Proceedings of the ASME 2010 10th Biennial Conference on Engineering Systems Design and Analysis
ESDA2010
July 12-14, 2010, Istanbul, Turkey

ESDA2010-24214

EXERGY, COST AND ENVIRONMENT AS OBJECTIVES IN PARTICLE SWARM OPTIMIZATION OF A BENCHMATK COGENERATION SYSTEM

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ABSTRACT

Multi-Objective Optimization of a benchmark cogeneration problem known as CGAM cogeneration system has been carried out from Exergetic, Economic and Environmental aspects simultaneously. CGAM Problem designs a cogeneration plant which delivers 30 MW of electricity and 14 kg/s of saturated steam at 20 bars. Since multi-objective calculus based optimization of real energy systems involves very complicated process, one of the most suitable techniques which uses a particular class of search algorithms known as Particle Swarm Optimization (MOPSO) is utilized and the advantages of this method is shown. This approach has been applied to find the set of Pareto optimal solutions with respect to the competing objective functions. In this study, the MOPSO algorithm uses 100 particles and 200 iterations. In order to facilitate the problem, the environmental objective function has been defined and expressed in cost terms. The thermodynamic modeling has been implemented comprehensively while economic analysis of this system conducted. Consideration of Five decision variables in modeling process made the final optimal solutions more realistic in comparison with previous studies in this field. Finally the result of optimization is introduced with 100 points on Pareto frontier.

INTRODUCTION

Cogeneration is the production of electrical energy and useful thermal energy from the same energy source. Cogeneration is important for numerous reasons. The first is that capturing the waste heat from power generation can result in an increase in efficiency [1]. This offers significant potential savings in energy costs. Additionally cogeneration is also more environmentally friendly than conventional fossil fuel power plants [2].

Optimization of thermal systems is one of the most important subjects in the energy engineering field [3]. Among the thermal systems, combined cycle cogeneration systems are analyzed by advanced thermodynamic topics. These topics include exergy, thermoeconomics and environment. Exergy analysis, which is the combination of first law and second law of thermodynamics, helps to highlight the thermodynamic inefficiencies of a system. It is clear that improving a system thermodynamically without considering economics and environment is misleading. Hence in design of thermal systems an integrated procedure should be performed to consider all these aspects.

Many researchers have started to develop links between exergy and economics. As a result, a new area called thermoeconomics or exergoeconomics has been formed [4]. The aim of the thermoeconomic analysis is to calculate the cost of each product of the systems and investigate the cost formation process in the systems. An example for comparison of different thermoeconomic methodologies to design optimization of a cogeneration plant has been presented as a test case, known as the CGAM problem [5-9]. These works initially represent a paradigmatic application of a single optimization problem. They utilized mathematical approaches in their optimization in which these methods suffer from the difficulty to find the final global optimum. Moreover single objective optimization in thermal systems is not excellent. We can not only consider the cost objectives and forget other aspects. In many cases system performance and environmental impacts are as important as cost effects and for small increase in cost term; more effective solutions will be reached.

In multi-objective optimization problems mathematical approaches are unsuccessful in finding the global optimum and most of them terminate at local optimum. Application of multi-objective optimization method in thermal systems is not very old. In 2002, Toffolo et al [10], considered two-objectives: energetic and economic objectives in optimization of CGAM problem. In their work shortcoming of the conventional mathematical optimization approaches in finding global optimum was relatively maintained; they used evolutionary algorithms (MOEAs) with a MATLAB Simulink model and presented a Pareto optimum frontier instead of single optimum solution of the conventional single objective optimization.

They improved their work by adding the environmental impact and introduced a three objectives optimization problem [11]. Unit damage costs were devoted to NOx and CO2 emissions and environmental objective was introduced in cost term. However their work still suffers some shortcoming arose from simplification in selecting of decision variables and constraints. To reduce the number of non-feasible solutions that their optimization algorithm may be faced during the optimization procedure, variable ε_{ap} was preferred to exit temperature on air side of the Air Preheater T_3 (variable used in the original CGAM problem). Furthermore among the five decision variables in original CGAM problem, they chose three of them ($r_{cp}, T_4, \varepsilon_{ap}$) while other two were held constant.

In 2008 sayyaadi [12], used a more suitable method in economic modeling (TRR method). He added environmental objective with cost objective function and introduced a Thermoenvironomic objective function and utilized this objective with exergetic aspect in two multi-objective optimization approaches. In comparison with previous studies in this field ([10, 11, 12]), this work utilizes faster and more confidant algorithm in optimization procedure (MOPSO) without any simplification with all five decisions variables. MOPSO algorithm can overcome the problem of non feasible solution which has been faced in previous studies. No decision variables are changed or fixed and all variables and constraints are in accordance with the original CGAM problem. These improvements lead to results which are more realistic than corresponding results obtained before.

PARTICLE SWARM OPTIMIZATION

It is common when working with design of energy systems to have situations with more than one objective. For instance, the objectives can simultaneously be to minimize the negative environmental impact of the process, maximize the profit and to maximize the safety of the process. These problems are referred to as multi objective Mathematical programming problems. Equation (1) shows how a multi objective optimization problem can be formulated mathematically:

$$\min\ f_j(X)\ \forall j \in \{1,2,3,....k\}\ subject\ to\ X \in L \tag{1}$$

Where we have $k \geq 2$ objective functions.

Particle swarm optimization; (PSO) is an exciting new methodology in evolutionary computation that is somewhat similar to a genetic algorithm in that the system is initialized with a population of random solutions. Unlike other algorithms, however, each potential solution (called a particle) is also assigned a randomized velocity and then flown through the problem hyperspace. Particle swarm optimization has been found to be extremely effective in solving a wide range of engineering problems. It is very simple to implement and solves problems very quickly.

In this work we develop a Multi-Objective Particle Swarm Optimizer with a dynamic fitness inheritance technique [13] to decrease the computational cost dealing with some multi-objective optimization test problems taken from literature. An external archive is used in this method to store the non-dominated solutions which are found along the process of optimization. The leaders of other particles that guide them to the Pareto-front are selected from the top portion of this archive in each iteration. Moreover, the concept of non-dominated sorting and crowding distance [14] is applied as NSPSO approach [15] to improve the convergence and diversity of the Pareto-optimal solutions. The comparison among the particles and their pbests is based on fully connected approach [16] to increase the selection pressure toward the true Pareto-front. In order to reduce the cost of computation during the process, we use a dynamic fitness inheritance technique which is proposed in [17]. The following formula calculates the new position of a particle in the objective space using fitness inheritance technique:

$$F_i(t) = F_i(t-1) + VF_i(t) \tag{2}$$

$$VF_i(t) = c_1 r_1 (F_{pbest-i} - F_i(t)) + c_2 r_2 (F_{gbest-i} - F_i(t)) \tag{3}$$

Where $F_i(t)$, $F_{pbest-i}$ and $F_{gbest-i}$ are $i-th$ objective function value for the current particle, and its pbest and gbest objective function values, respectively. The parameter p_i , called inheritance or approximation proportion, indicates the proportion of particles that their objective function values must be inherited or approximated instead of evaluation in each iteration. As the Pareto-optimal solutions at the end of the optimization process must be true values of the objective functions, no inherited objective values can enter into the final external archive. To determine the amount of p_i , following nonlinear function is used:

$$p_i = f(x) = x^2\ ;\ x = \frac{gen}{Gen} \tag{4}$$

Where gen is the number of current iteration and Gen is the total number of iterations.

APPLICATION OF ALGORITHM TO A CASE STUDY

In 1990, a group of concerned specialists in the field of Thermoeconomics (C. Frangopoulos, G. Tsatsaronis, A. Valero, and M. von Spakovsky) 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 [5]. The CGAM problem originally is an economic optimization of a simple cogeneration system which involves physical, thermodynamic, and economic models. It assumes ideal gas behavior and constant heat capacities. The CGAM Problem designs a cogeneration plant which delivers 30 MW of electricity and 14 kg/s of saturated steam at 20 bars. The installation consists of an air compressor (AC), air preheater (APH), combustion chamber (CC), gas turbine (GT), and HRSG. Air preheater uses thermal energy from the combustion gas leaving gas turbine to heat the air entering the combustion chamber. Structure of this cogeneration plant is shown in Fig. 1. HRSG is composed of an economizer (EC) section where the feed water is heated and an evaporator (EV) section where the heated water is vaporized into steam. Other specifications and operating condition of the CGAM problem for base case design are [4]:

$T1=298.15K$, $P1=1.01325bar$; $T8=298.15K$, $P8=20bar$; $T10=298.15K$, $P10=12bar$;
$T3=850K$; $T4=1520K$; $P2/P1=10$; $\eta sc=0.86$; $\eta st=0.86$

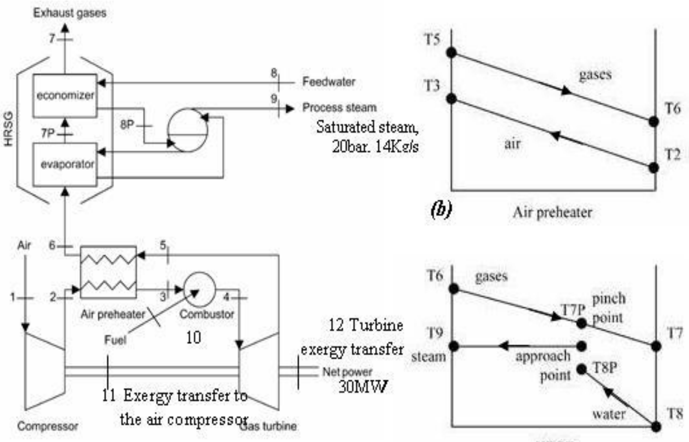

Figure 1. SCHEMATIC FLOW DIAGRAM OF THE CGAM [4].

THERMODYNAMIC MODEL

Thermodynamic modeling has been carried out in accordance to the procedure presented in [5, 10, 11]. Utilized thermodynamic model is developed based on the following basic assumptions [10, 11, 5]:

- All processes are steady state.
- Principle of ideal-gas mixture is applied for air and combustion products.
- Fuel is natural gas and it is assumed to be 100% methane. Methane is an ideal gas.
- Heat loss from the combustion chamber is considered to be 2% of the fuel lower heating value. All other components are considered adiabatic.
- Constant pressure loss ratios are considered in components.
- Restricted dead state is P0=1.013 bar and T0=25°C.
- 3% and 5% pressure losses are assumed for air and gases in the air preheater, respectively.
- 5% pressure losses are assumed for gases in HRSG and combustion chamber.

THERMOECONOMIC MODEL

The economic model takes into account the cost of components, including amortization and maintenance, and the cost of fuel consumption. In order to define a cost function which depends on the optimization parameters of interest, component costs have to be expressed as functions of thermodynamic variables [4, 5]. In the CGAM problem, purchase cost functions for each plant component are already supplied. In this research, these equations with their related constants have been considered in accordance with [4, 5].

Governing equation of thermoeconomic model for the cost balancing of a component of an energy system is as follow [4]:

$$\sum_{j=1}^{n}(c_j\dot{E}_j)_{k,in} + \dot{Z}_k^{CI} + \dot{Z}_k^{OM} = \sum_{j=1}^{m}(c_j\dot{E}_j)_{k,out} \qquad (5)$$

Where cj is the unit cost of exergy for the jth stream to/from the component, $\dot{E}_j$ is exergy flow for the jth stream to/from the component and $\dot{Z}_k^{CI}$ and $\dot{Z}_k^{OM}$ are related cost of capital investment and operating and maintenance for the component kth obtained in economic model. In Eq. (5), n and m are total number of inlet and outlet exergy to/from the component kth, respectively. Developing Eq. (5) for each component of CGAM problem along with auxiliary costing equations (according to P and F rules, see [4]) leads to the following system of equations. The system of 12 equations and 12 unknowns as indicated by Eq. 6 is solved to obtain the cost of streams 1 to 12 for CGAM problem.

$$\begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 1 & -1 & 0 & 1 & -1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{\dot{E}_5} & \frac{-1}{\dot{E}_6} & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & -1 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & -1 & 0 & 0 & 0 & 0 & 0 & -1 & -1 \\ 0 & 0 & 0 & \frac{1}{\dot{E}_4} & \frac{-1}{\dot{E}_5} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \frac{1}{\dot{E}_{11}} & \frac{-1}{\dot{E}_{12}} \\ 0 & 0 & 0 & 0 & 0 & 1 & -1 & 1 & -1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1}{\dot{E}_6} & \frac{-1}{\dot{E}_7} & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} \dot{C}_1 \\ \dot{C}_2 \\ \dot{C}_3 \\ \dot{C}_4 \\ \dot{C}_5 \\ \dot{C}_6 \\ \dot{C}_7 \\ \dot{C}_8 \\ \dot{C}_9 \\ \dot{C}_{10} \\ \dot{C}_{11} \\ \dot{C}_{12} \end{bmatrix} = \begin{bmatrix} 0 \\ -\dot{Z}_{AC} \\ -\dot{Z}_{APH} \\ 0 \\ -\dot{Z}_{CC} \\ FC_L \\ \tau \\ -\dot{Z}_{GT} \\ 0 \\ 0 \\ -\dot{Z}_{HRSG} \\ 0 \\ 0 \end{bmatrix} \qquad (6)$$

COMBUSTION POLLUTANTS

The original CGAM problem does not perform calculations on formation of pollutants within the combustion chamber. A simple model, based on semi-analytical correlations [18], is added here to determine pollutant emissions to setup of an environmental objective function. Adiabatic flame temperature in the primary zone of the combustion chamber is derived from the expression by Gulder [19]:

$$T_{pz} = A\sigma^{\alpha} \exp(\beta(\sigma + \lambda)^2)\pi^x \theta^y \psi^z \qquad (7)$$

where π is a dimensionless pressure p/pref (p being the combustion pressure p3, and pref = 101325 Pa); θ is a dimensionless temperature T/Tref (T being the inlet temperature T3, and Tref = 300 K); ψ is the H/C atomic ratio ($\psi = 4$, fuel being pure methane); $\sigma = \phi$ for $\phi \le 1$ (ϕ being the fuel to air equivalence ratio) and $\sigma = \phi - 0.7$ for $\phi > 1$. ϕ is equivalent fuel to air ratio that is considered equal 0.64 in this work[11]. x, y and z are quadratic functions of σ in accordance with the following equations [19]:

$$x = a_1 + b_1\sigma + c_1\sigma^2 \qquad (8)$$

$$y = a_2 + b_2\sigma + c_2\sigma^2 \qquad (9)$$

$$z = a_3 + b_3\sigma + c_3\sigma^2 \qquad (10)$$

In Eq. (7) to (11) parameters denoted as A, α, β, λ, a_i, b_i and c_i are constants presented in [19]. In order to have an accurate prediction, four sets of constants have been determined for the following ranges [18]:

$$\begin{gathered} 0.3 \le \phi \le 1.0 \text{ and } 0.92 \le \theta < 2.0 \\ 0.3 \le \phi \le 1.0 \text{ and } 2.0 \le \theta \le 3.2 \\ 1.0 < \phi \le 1.6 \text{ and } 0.92 \le \theta < 2.0 \\ 1.0 < \phi \le 1.6 \text{ and } 2.0 \le \theta \le 3.2 \end{gathered} \qquad (11)$$

The values of constants for each range classification are listed in [18].

The adiabatic flame temperature is used in the semi-analytical correlations proposed by Rizk and Mongia [18] to determine the pollutant emissions in grams per kilogram of fuel:

$$NO_x = \frac{0.15E16\tau^{0.5} \exp(-71100 / T_{pz})}{p_3^{0.05} (\Delta p_3 / p_3)^{0.5}} \qquad (12)$$

$$CO = \frac{0.179E9 \exp(7800 / T_{pz})}{p_3^2 \tau (\Delta p_3 / p_3)^{0.5}} \qquad (13)$$

Where τ is residence time in the combustion zone (τ is assumed constant and is equal to 0.002 s [11]). Tpz is primary zone combustion temperature, p3 is combustor inlet pressure, Δp3/p3 is non-dimensional pressure drop in the combustor (Δp3/p3 = 0.05 as in the CGAM problem [5]).

Note that the primary zone temperature is used in NOx correlation instead of the stochiometric temperature, since the maximum attainable temperature in premixed flames is Tpz, as pointed out by Lefebvre [19].

OBJECTIVE FUNCTIONS, DECISION VARIABLES AND CONSTRAINTS

Three objective functions of the multi-criteria optimization problem are the total exergetic efficiency (to be maximized), the total cost rate of products (to be minimized) and the environmental impact (to be minimized). Third objective function expresses the environmental impact as total pollution damage cost ($/s) due to CO2 and NOx emissions by multiplying their respective flow rates by their corresponding unit damage cost [20] (c_{CO_2} and c_{NO_x} are equal to 0.02086 $/kgCO2 and 6.853 $/kgNOx, respectively [11]). Mathematical formulation of objective functions is as following,

Exergetic:

$$\varepsilon_{tot} = \frac{\dot{W}_{NET} + \dot{m}_{steam}(e_9 - e_8)}{\dot{m}_{fuel} e_{fuel}} \qquad (14)$$

Cost:

$$\dot{C}_{P,tot} = \dot{C}_{F,tot} + \dot{Z}_{tot}^{CI} + \dot{Z}_{tot}^{OM} \qquad (15)$$

Environmental:

$$\dot{C}_{env} = c_{CO2}\dot{m}_{CO_2} + c_{NO_X}\dot{m}_{NO_X} \qquad (16)$$

In this paper, for keeping the consistency with the original CGAM problem [4-9], same decision variables have been

selected as follows. With employing this algorithm there is no need to change of the decision variables for overcoming the occurrence of non feasible solutions as previous works do.
Decision variables are:

- Compressor pressure ratio p2/p1
- Isentropic efficiency of the compressor ηsc
- Isentropic efficiency of the turbine ηst
- Temperature of the air entering the combustion chamber T3
- Temperature of the combustion products entering the gas turbine T4

Although the decision variables may be varied in optimization procedure, each decision variable is normally required to be within a given range as follow:

$$6 \leq p_2/\,p_1 \leq 16 \qquad (17)$$

$$0.6 \leq \eta_{sc} \leq 0.9 \qquad (18)$$

$$0.6 \leq \eta_{st} \leq 0.92 \qquad (19)$$

$$700 \leq T_3 \leq 1000K \qquad (20)$$

$$1200 \leq T_4 \leq 1550K \qquad (21)$$

Heat exchange between hot and cold streams in air preheater and HRSG should satisfy the following feasibility constraints:

Air preheater:

$$T5 > T3 \qquad (22)$$

$$T6 > T2 \qquad (23)$$

HRSG:

$$\Delta TP = T7P - T9 > 0 \qquad (24)$$

$$T6 \geq T9 + \Delta TP \qquad (25)$$

$$T7 \geq T8 + \Delta TP \qquad (26)$$

$$T7P > T8P \qquad (27)$$

$$T7 \geq 378.15K \qquad (28)$$

Last constraint is an additional constraint with respect to the original CGAM problem imposed on exhaust gases temperature, which must not fall below 378.15K (105 ºC). This limitation is considered to prevent the condensation of water vapor exist in the combustion products at outlet section of economizer. The condensation of water vapor in presence of carbon dioxide may leads to formation of carbonic acid which is corrosive material and can damage the economizer surface.

RESULTS AND DISCUSSION

In this study, the MOPSO algorithm uses 100 particles and 200 iterations. The constant coefficients of $c_1 = 2$ and $c_2 = 2$ are applied to consider both social and cognitive characteristics of each particle equally. The inertia factor value $w = 1$ is used to control the exploration and exploitation of the swarm in the search space. This value presents a reasonable global search characteristic of the swarm during the process of optimization. To control the magnitude of velocity, maximum amount of velocities are adjusted to the subtraction of lower boundaries from upper boundaries multiplied by 0.1. If a particle goes beyond the variables' boundaries, then its value is reintegrated into the lower or upper boundary and its velocity is multiplied by -1 having the effect of searching the opposite direction.
First in order to evaluate advantages and robustness of the MOPSO approach, the results are compared to the original CGAM problem [9] solved using conventional mathematical optimization approach. In this regard, the thermodynamic and economic model is built based on simple thermodynamic and economic models utilized in [5]. As we mentioned before, in original CGAM problem the economic objective had been considered alone without considering the environmental or efficiency aspects and an optimum point from the sight of economics was introduced. In Tab.1 the comparison between original CGAM problem and a point on Pareto domain witch has the least cost is shown:

Table 1. COMPARISON OF RESULTS FOR OPTIMIZATION OF ORIGINAL CGAM PROMLEM OBTAINED IN THIS PAPER WITH THOSE OBTAINED BY CONVENTIONAL OPTIMIZATION APPROACHES IN [9]

Objective function, decision variables, costing and operating parameters ,etc	Conventional optimization approaches presented in [9]	Optimization via MOPSO Algorithms presented in this work
Total Cost Rate ($/s)	0.362009	0.36379691
Environmental Cost Rate ($/s)	0.10955	0.10492247
Exergetic efficiency (%)	50.664	51.261090
$T_3(K)$	914.28	920.19
$T_4(K)$	1492.63	1492.47
η_{sc}	0.8468	0.8306
η_{st}	0.8786	0.8456
p_2/p_1	8.52	7.70

As it can be seen from Tab.1, the point introduced from MOPSO algorithm is totally more effective, while the cost was increased a bit; exergetic efficiency and environmental effects are improved.
In multi-objective optimization, comprehensive thermodynamic, economic and environmental models are implemented and all results are summarized in two figures below. Fig. 2, 3 presents the Pareto optimum solutions in two different view for CGAM problem with three objective functions indicated in Eq. (14,15 , 16) and constraints

represented in Eq. (17) to (28). Points on the surfaces of the Pareto fronts (Figs. 2, 3) represent the best possible tradeoffs among the three objectives. Points in the space bounded by these surfaces represent solutions that are not Pareto optimal because at least one of their objective functions takes a worse value than that of a solution on the Pareto front, the others possibly being equal.

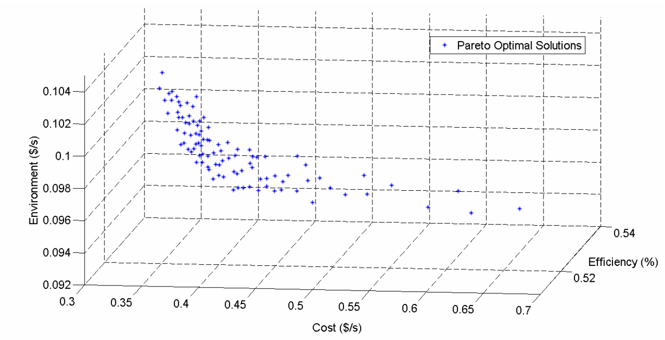

Figure 2. THE SET OF PARET OPTIMAL SOLUTIONS VIEW1

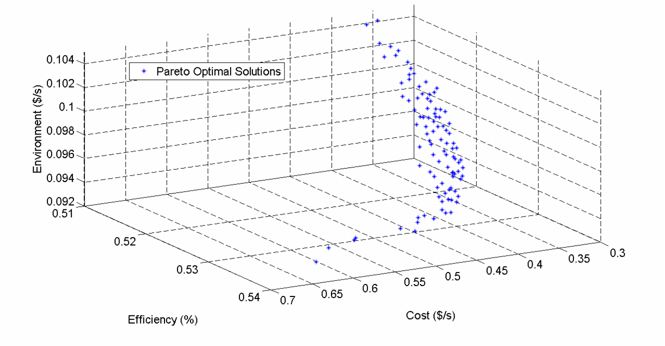

Figure 3. THE SET OF PARET OPTIMAL SOLUTIONS VIEW2

As we can see, problems of non feasible solutions are overcome and the shape of Pareto optimal solution with MOPSO algorithm is more appropriate in contrast with previous studies. During the optimization procedure this algorithm dos not stop on marginal points. With the aid of this method we can introduce 100 optimal points on Pareto frontier in the decision making space. Each of them have a special priority and can be selected from a special view point. Moreover in optimization procedure all decision variables and constraints are selected in accordance with the original CGAM problem and there is no necessity for changing decision variables or range of constraint. [10, 11]

In Figs 4 to 6, for better understanding of the trend of Pareto optimal solutions, Pareto frontier has been seen from the view point of two objectives. Among these three objective functions, each pair of them are selected and drawn separately. At first we select “exergetic efficiency” with “cost” and show them in one diagram. The shape of the Pareto optimal solution is clearly in accordance with previous study in this field [10, 12].

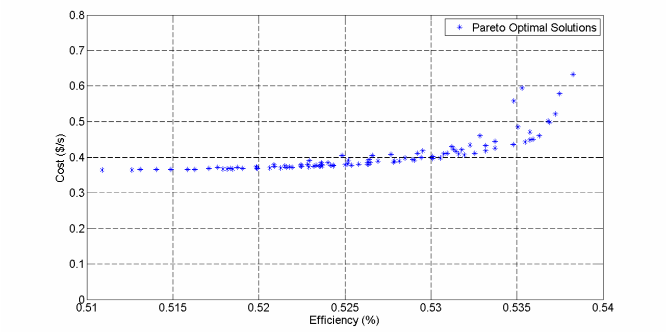

Figure 4. THE SET OF PARETO OPTIMAL FOR COST AND EFFICIENCY

Also the trend for environment-cost and environment-efficiency are shown in Figs below.

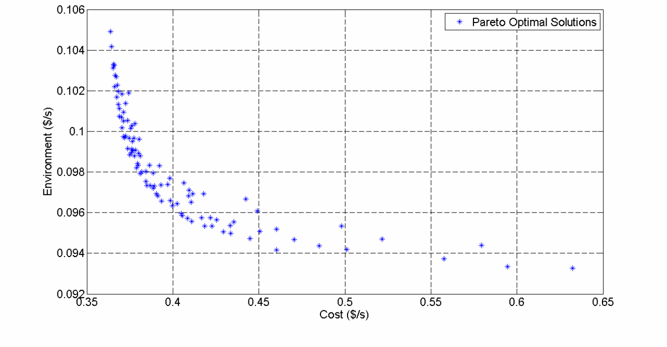

Figure 5. THE SET OF PARETO OPTIMAL FOR COST AND ENVIRONMENT

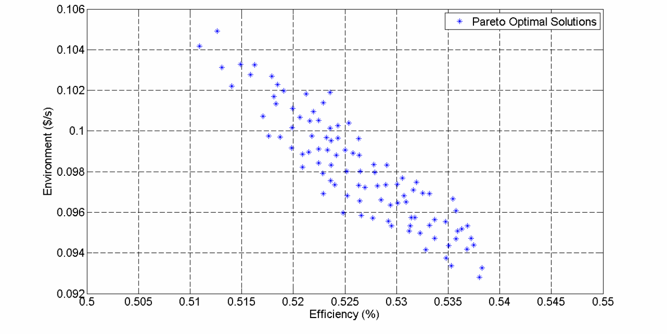

Figure 6. THE SET OF PARETO OPTIMAL FOR ENVIRONMENT AND EFFICIANCY

The information related to minimum cost, minimum environmental impacts and maximum exergetic efficiency and other connected data for each of them,are summarized in Tab.2 to Tab.4. As we can see these selected three points, among the Pareto front, have a special priority in one of the objectives and are suitable when one of the objectives are more important in decision making process. In Tab.2, we summarize the information related to cost optimum point on Pareto front and value of other two objectives in this point. Table 3, 4 are devoted to minimum of environmental damage cost and maximum of exergetic efficiency respectively.

Table 2. COST OPTIMUM POINT AND THE VALUE OF TWO OBJECTIVES IN ACCORDANCE WITH THIS POINT

Objective function, decision variables, costing and operating parameters ,etc	Cost optimum point and the value of two objectives
Total Cost Rate ($/s)	0.36379691
Environmental Cost Rate ($/s)	0.10492247
Exergetic efficiency (%)	51.26109
$T_3(K)$	890
$T_4(K)$	1490
η_{sc}	0.852
η_{st}	0.883
p_2 / p_1	10.2

Table 3. ENVIRONMENT OPTIMUM POINT AND THE VALUE OF TWO OBJECTIVES IN ACCORDANCE WITH THIS POINT

Objective function, decision variables, costing and operating parameters ,etc	Environmental optimum point and the value of two objectives
Total Cost Rate ($/s)	1.0819765
Environmental Cost Rate ($/s)	0.092795284
Exergetic efficiency (%)	53.801762
$T_3(K)$	804
$T_4(K)$	1540
η_{sc}	0.899
η_{st}	0.914
p_2 / p_1	12.8

Table 4. EXERGETIC OPTIMUM POINT AND THE VALUE OF TWO OBJECTIVES IN ACCORDANCE WITH THIS POINT

Objective function, decision variables, costing and operating parameters ,etc	Exergetic optimum point and the value of two objectives
Total Cost Rate ($/s)	0.63225007
Environmental Cost Rate ($/s)	0.093254651
Exergetic efficiency (%)	53.826441
$T_3(K)$	813
$T_4(K)$	1550
η_{sc}	0.891
η_{st}	0.913
p_2 / p_1	13.2

CONCLUSION

An alternative to previously presented calculus based optimization approaches named MOPSO algorithm was utilized for multi-objective optimization of typical cogeneration system called CGAM problem. The proposed evolutionary algorithm was shown to be a powerful and effective tool in finding the set of the optimal solutions for the choice of optimum design variables in the CGAM cogeneration plant in comparison to the conventional mathematical optimization algorithm. One of the main advantages of presented method was obtained from the comprehensive thermodynamic and economic modeling with no need for simplification and change of decision variables or constraints that was implemented along with the MOPSO algorithm which was shown that is able to achieve better result than conventional mathematical approach and other evolutionary algorithm. It was shown that multi-criteria optimization approach, which is a general form of single objective optimization, enables us to consider various and ever competitive objectives.

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