [8]:

$$ex^{ch}_{mix} = \left[\sum_{i=1}^{n} X_i ex^{ch_i} + RT_0 \sum_{i=1}^{n} X_i Ln X_i + G^E\right] \qquad (6)$$

The last term, G^E, which is the excess free Gibbs energy is negligible at low pressure at a gas mixture. One can generalize the chemical exergy concept of fuel to every $C_\alpha H_\beta N_\gamma O_\delta$ component [17]. The molar chemical exergy ex_c^{ch} of such a component will be:

$$ex_c^{ch} = (\mu_{c,0} - \mu_c^e) \qquad (7)$$

For the evaluation of the fuel exergy, the above equation can not be used. Thus, the corresponding ratio of simplified exergy is defined as the following:

$$\xi = ex_f / LHV_f \tag{8}$$

Due to the fact that for the most of usual gaseous fuels, the ratio of chemical exergy to the Lower Heating Value is usually close to 1, one may write [2]:

$$\xi_{CH_4} = 1.06$$
$$\xi_{H_2} = 0.985 \tag{9}$$

For gaseous fuel with CxHy, the following experimental equation is used to calculate ξ [3]:

$$\xi = 1.033 + 0.0169\frac{y}{x} - \frac{0.0698}{x} \tag{10}$$

In the exergy analysis of power plants, the exergy of steam is calculated at all states and the changes in the exergy are determined for each major component. The source of exergy destruction (or irreversibility) in combustion chamber is mainly combustion (chemical reaction) and thermal losses in the flow path respectively. However, the exergy destruction in the heat exchangers of the system i.e. compressor, air preheater, is due to the large temperature difference between the hot and cold fluid.

3 Thermodynamic modelling of gas turbine power plant

Having known the values of decision variables (rc, ηac, ηgt, T3 and T5)for a set of fixed demands of electrical power and process steam, the values of temperature and pressure in all lines of system, shown in figure(1), can be computed. Consequently, the value of fuel mass flow rate (m_f), which should be expressed in terms of decision variables, is determined. The relations of thermodynamic modelling are as follows:

Air compressor

$$T_2 = T_1\left\{1 + \frac{1}{\eta_{AC}}\left[r_c^{\frac{\gamma_a - 1}{\gamma_a}} - 1\right]\right\} \tag{11}$$

$$\dot{W}_{AC} = \dot{m}_a . C_{p,a}(T_2 - T_1) \tag{12}$$

Air preheater

$$\dot{m}_a(h_3 - h_2) = \dot{m}_g(h_6 - h_7) \tag{13}$$

$$\frac{P_3}{P_2} = (1 - \Delta P_{aph}) \tag{14}$$

Combustion chamber

$$\dot{m}_a h_3 + \dot{m}_f LHV = \dot{m}_g h_5 + (1 - \eta_{cc})\dot{m}_f LHV \tag{15}$$

$$\frac{P_4}{P_3} = (1 - \Delta P_{cc}) \tag{16}$$

Gas Turbine

$$T_6 = T_5\left\{1 - \eta_{gt}\left[1 - \left(\frac{p_5}{p_6}\right)^{\frac{1-\gamma_g}{\gamma_g}}\right]\right\} \tag{17}$$

$$\dot{W}_{gt} = \dot{m}_a . C_{p,g}(T_5 - T_6) \tag{18}$$

3.1 Objective Function

The objective function is defined as the sum of three parts; the operational cost rate, which is related to the fuel expense, the rate of capital cost which stands for the capital investment and maintenance expenses, and the corresponding cost for the exergy destruction. Therefore, the objective function represents total cost rate of the plant in terms of dollar per unit of time.

$$O.F = c_f \dot{m}_f LHV + \sum \dot{Z}_k + \sum \dot{C}_{D,k} \tag{19}$$

Since the amount of ultimate products (net power and process steam) are fixed, the objective function is to be minimized so that the values of optimal design parameters would be obtained. For calculating the rate of operating cost equation, we have:

$$\dot{C}_f = c_f \dot{m}_f LHV \tag{20}$$

In which c = 0.003 $/MJ is the regional cost of fuel per unit of energy, $\dot{m}_f$ is the fuel mass flow rate, and LHV = 50000 kJ/kg is the lower heating value of Methane.

For expressing the purchase cost of equipment in terms of design parameters, several method have been suggested [5, 13, and 16]. In this paper we used the cost functions mentioned in Ref. [5]. However, some modifications were made to tailor these results to the regional conditions in Iran and taking into account the inflammation rate. For converting the capital investment into cost per time unit:

$$\dot{Z}_k = Z_k.CRF.\varphi/(N \times 3600) \tag{21}$$

Where, Z_k is the purchase cost of kth component in dollar, CRF (18%) is the capital recovery factor, N is the annual number of the operation hours of the unit (7500 hr), and φ (1.06) is the maintenance factor. Finally, in order to determine the cost of exergy destruction of each component, first the value of exergy destruction, $E_{D,K}$, were computed using exergy balance equation:

$$\dot{E}_{D,K} = \dot{E}_{F,K} - \dot{E}_{P,K} - \dot{E}_{L,K} \tag{22}$$

Where $E_{F,K}$ represents the fuel exergy rate for kth component, and $E_{P,K}$ stands for the product exergy rate of kth component, $E_{L,K}$ and $E_{D,K}$ are exergy lost and exergy destruction rate of that component respectively. For each flow line in the system, a parameter called flow cost rate C ($/sec) is defined. Subsequently, the cost balance equation is applied to each component, in form of:

$$\dot{Z}_k + \sum \dot{C}_{in,,k} = \sum \dot{C}_{out,k} \tag{23}$$

$$\dot{C}_j = c_j E_j \tag{24}$$

In which C_j and c_j are, flow cost rate and unit cost of exergy for the jth flow line respectively. After writing the cost balance equation for all components of the system, a set of linear algebraic equations was formed and solved for C_j and c_j. Finally the rate of exergy destruction in each component is defined as fallows

$$\dot{C}_{D,k} = c_{F,k}\dot{E}_{D,k} \qquad (25)$$

In which $C_{D,K}$ is the cost rate of exergy destruction in kth component ,and cF,k is the cost per unit of exergy of the line entering the kth component. Hence, for a group of decision variables (design parameters) the value of $\sum \dot{C}_{D,k}$ for the whole system was determined.

4 Evolutionary algorithms

Evolutionary algorithms apply an iterative, stochastic search strategy to find an optimal solution (Fig. 2). Principles of biological evolution are imitated in a very simplified manner. Characteristic feature of an evolutionary algorithm is a population of individuals. An individual consists of the values of the decision variables (here: structural and process variables) and is a potential solution to the optimization problem. A “black box” model of the power plant and an objective function are used to evaluate the fitness of each individual. Pairs of individuals are selected to create new individuals based on their performance to optimize the objective function. In general, a constant number of individuals constitute the population in which deterministic and stochastic operators select and manipulate parts of the individuals. Individuals of the initial population are often generated randomly, but the results of previous optimization runs or expected optimal solutions might also be included. Each individual is evaluated to calculate its fitness. Here, the evaluation involves the simulation of the thermodynamic behaviour of the power plant, estimates for the purchased-equipment costs, and an economic analysis. Additional penalty terms are added to the fitness value if an individual violates any constraint. After a fitness value has been assigned to each individual in the initial population, some of the individuals are selected for the mating pool. Better individuals are given more opportunities to contribute to the next generation of new individuals (“survival of the fittest”). Next, recombination and mutation operators are applied to the individuals in the mating pool, producing the off springs. These operators randomly combine and slightly modify the decision variables of different individuals in the mating pool so that an offspring might achieve a better fitness than its parents. Since the evolutionary algorithm maintains a fixed-size population, individuals with a higher fitness value are selected with a higher probability for the next generation (replacement, Fig. 2). The iteration loop is repeated several times until the maximum number of generations is reached. Evolutionary optimization techniques include genetic algorithms and evolution strategies among others. A detailed introduction to evolutionary computation is presented in [18, 19]. Choosing appropriate parameter settings for the evolutionary algorithm is a time-consuming task and many times the result of trial-and-error. Preliminary examinations have shown [20] that, in this application, the diversity in a single population quickly decreases and the algorithm converges to a suboptimal solution. An individual with a new process structure, even the optimal one, might need a few generations to improve the values of its process variables and to be competitive with the best individuals in the population. However, the best existing individual generates several offspring of good performance. The individual with the new process structure is often inferior to these solutions and is quickly removed from the population.

5 Power Plant specification

A schematic of a 120-MW gas turbine system is given in Figure 1 and shows the main work and exergy flows and the state points which we accounted for in this analysis. The system consists of an air- compressor (AC), a combustion chamber (CC), an air-preheater (APH), and a gas-turbine (GT). The mass flow rate of air to the compressor at is 497 kg/s. By means of thermodynamic modelling which has been introduced in section 3, one can calculate the properties of each line of figure (1). For having a good insight of our study, the results of thermodynamic simulation were compared with the actual properties of each line of this power plant. The results of both types are shown in figure (3). To verify the correctness of the modelling output results, they were compared with the measured outputs obtained from an actual running gas turbine power plant (Mahshahr Power Plant with 116 MW power output, North of Iran). The temperature profile of this plant obtained by the simulation program of the measured results compared and shown in figure (3) the average difference value of two groups of results was about (10.1%) with the maximum value of 20% in gas turbine exit temperature. This verifies the correct performance of the developed simulation code to model the thermal performance of gas turbine cycle.

6 Results and discussions (Optimization)

In this study both optimization and exergy analysis of one of the largest gas turbine power plants in Iran was performed. The objective function which is given to evolutionary algorithm (i. e Genetic Algorithm) is considered here. As it was mentioned in part (3.1) the objective function is a summation of three important parts. The convergence of objective function is shown in figure (4). As it is shown in this figure the objective function is reached to the final amount after almost 70 generations. It looks as if our developed code has a powerful converge and it is well-developed. Moreover, the variation of each decision variable versus number of generation is shown in figure(5-9). As it is clear in these mentioned figures, in first 50 generations the variation of decision variables are much more than other generation numbers because searching in first intervals are more sensitive. Thus, after some generations the objective function finds the real decision variables. The optimization code which is Genetic Algorithm is so accessible because the number of generation is considered as an input. This input generation number strongly depends on the configuration of power cycle and our constraints. Therefore, the number of generations almost 300 is found suitable for this problem. On the other hand, in Iran the cost of fuel varies every year. Thus, the effect of variation on decision variables versus unit cost of fuel is a good tool for estimating them in order to have a good insight of our study. These results are shown in figures (10-15). Furthermore, the variations of the optimal decision variables versus unit cost of fuel reveal that by increasing the fuel cost, the pressure ratio rc (Fig.10), compressor isentropic efficiency ηAC (Fig.11), turbine isentropic efficiency ηT (Fig.14) and combustion chamber inlet temperature T3 (Fig.12) increase. Bigger ηAC and ηT guarantee less exergy destruction in compressor and turbine as well as less net cycle fuel consumption and operating cost. Increasing T5, also decreases the exergy destruction in combustion chamber and saves fuel consumption as well. However, due to the fact that any increase in T5 increases the turbine and combustion chamber investment costs, T5 can only increase within a certain limit. By increasing the above design parameters the capital cost of components (equipment) increase. These costs in summation with the operational cost were minimized using GA optimization technique. When, the cost of fuel increases the value of objective function decreases. By increasing the fuel cost the value of objective function increases thus in this case Genetic Algorithm works by finding a less mass fuel rate of combustion chamber because in Eq(17) the first term deals with mass flow rate. Thus, by increasing Cf the second part of Eq(17) increases so the decision variables should be selected in the way that the mass flow rate of combustion chamber decreases. Furthermore, the variation of objective function versus fuel cost is shown in Figure (15).

It should be noted that with obtaining the optimum values of the design parameters, one may choose an available system in the market with specifications as close as possible to the optimum designed one. Furthermore, one may input the data provided by manufacturers into simulation program and choose a gas turbine system among the others, which provides the lowest values of the objective function.

7 Exergy results

In this part of the paper we focus on the concept of exergy. Therefore, by using the Eq(1) for each part of this power plant, exergy destruction of them is determined.

Figure (16) shows the exergetic efficiency of components of the gas-turbine plant. The exergetic efficiency of the total plant is also shown: it amounts to 36.08%. It is shown that the exergetic efficiency of the combustion chamber is much lower than that of other plant components, due to the high irreversibility in the former.

In comparison with other plant components, the combustion chamber destructs the largest amount of total inlet exergy into the plant, as shown in Figure (16). This figure shows also that 84.01% of the total inlet exergy is wasted in the plant.

The variation of exergy destruction and exergy destruction versus unit cost of fuel in compressor is shown in fig(17) .As it is clear in this figure, by increasing the cost of fuel the exergy efficiency of compressor increases because in Eq(17) the third term represents the cost of exergy destruction. Thus, in this way the exergy destruction should decrease in order to decrease the objective function. Figure (18) shows the variation of combustion chamber exergy destruction and exergy efficiency of combustion chamber. It is obvious that by increasing the unit cost of fuel, the combustion chamber inlet temperature increases so the exergy destruction of this part is decreased too. Thus, in order to have an optimized gas turbine power plant one thing which plays a key issue is exergy destruction of the total plant.

7 Conclusion

1- The determined optimum design parameters for gas turbine plant apparently show a trade-off between thermodynamically and economically optimal designs. For example, from thermodynamic point of view, the decision variable ηac should be selected as high as possible while this leads to an increase in capital cost. It should be noted that any change in the numerical values of a decision variable not only affects the performance of the related equipment but also all the performance of other equipments as well.

2- It can be deduced from the Figures (10-15) that by increasing the fuel price the values of decision variable in thermoeconomically optimal design tend to those of thermodynamically optimal design.

3. Having been discussing about exergy analysis, we can conclude that in gas turbine power plant the exergy destruction of combustion chamber is much more than other components .It is due to the fact that the combustion reaction and its high temperature are the most significant sources of exergy destruction in the combustion chamber which can be reduced by increasing the gas turbine inlet temperature. On the other hand, we know that there is a limitation of increasing the turbine inlet temperature due to the fact that iron does not stand high temperature. Therefore, in this regard, GT turbine blade cooling is very important. The effect of blade cooling technologies on gas turbine exergy destruction cab

be discussed in others researches.

8 Figures:

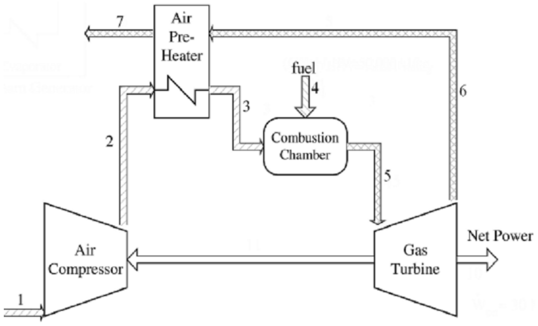

Figure (1): Schematic diagram of gas turbine power plant

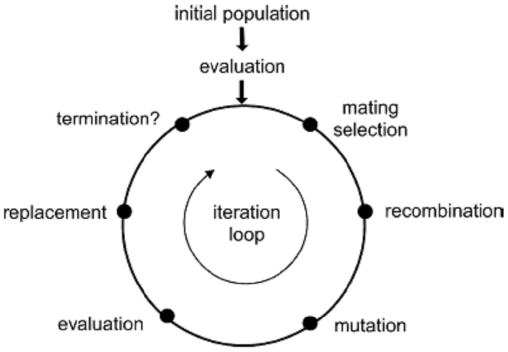

Figure (2): Basic concept of evolutionary algorithm.

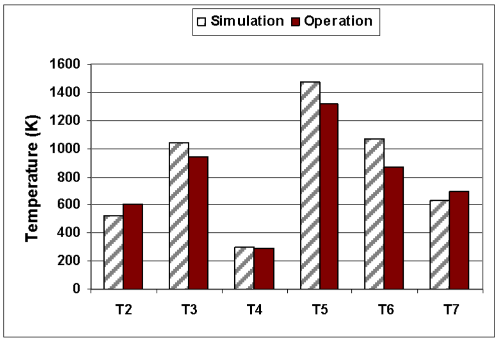

Figure (3): Variation of gas temperature in each line of the gas turbine power plant

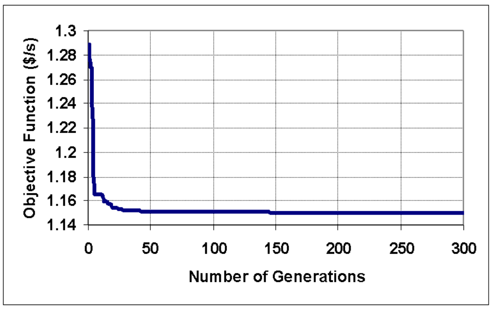

Figure (4): Convergence of objective function after each generation.

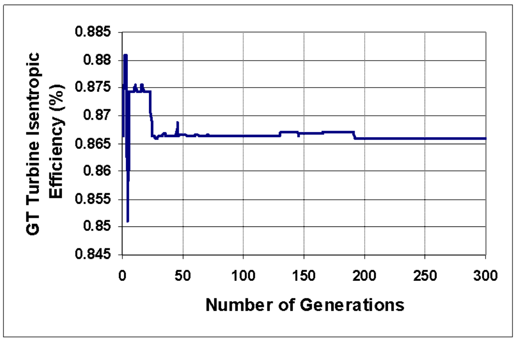

Figure (9): Variation of gas turbine isentropic efficiency with generations.

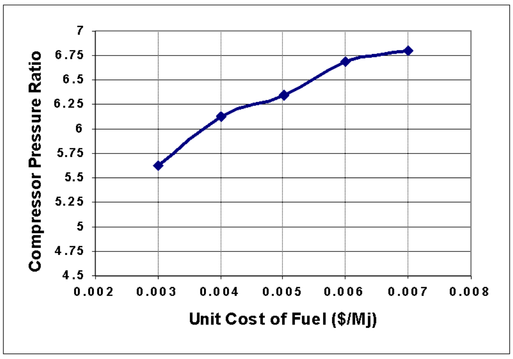

Figure (10): The effect of fuel unit cost on the optimal value of compressor pressure ratio, r_{AC}.

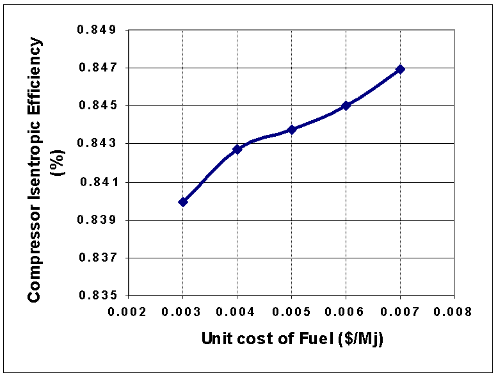

Figure (11): The effect of fuel unit cost on the optimal value of compressor isentropic efficiency.

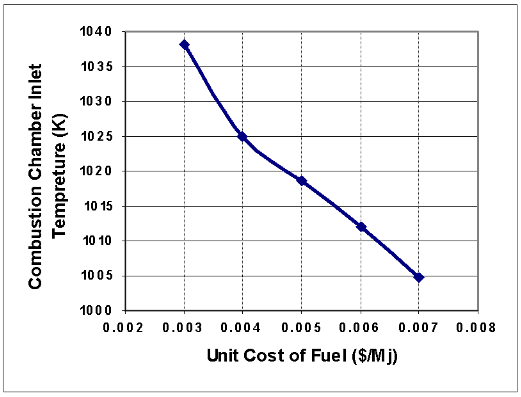

Figure (12): The effect of fuel unit cost on the optimal value of combustion chamber inlet temperature.

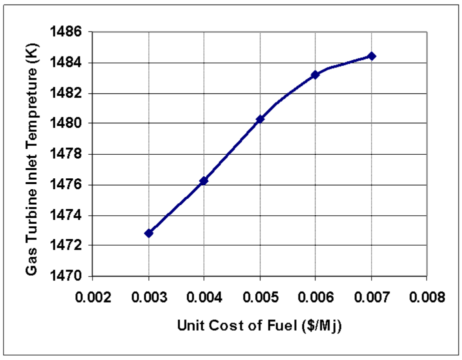

Figure (13): The effect of fuel unit cost on the optimal value of gas turbine inlet temperature.

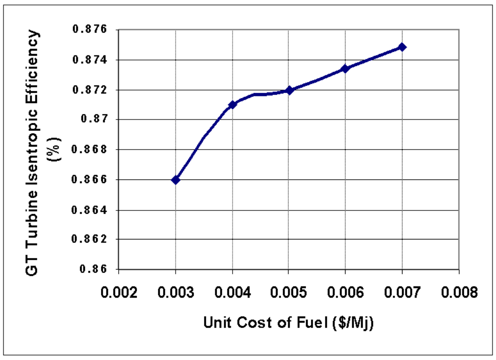

Figure (14): The effect of fuel unit cost on the optimal value of gas turbine isentropic efficiency.

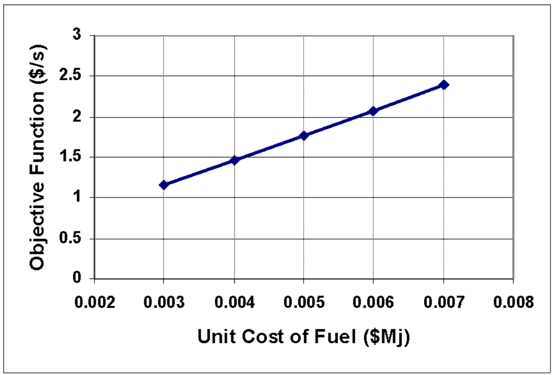

Figure (15): The effect of fuel unit cost on the objective function

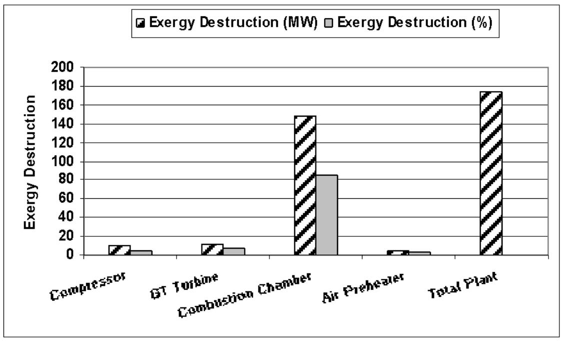

Figure (16): Exergy destruction of each component of gas turbine plant.

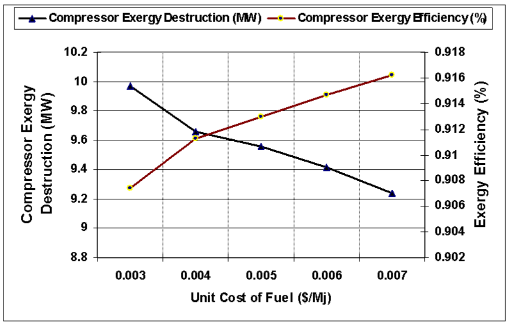

Figure (17): Exergy destruction and exergy efficiency of compressor versus unit cost of fuel

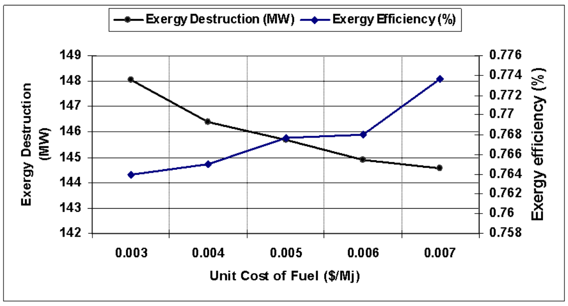

Figure (18): Exergy destruction and exergy efficiency of combustion chamber versus unit cost of fuel.

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