OPTIMIZATION OF MICRO COMBINED HEAT AND POWER GAS TURBINE BY GENETIC ALGORITHM

by

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In this paper, a comprehensive thermodynamic modeling and multi-objective optimization of a micro turbine cycle in combined heat and power generation are presented, which provides 100 kW of electric power. This combined heat and power system is composed of air compressor, combustion chamber, air preheater, gas turbine, and a heat recovery heat exchanger. At the first stage, the each part of the micro turbine cycle is modeled using thermodynamic laws. Next, with using the energetic and exergetic concepts and applying economic and environmental functions, the multi-objectives optimization of micro turbine in combined heat and power generation is performed. The design parameters of this cycle are compressor pressure ratio (r_{AC}), compressor isentropic efficiency, gas turbine isentropic efficiency, combustion chamber inlet temperature, and turbine inlet temperature. In the multi-objective optimization three objective functions, including the combined heat and power exergy efficiency, total cost rate of the system products, and CO_2 emission of the whole plant, are considered. The exergo-environmental objective function is minimized whereas power plant exergy efficiency is maximized usinga Genetic algorithm. To have a good insight into this study, a sensitivity analysis of the result to the fuel cost is performed. The results show that at the lower exergetic efficiency, in which the weight of exergo-environmental objective is higher, the sensitivity of the optimal solutions to the fuel cost is much higher than the location of the Pareto frontier with the lower weight of exergo-environmental objective. In addition, with increasing exergy efficiency, the purchase cost of equipment in the plant is increased as the cost rate of the plant increases.

Key words: *distribute generation, multi-objective, optimization, micro turbine*

Introduction

In recent years, decentralized power generation has resulted in remarkable results concerning the decrease in wastes and power waste and the increase in reliability. This way, local small power plants will further contribute in power generation, and in the not too distant future,

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they will replace large and centralized power plants. Gas micro-turbines are addressed as one of the most serious options for decentralized energy generation. The reasons behind the use of micro-turbines as one of the main energy generation choices in commercial, administrative, residential and other sections include higher efficiency in the co-generation state, lower pollution, lower commissioning time, higher runtime, and lower maintenance (due to lower movable parts). Therefore, optimization of such systems is of the greatest importance in the area of power generation. Combined heat and power (CHP) systems are considered the best option to produce both heat and power simultaneously due to increased efficiency and reduced energy cost. Energy utilization is essentially governed by thermodynamic principles (particularly by exergy). It is well known that exergy analysis can be used as a potential tool to determine the location, type, and true magnitude of exergy loss (or destruction) [1]. Exergo-economics combines the exergy analysis with the economic principles and incorporates the associated costs of the thermodynamic inefficiencies in the total product cost of an energy system [2]. These costs can conduct designers to understand the cost formation process in an energy system, in which the task is usually focuses on minimization of the unit cost of the system product [3]. Numerous researchers, *e. g.* [4, 5] have conducted exergy and exergo-economic analysis and optimization for thermal systems. It becomes essential to use the optimization procedure considering thermodynamics laws as well as exergo-economics. In fact, the main objectives, in this regard, involved in the design optimization process are as follows [6]: thermodynamically (*e. g.* maximum efficiency, minimum fuel consumption, minimum irreversibility, and so on), economically (*e. g.* minimum cost per unit of time, maximum profit per unit of production), and environmentally (*e. g.* limited emissions, minimum environmental impact). Some researchers have carried out optimization for power plants and CHP systems [7]. They usually use evolutionary algorithm in their studies. Pourhasanzadeh [8] performed the optimization of a micro gas turbine (GT) by genetic algorithm method which is a new method in optimizing problems. Ehyaei *et al*. [9] performed the optimization of a micro GT by exergy, economic and environmental impact analyses, with various fuels. They showed that the results are less influenced by the fuel type; yet, the efficiency of the second law as well as total expenses of operation of the system is independent of fuel type. Sanayeh *et al*. [10] make use of energy-economic analysis to select the type and number of micro-turbines required for power and heat load curve during one year and considered the annual profit as the objective function. Sahoo [5] carried out the exergo-economic analysis and optimization of a co-generation system using evolutionary programming. He optimized the CHP unit using exergo-economic principles and evolutionary programming.

In the present paper, a comprehensive thermodynamic modeling of a CHP system used in the micro turbine cycle, which provides 100 kW of electric power is performed based on the thermodynamic relations. For optimization, three objective functions including the CHP exergy efficiency, total cost rate of the system product, and the cost rate of environmental impact are considered. Further, the environmental impact is integrated with the thermo-economic objective function and defined as a new objective function in this study. The thermo-environomic objective function is minimized while CHP micro turbine exergy efficiency is maximized using a genetic algorithm. Moreover, to have a good insight into this analysis, the amount of CO_2 emission is considered as another objective function. Hence, this objective function is minimized while exergy efficiency is maximized. Accordingly, the design parameters are compressor pressure ratio (r_{AC}), compressor isentropic efficiency (η_{AC}), GT as entropic efficiency (η_{GT}), combustion chamber (CC) inlet temperature (T_3), and GT inlet temperature (T_4). Moreover, the sensitivity analysis is conducted to have a good insight into this research.

Energy analysis

Micro-turbines have undeniable advantages for generating power and heat required for local consumptions, therefore, the efficiency optimization of their systems and the decrease in their function and operation expenses are of high importance. Exergo-economic analysis helps designers to find ways to improve the performance of a system in a cost effective way [7]. The energy balance equations for various parts of the CHP plant (fig. 1) are [11-13]:

– air compressor

$$T_2 = T_1 \left\{ 1 + \frac{1}{AC} \left[r_{AC}^{\frac{(\gamma_a - 1)}{\gamma_a}} - 1 \right] \right\} \tag{1}$$

$$\dot{W}_{\mathrm{AC}} = \dot{m}_{\mathrm{a}} C_{\mathrm{P,a}} (T_2 - T_1) \tag{2}$$

– air preheater (APH)

$$\dot{m}_{\mathrm{a}} C_{\mathrm{P,a}} (T_3 - T_2) = \dot{m}_{\mathrm{g}} C_{\mathrm{P,g}} (T_5 - T_6) \eta_{\mathrm{rec}} \tag{3}$$

$$P_3 = P_2 (1 - \Delta P_{\mathrm{g,rec}}) \tag{4}$$

$$P_6 = P_5 (1 - \Delta P_{\mathrm{g,rec}}) \tag{5}$$

– combustion chamber

$$\dot{m}_{\mathrm{a}} h_3 + \dot{m}_{\mathrm{f}} LHV = \dot{m}_{\mathrm{g}} h_4 + (1 - \eta_{\mathrm{cc}}) \dot{m}_{\mathrm{f}} LHV \tag{6}$$

$$P_4 = P_3 (1 - \Delta P_{\mathrm{cc}}) \tag{7}$$

– combustion equation

$$\begin{aligned} &\lambda \mathrm{CH_4} + (X_{\mathrm{O_2}} \mathrm{O_2} + X_{\mathrm{N_2}} \mathrm{N_2} + X_{\mathrm{H_2O}} \mathrm{H_2O} + X_{\mathrm{CO_2}} \mathrm{CO_2} \rightarrow (\lambda + X_{\mathrm{CO_2}}) \mathrm{CO_2} + \\ &+ (X_{\mathrm{O_2}} - 2\lambda) \mathrm{O_2} + (2\lambda + X_{\mathrm{H_2O}}) \mathrm{H_2O} + X_{\mathrm{N_2}} \mathrm{N_2} \end{aligned} \tag{8}$$

– gas turbine

$$T_5 = T_4 \left\{ 1 - \eta_{GT} \left[1 - \left(\frac{P_4}{P_5} \right)^{\frac{1-\gamma_g}{\gamma_g}} \right] \right\} \tag{9}$$

$$\dot{W}_{\mathrm{GT}} = \dot{m}_{\mathrm{g}} C_{\mathrm{p,g}} (T_4 - T_5) \tag{10}$$

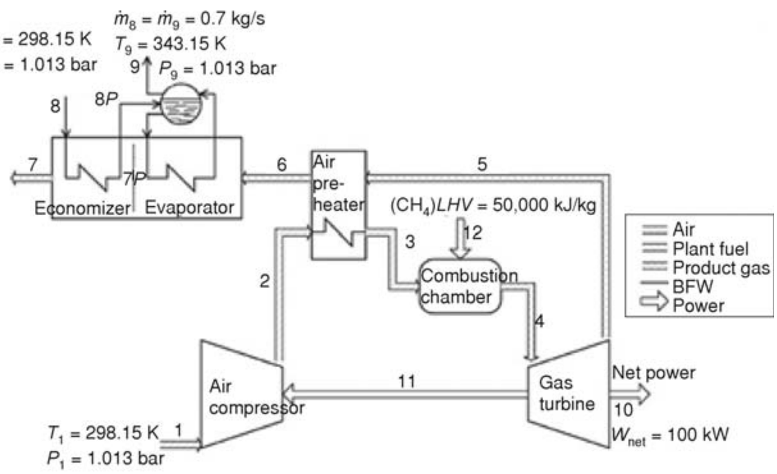

Figure 1. The schematic diagram of the CHP micro turbine

$$\dot{m}_{\mathrm{g}} = \dot{m}_{\mathrm{a}} + \dot{m}_{\mathrm{f}} \tag{11}$$

$$\dot{W}_{\mathrm{net}} = \dot{W}_{\mathrm{GT}} - \dot{W}_{\mathrm{AC}} \tag{12}$$

– heat recovery

$$\dot{m}_{\mathrm{s}}(h_9 - h_8) = \dot{m}_{\mathrm{g}}(h_6 - h_7) \tag{13}$$

$$\dot{m}_{\mathrm{s}}(h_9 - h_{8\mathrm{p}}) = \dot{m}_{\mathrm{g}}(h_6 - h_{7\mathrm{p}}) \tag{14}$$

$$P_0 = P_6(1 - \Delta P_{\mathrm{hrsg}}) \tag{15}$$

In addition, some assumptions are made for analysis [14, 15]:

– all the processes are steady-state steady-flow,
– the air and combustion products are treated as ideal gases,
– the fuel injected to the CC is assumed to be pure methane, and
– pressure drop in CC, preheater and heat recovery are: ΔP_{cc} = 5%, $\Delta P_{\mathrm{a,rec}}$ = 5%, $\Delta P_{\mathrm{g,rec}}$ = 3%, and ΔP_{hrsg} = 5%
– the dead properties are P_0 = 1.013 bar and T_0 = 298.15 K.

Exergy analysis

We are now in an era where not only the quantity of energy, but also the quality of energy is of the greatest importance, and we need to consider both quality and quantity of the energy used to achieve the ultimate goal of sustainable development. As is well known, the first law of thermodynamics states that energy is neither produced nor destroyed, and what we know is that it just changes form (from heat to work in a steam power plant or work to heat/cold in a heat pump/refrigerator).One can define the first law efficiency (so-called: energy efficiency) as the energy of the useful streams leaving the process divided by the energy of all streams entering. Since the first law is about the conservation of energy principle and considers that all processes are reversible, energy efficiency becomes meaningless due to the fact that all practical processes are irreversible and require us to find a better measure: second law (exergy) efficiency. Exergy can be divided into four distinct components. The two important ones are the physical exergy and chemical exergy. In this study, the two other components, which are kinetic exergy and potential exergy, are assumed to be negligible as the elevation and speed have negligible changes. The physical exergy is defined as the maximum theoretical useful work obtained as a system interacts with an equilibrium state. The chemical exergy is associated with the departure of the chemical composition of a system from its chemical equilibrium. [7] The chemical exergy is an important part of exergy in combustion process [11-13].

$$\dot{E}_{\mathrm{X_T}} = \dot{E}_{\mathrm{X_{ph}}} + \dot{E}_{\mathrm{X_{ch}}} \tag{16}$$

$$e_{\mathrm{X_{ph}}} = (h - h_0) - T_0(S - S_0) \tag{17}$$

Here, T [K] is the absolute temperature and (0) refer to the ambient conditions, respectively. The mixture chemical exergy is defined as [12]:

$$ex_{mix}^{ch} = \sum_{i=1}^{n} y_i ex^{ch_i} + RT_0 \sum_{i=1}^{n} y_i \ln y_i \tag{18}$$

For the evaluation of the fuel exergy, the above equation cannot be used. Thus, the corresponding ratio of simplified exergy is defined as [12]:

$$\zeta = \frac{ex_{\mathrm{f}}}{LHV_{\mathrm{f}}} \tag{19}$$

Because for most of usual gaseous fuels, the ratio of chemical exergy to lower heating value (*LHV*) is usually close to 1, one may write [12]:

$$\zeta_{\mathrm{CH}_4} = 1.037 \tag{20}$$

The exergy of each line is calculated in all states and the changes in exergy are determined for each major component. The sources of exergy destruction (or irreversibility) in CC are mainly the combustion or chemical reaction and thermal losses in the flow path. However, the exergy destruction in the heat exchanger of the system, *i. e.* APH and HRSG, is due to the large temperature difference between the hot and cold fluids [7].

Table 1.The exergy destruction rate and exergy efficiency equations for plant components.

Components	Exergy efficiency	Exergy destruction
Compressor	$\dot{E}_{\mathrm{D,AC}} = \dot{E}_1 - \dot{E}_2 + \dot{W}_{\mathrm{AC}}$	$\eta_{\mathrm{AC}} = \dfrac{\dot{E}_2 - \dot{E}_1}{\dot{W}_{\mathrm{AC}}}$
Combustion chamber	$\dot{E}_{\mathrm{D,CC}} = \dot{E}_3 + \dot{E}_{\mathrm{f,cc}} - \dot{E}_4$	$\eta_{\mathrm{CC}} = \dfrac{\dot{E}_4}{\dot{E}_3 + \dot{E}_{\mathrm{f,cc}}}$
Gas turbine	$\dot{E}_{\mathrm{D,GT}} = \dot{E}_4 - \dot{E}_5 - \dot{W}_{\mathrm{GT}}$	$\eta_{\mathrm{GT}} = \dfrac{\dot{W}_{\mathrm{GT}}}{\dot{E}_4 - \dot{E}_5}$
Air preheater	$\dot{E}_{\mathrm{D,Rec}} = (\dot{E}_5 - \dot{E}_6) - (\dot{E}_3 - \dot{E}_2)$	$\eta_{\mathrm{Rec}} = 1 - \dfrac{\dot{E}_{\mathrm{D,Rec}}}{\sum_{\mathrm{i,Rec}} \dot{E}}$
Heat recovery steam generator (HRSG)	$\dot{E}_{\mathrm{D,HRSG}} = \sum\limits_{i,HRSG} \dot{E} - \sum\limits_{o,HRSG} \dot{E}$	$\eta_{\mathrm{HRSG}} = \dfrac{\dot{E}_9 - \dot{E}_8}{\dot{E}_6 - \dot{E}_7}$

Exergo-economic analysis

Economic model

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 thermo-economics (exergo-economics). Moreover, the economic model considers the cost of the components including the amortization and maintenance and the cost of fuel combustion. In order to define a cost function which depends on optimization parameters of interest, component cost should be expressed as a function of thermodynamic design parameters [11].

To convert the capital investment into cost per time unit, one may write [16, 17]:

$$\dot{Z}_{\mathrm{K}} = \frac{Z_{\mathrm{K}} CRF \emptyset}{N 3600} \tag{21}$$

where Z_{K} is the purchase cost of k^{th} component in USD, The expression for each component of the GT plant and economic model is presented in tab 4. The capital recovery factor (CRF) depends on the interest rate as well as estimated equipment life time. (Value of CRF in this paper is: 0.182) [16].

N is the annual number of the operating hours of the unit, (8000 hours) and $\emptyset = 1.06$ [16] is the maintenance factor. Cost of fuel rate is defined as [12]:

$$\dot{C}_{\mathrm{f}} = \dot{m}_{\mathrm{f}} \times C_{\mathrm{f}} \times LHV \tag{22}$$

Here, *LHV* is lower heating value (for methane it is equal to 50000 kJ/kg).

Exergo-environmental analysis

In order to minimize the environmental impacts, the objective is to increase the efficiency of energy conversion processes and, thus, decrease the amount of fuel and the related overall environmental impacts, especially the release of carbon dioxide as a major greenhouse gas. For this reason, one of the major goals of the present work is to consider the environmental impacts as producing the CO and NO_x. As discussed in [17], the adiabatic flame temperature in the primary zone of the CC is derived as [7]:

$$T_{\mathrm{PZ}} = A\sigma^{\alpha} \exp[\beta(\sigma + \lambda)^2]\pi^x \theta^y \Psi^z \tag{23}$$

where π is the dimensionless pressure (P/P_{ref}), q – the dimensionless temperature (T/T_{ref}), ψ – the H/C atomic ratio, $\sigma = \phi$ for $\phi \leq 1$ (ϕ is mass ratio) and $\sigma = \phi - 0.7$ for $\phi > 1$, and x, y, and z are quadric functions of σ based on the following equations:

$$x = a_1 + b_1\sigma + c_1\sigma^2, \quad y = a_2 + b_2\sigma + c_2\sigma^2, \quad z = a_3 + b_3\sigma + c_3\sigma^2 \tag{24}$$

Parameters are presented in [17] as listed in tab. 2. The amount of CO and NO_x produced in the CC and combustion reaction are changed mainly by the adiabatic flame temperature as well. To determine the pollutant emission in grams per kilogram of fuel, the proper equations are derived as follows [18]:

$$\dot{m}_{\mathrm{NO}_x} = \frac{0.15E16\dot{m}_{\mathrm{CH}_4}\tau^{0.5}\exp\left(\dfrac{-71100}{T_{\mathrm{PZ}}}\right)}{P_3^{0.05}\left(\dfrac{\Delta P_3}{P_3}\right)^{0.5}} \tag{25}$$

Table 2. Constants for eqs. (23) and (24) [17, 18]

Constants	$0.3 \leq \phi \leq 1$		$1 \leq \phi \leq 1.6$	
	$0.92 \leq \theta \leq 2$	$2 \leq \theta \leq 3.2$	$0.92 \leq \theta \leq 2$	$2 \leq \theta \leq 3.2$
A	2361.7644	2315.752	916.8261	1246.1778
α	0.1157	–0.0493	0.2885	0.3819
β	–0.9489	–1.1141	0.1456	0.3479
λ	–1.0976	–1.1807	–3.2771	–2.0365
a_1	0.0143	0.0106	0.0311	0.0361
b_1	–0.0553	–0.045	–0.078	–0.085
c_1	0.0526	0.0482	0.0497	0.0517
a_2	0.3955	0.5688	0.0254	0.0097
b_2	–0.4417	–0.55	0.2602	0.5020
c_2	0.141	0.1319	–0.1318	–0.2471
a_3	0.0052	0.0108	0.0042	0.017
b_3	–0.1289	–0.1291	–0.1781	–0.1894
c_3	0.0827	0.0848	0.098	0.1037

$$\dot{m}_{CO} = \frac{0.179E9\dot{m}_{CH_4}\tau^{0.5}\exp\left(\dfrac{78000}{T_{PZ}}\right)}{P_3^2\tau\left(\dfrac{\Delta P_3}{P_3}\right)^{0.5}} \tag{26}$$

where τ is the residence time in the combustion zone (τ is assumed to be 0.002 s), T_{PZ} – the primary zone combustion temperature, and $(\Delta P_3/P_3)$ – the non-dimensional pressure drop in the CC.

Optimization

Definition of the objective functions

Three objective functions including exergy efficiency (to be maximized), the total cost rate of product and environmental impact (to be minimized) and CO_2 emission (to be minimized) are considered for multi-objective optimization. The second objective function expresses the environmental impact as the total pollution damage (\$/s) due to CO and NO_x emission by multiplying their respective flow rates by their corresponding unit damage cost (C_{CO}, C_{NO_x} are equal to 0.02086 \$/kg_{CO} and 6.853 \$/kg_{NO_x}). In the present work, the second objective function is the sum of the thermodynamic and Environomic objectives. Owing to the importance of environmental effects, the third objective function is considered as CO_2 emission which is produced in the CC. This amount of CO_2 emission is obtained from combustion equation discussed in *Energy analysis*. [7] The objective function for this analysis is considered as [18]:
CHP plant exergy efficiency

$$\eta_{total} = \frac{\dot{W}_{net} + \dot{m}_9(e_9 - e_8)}{\dot{m}_f LHV\zeta} \tag{27}$$

Total cost rate

$$\dot{C}_{Tot} = \dot{C}_F + \sum_K \dot{Z}_K + \dot{C}_{env} \tag{28}$$

Where

$$\dot{C}_{env} = \dot{m}_{CO}C_{CO} + \dot{m}_{NO_x}C_{NO_x} \tag{29}$$

CO_2 emissions

$$\varepsilon = \frac{\dot{m}_{CO_2}}{\dot{W}_{net}} \tag{30}$$

Decision variables and constraints

The decision variables (design parameters) in this study are compressor pressure ratio (r_{AC}), compressor isentropic efficiency (η_{AC}), GT isentropic efficiency (η_{GT}), CC inlet temperature (T_3), and GT inlet temperature (T_4). Even though the decision variables may be varied in the optimization procedure, each decision variable is normally required to be within a reasonable range. The list of these constraints and the reasons for their applications are summarized based on [19] and listed in tab. 3.

In every optimization, it is essential to define constraints. Therefore, according to fig. 2, the following constraints should be satisfied in heat exchangers (and heat recovery) [7]:

$$T_3 > T_2, \quad T_6 > T_2, \quad T_5 > T_3, \quad T_4 > T_3 \tag{31}$$

$$T_6 > T_9, \quad T_{7p} > T_9 + \Delta T_{pinch} \tag{32}$$

Table 3. The list of constraints for optimization [11]

Constraints	Reason
$T_4 < 1300$ K	Material temperature limit
$r_{AC} < 6$	Commercial availability
$\eta_{AC} < 0.9$	Commercial availability
$\eta_{GT} < 0.92$	Commercial availability

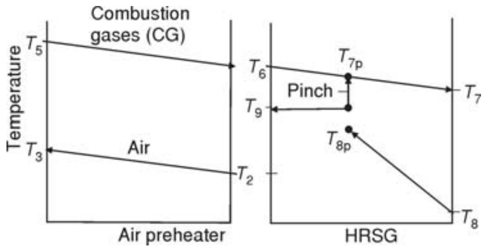

Figure 2. Temperature distribution in the air pre-heater and the HRSG

Genetic algorithm for multi-objective optimization

Multi-objective optimization

A multi-objective problem consists of optimization (*i. e.* minimization or maximization) of several objectives simultaneously, with a number of inequality or equality constraints. An algorithm based on non-dominated sorting was proposed by Srinivas and Deb and called non-dominated sorting genetic algorithm (NSGA). This was later modified by Deb *et al*. [20, 21] who eliminated higher computational complexity, lack of elitism and the need for specifying the sharing parameter. This algorithm is called NSGA-II which is coupled with the objective functions developed in this study for optimization [7].

Tournament selection

Each individual competes exactly in two tournaments with randomly selected individuals, a procedure which imitates survival of the fittest in nature. The advantage of this method is that if one of the members has a very high score, only this member participates in the competition in which participates and has nothing to do with other competitions so as to decrease the chance of the other relatively appropriate members.

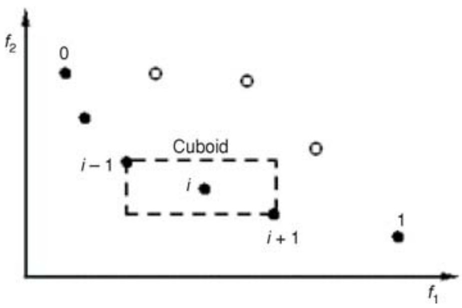

Figure 3. The crowding distance calculation

Crowding distance

The crowding distance of an individual is the perimeter of the rectangle with its nearest neighbors at diagonally opposite corners (fig. 3) [22]. Hence, if individual $X^{(a)}$ and individual $X^{(b)}$ have the same rank, the one which has a larger crowding distance is better [7].

Results and discussion

Optimization results

Figure 4 relates to Multi-objective optimization Pareto curve of objective functions (27 to 30). As shown in the figure, while exergy efficiency increases to approximately 40%, total cost of the products will increase a little. With increase of exergy efficiency from 40% to 41%, we see average increase in cost of the products and also increase of exergy efficiency from 44% leads to considerable increase of total cost rate.

As shown in fig. 4, maximum exergy efficiency is 42% which relates to point C while this point has maximum total cost of the product. On the other hand, the minimum cost relates to design point (A). Design point (C) is the optimal point in single-objective optimization of exergy efficiency and also design point (A) is the optimal point in single-objective optimization of total cost. In multi-objective optimization, each of the points in Pareto curve is an optimal answer and designer selects one of them based on the appropriate conditions. Decision-making process is usually performed with help of an assumed point which was named equilibrium in fig. 4. In this point, each one of the objective functions has its own optimal values independent of another objective function. Considering fig. 4, both objective functions cannot have their optimal values simultaneously and as the figure shows, equilibrium point is not a design point on Pareto curve. The nearest point on Pareto curve to equilibrium point may be regarded as a final desirable solution but condition for stability of the selected point is very important when one of the objective functions changes.

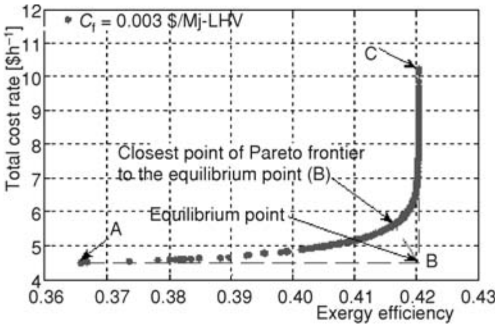

Figure 4. Pareto frontier: best trade off values for the objective functions

Total cost rate and emissions

In this section, the two objective functions include total cost and CO_2 emission. Results of multi-objective optimization are shown in fig. 5. As this figure shows, if we want to reduce CO_2 emission which is majorly dependent on thermodynamic properties of cycle components such as isentropic efficiency of a compressor and gas turbine, total cost of the equipment will increase.

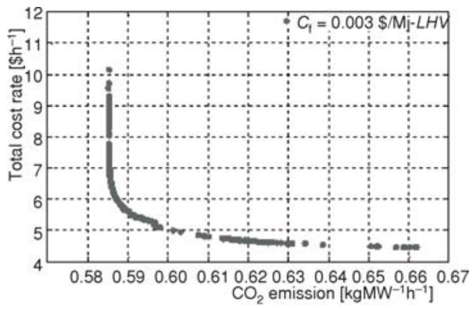

Figure 5. Pareto frontier for total cost rate *vs.* CO_2 emission

Sensitivity analysis

In this section, we study fuel price changes on both objective functions to understand optimization problem intuitively. Figure 6 shows sensitivity of Pareto curve for different values of fuel price. This curve shows that Pareto front is relocated with increase of fuel price. In higher exergy efficiencies which total cost of the system is higher, sensitivity of optimal solutions to fuel price is much higher than that of Pareto curve with lower total cost of the system. In fact, sensitivity of economic parameter of fuel price is not so effective on objective function of exergy efficiency. In addition, in higher exergy efficiencies, power plant equipment purchasing cost and as a result total cost will increase. Therefore, in a constant value of exergy efficiency, this objective function increases consid-

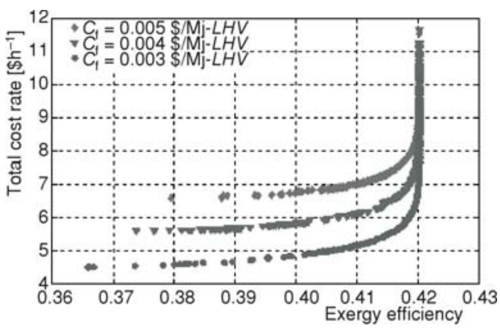

Figure 6. Sensitivity of Pareto optimum solution to the specific fuel cost

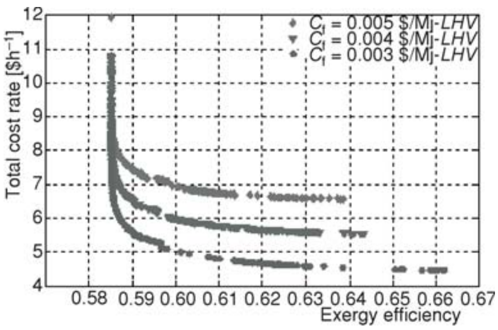

Figure 7. Sensitivity of Pareto optimum solution to the specific fuel cost

ering that fuel price plays effective role in total cost of the products.

Figure 7 shows Pareto curve sensitivity analysis for general CO_2 emission with change in fuel cost. This figure shows that in order to have a cycle which produces less CO_2, we may select the components such that thermodynamic parameters such as isentropic efficiency are higher leading to more purchasing cost of the equipment. In addition, increase of fuel price will increase this objective function due to importance of role of fuel price on total cost of the product.

Conclusions

In this paper, thermodynamic modeling and multi-objective optimization of gas micro turbine of 100 kW have been done by producing power and heat simultaneously. By defining objective function of exergy efficiency and total cost of system, we performed multi-objective optimization of micro turbine and obtained Pareto curves of objective functions. For CO_2 emission, a distinctive objective function was considered. It means that CO_2 gas emission is minimized for kWh function of micro turbine cycle. Pareto optimal solution sensitivity analysis was also studied for any change in values of fuel price. Results of this analysis show that total cost will increase in higher exergy efficiency. In addition, sensitivity of cost objective function to fuel price in higher exergy efficiencies is much higher than that in lower exergy efficiencies.

Table 4. Equations for calculating the Purchase costs (*Z*) for the components [7]

System component	Capital or investment cost functions
AC	$Z_{\mathrm{AC}}=\left(\dfrac{C_{11}\dot{m}_a}{C_{12}-\eta_{AC}}\right)\left(\dfrac{P_2}{P_1}\right)\ln\left(\dfrac{P_2}{P_1}\right)$
CC	$Z_{\mathrm{AC}}=\left(\dfrac{C_{21}\dot{m}_a}{C_{22}-\dfrac{P_4}{P_3}}\right)[1+e^{(C_{23}T_4-C_{24})}]$
GT	$Z_{\mathrm{GT}}=\left(\dfrac{C_{31}\dot{m}_{\mathrm{g}}}{C_{32}-\eta_{\mathrm{GT}}}\right)\ln\left(\dfrac{P_4}{P_5}\right)[1+e^{(C_{33}T_4-C_{34})}]$
APH	$Z_{\mathrm{APH}}=C_{41}\left[\dfrac{\dot{m}_{\mathrm{g}}(h_5-h_6)}{(U)(\Delta TLM)_{\mathrm{EV}}}\right]^{0.6}$
HRSG	$Z_{HRSG}=C_{51}\left[\left(\dfrac{\dot{Q}_{\mathrm{EC}}}{(\Delta TLM)_{\mathrm{EC}}}\right)^{0.8}+\left(\dfrac{\dot{Q}_{\mathrm{EV}}}{(\Delta TLM)_{\mathrm{EV}}}\right)^{0.8}\right]+C_{52}\dot{m}_{\mathrm{s}}+C_{53}\dot{m}_g^{1.2}$

Table 5. Constants used in the equations of tab. 4 for the Purchase cost of the components (tab. 4)

AC	C_{11} = 39.5 \$/(kg/s), C_{12} = 0.9
CC	C_{21} = 25.6 \$/(kg/s), C_{22} = 0.995, C_{23} = 0.018 K^{-1}, C_{24} = 26.4
GT	C_{31} = 266.3\$/(kg/s), C_{32} = 0.92, C_{33} = 0.036 K^{-1}, C_{34} = 54.4
APH	C_{21} = 2290 \$/$m^{1.2}$, U = 0.018 kW/(m^2K)
HRSG	C_{51} = 3650 \$/(kW/K)0.8, C_{52} = 11820 \$/(kg/s), C_{53} = 658 \$/(kg/s/)$^{1.2}$

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