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Effect of Ambient Temperature on Exergetic and Exergoeconomic Parameters of a CHP System

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Abstract

Exergy analysis permits the localization and counting of the inefficiency degree informing the most inefficient components in a system and exergoeconomic analysis methodologies combine economic and thermodynamic analysis by exerting the cost concept to exergy. This paper presents exergetic and exergoeconomic analysis of a Diesel engine based Combined Heat and Power (CHP) system that produces 277 kW of electricity and 282 kW of heat. For this purpose, the CHP system is first thermodynamically analyzed through energy and exergy. Then cost balances and auxiliary equations are applied to subsystems, hence, cost formation in the plant is observed. The exergoeconomic analysis is based on specific exergy costing (SPECO) method. Finally a parametric study is used to show effect of ambient temperature on important energy, exergy and exergoeconomic parameters of the CHP system. The results show that increasing ambient temperature decreases the exergetic efficiency of the system but it has a positive effect on the work output, heating power and cost of exergy destruction.

Keywords: Exergy, Exergoeconomics, SPECO, CHP, Ambient temperature

1. Introduction

Recently, worldwide concern about energy crisis and climate changes has provided continuous opportunities to extend energy efficient technologies. On the other hand, economic constraints and environmental considerations make it necessary to improve the performance of energy conversion systems [1]. Combined Heat and Power (CHP) systems have emerged as an effective method of energy conversion due to involving both production of electricity and useful thermal energy in one operation. These systems utilize the waste heat produced during electricity generation and allow more efficient fuel consumption [2]. Because CHP systems produce both useful thermal energy and electricity, the efficiency of energy production can be increased from current levels that vary from 35% to 55% in the conventional power plants to over 80% in the combined heat and power systems [3].

The second law of thermodynamics combined with economics represents a very powerful tool for the systematic study of energy systems. This combination forms the basis of the relatively new field of thermoeconomics or exergoeconomics. Exergoeconomics combines exergy analysis with conventional cost analysis in order to evaluate and optimize the performance of energy systems [4].

Many researchers have conducted exergy and exergoeconomic analyses for CHP systems. Colpan and Yesin [5] analyzed the energetic, exergetic and thermoeconomic aspects of the Bilkent combined cycle cogeneration plant. Cardona and Piacentino [6] presented a new method to exergoeconomic analysis and design of variable demand energy systems. Also Baghernejad and Yaghoubi [7] presented exergoeconomic analysis and optimization of an Integrated Solar Combined Cycle System (ISCCS) using genetic algorithm.

Power plants and CHP systems based on internal combustion engines are not a new idea but there have been no many studies on Diesel engine based ones in literature. In the present work, the exergoeconomic analysis is performed to the Diesel engine based CHP system that considered by Aceves et al. [8] for combined power and heating applications. The system is thermodynamically analyzed through energy and exergy. Then cost balances and auxiliary equations are applied to subsystems. Moreover a parametric study is used to show effect of ambient temperature on important energy, exergy and exergoeconomic parameters of the system.

2. System Description

Figure 1 shows a schematic diagram of the system. The Diesel engine intake air is first compressed to 3 bar absolute. The Diesel engine operates at compression ratio (15:1) and equivalence ratio of the engine is 0.7. Also the fuel heating power into engine is 600 kW and the fuel used in the engine is Diesel fuel. The engine exhaust gases flow through the turbine of the turbocharger unit to generate needed shaft work for the compressor. The cooling water loop goes from the engine to a heat exchanger being heated by exhaust gases. Process heat generated in the CHP system is recovered from this hot water and then the water is circulated into the engine [8].

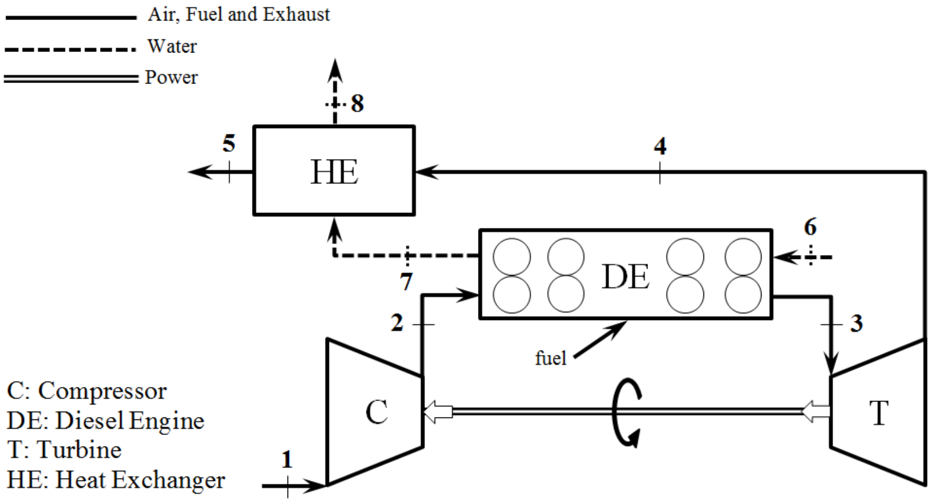

Figure 1. A schematic diagram of the CHP system

3. Exergoeconomic Analysis

Exergoeconomics based on the concept that exergy is the only rational basis for assigning monetary costs to the interactions that a system experiments with its surroundings and to the sources of thermodynamic inefficiencies within it [9]. There are different exergoeconomic approaches. We used specific exergy costing method (SPECO) in this study. This method is based on specific exergies and costs per exergy unit, exergetic efficiencies, and the auxiliary costing equations for components of thermal systems [10].

3.1. Application of SPECO Method to the System

SPECO method consists of three main steps: (i) identification of energy and exergy streams, (ii) definition of *fuel* and *product* for each component of thermal system and (iii) allocation of cost equations [10]. In the following sections, these steps are applied to the system.

3.2. Analysis of Energy and Exergy Streams

Energy and exergy balances for any steady state system can be written as:

$$\dot{Q} + \sum \dot{m}_i h_i = \dot{W} + \sum \dot{m}_e h_e \tag{1}$$

$$\dot{E}_Q + \sum \dot{m}_i e_i = \dot{E}_W + \sum \dot{m}_e e_e + \dot{E}_D \tag{2}$$

where $\dot{E}_D$ is the exergy destruction.

Because the kinetic and potential energy changes are insignificant, the total exergy rate is considered to be sum of the physical exergy and chemical exergy:

$$\dot{E} = \dot{E}_{ph} + \dot{E}_{ch} \tag{3}$$

The energy and exergy efficiencies are generally defined as [11]:

$$\eta = \left(\frac{energy\ in\ products}{total\ energy\ input}\right) \tag{4}$$

$$\varepsilon = \left(\frac{exergy\ in\ products}{total\ exergy\ input}\right) \tag{5}$$

The rate of exergy destruction in a system for the *k*th component can be compared to the exergy rate of the fuel provided to the overall system as [11]:

$$y_{D,k} = \frac{\dot{E}_{D,k}}{\dot{E}_f} \tag{6}$$

Also, the component exergy destruction rate can be compared to the total exergy destruction rate within the system as:

$$y^*_{D,k} = \frac{\dot{E}_{D,k}}{\dot{E}_{D,total}} \tag{7}$$

Table 1 shows the thermodynamic data of the CHP plant according to the nomenclature shown in Figure 1. These data are obtained from developed EES (Engineering Equation Solver) thermodynamic model for the system.

Table 1. Thermodynamic properties of fluids of the CHP system

State no.	Fluid	T (˚C)	P (bar)	h (kJ/kg)	s (kJ/kg K)	$\dot{m}$ (kg/s)	e_{ph} (kJ/kg)	e_{ch} (kJ/kg)	$\dot{E}$ (kW)
1	Air	27	1	300.6	5.706	0.2935	0	0	0
2	Air	156.5	3	431.3	5.753	0.2935	116.7	0	34.26
3	Exhaust	635.5	3	942.7	6.547	0.3075	389.7	51.15	135.6
4	Exhaust	443.1	1	730.8	6.601	0.3075	161.7	51.15	65.46
5	Exhaust	165	1	439.9	6.088	0.3075	24.73	51.15	23.34
6	Water	80	2	335	1.075	1.75	17.65	0	30.88
7	Water	106.1	2	444.9	1.375	1.75	37.42	0	65.49
8	Water	118.2	2	496	1.508	1.75	48.72	0	85.26

Definition of Fuel (F) and Product (P)

In describing the exergy flow through the components of the system, *fuel* and *product* terms must be recognized for each one. The fuel represents the resources needed to generate the product and it is not necessarily restricted to being an actual fuel such as natural gas, oil, and coal. The product represents the desired result produced by the system. Both the fuel and the product are represented in terms of exergy [7]. Definitions of the exergies of fuels $\dot{E}_F$ and products $\dot{E}_P$ for the components of the system are given in Table 2.

Table 2. Definitions of $\dot{E}_F$ and $\dot{E}_P$ for the components of the system

Component	$\dot{E}_F$	$\dot{E}_P$
Compressor	$\dot{W}_C$	$\dot{E}_2 - \dot{E}_1$
Diesel engine	$\dot{E}_f + \dot{E}_2 + \dot{E}_6$	$\dot{E}_3 + \dot{E}_7 + \dot{W}_{DE}$
Turbine	$\dot{E}_3 - \dot{E}_4$	$\dot{W}_T$
Heat Exchanger	$\dot{E}_4 - \dot{E}_5$	$\dot{E}_8 - \dot{E}_7$

3.3 Cost-Balance Equations of the System

Exergy costing involves cost balance for each component of the system. A cost balance equation applied to the *k*th component shows that the sum of cost rates associated with all exiting exergy streams equals the sum of cost rates of all entering exergy streams plus the cost rate due to capital investment and operating and maintenance expenses. The sum of the last two terms is denoted by $\dot{Z}_k$ [7].

Now, for each flow line in the system, a parameter called flow cost rate $\dot{C}$ ($/s) is defined and the cost balance equation for a component receiving heat and generating power is written as [7]:

$$\sum_e \dot{C}_{e,k} + \dot{C}_{w,k} = \dot{C}_{q,k} + \sum_i \dot{C}_{i,k} + \dot{Z}_k \tag{8}$$

One can write:

$$\sum (c_e \dot{E}_e)_k + c_{w,k} \dot{W}_k = c_{q,k} \dot{E}_{q,k} + \sum (c_i \dot{E}_i)_k + \dot{Z}_k \tag{9}$$

$$\dot{C}_j = c_j \dot{E}_j \tag{10}$$

For calculating the cost of exergy destruction in the components of the system, first we should solve the cost balance equations for each one. Generally, if there are N exergy streams exiting the component, we have N unknowns and only one equation, the cost balance. Therefore, we need to formulate N–1 auxiliary equations. This is performed with the aid of the F and P principles in the SPECO approach [10].

Developing cost balance equation for each component of the system and auxiliary equations (according to F and P rules of the SPECO method) leads to the following system of equations:

$$\dot{C}_2 = \dot{C}_{W_C} + \dot{C}_1 + \dot{Z}_C \tag{11}$$

$$\dot{C}_7 + \dot{C}_3 + \dot{C}_{W_{DE}} = \dot{C}_2 + \dot{C}_6 + \dot{C}_{fuel} + \dot{Z}_{DE} \tag{12}$$

$$\frac{\dot{C}_6}{\dot{E}_6} = \frac{\dot{C}_7}{\dot{E}_7} \tag{13}$$

$$\dot{C}_4 + \dot{C}_{W_T} = \dot{C}_3 + \dot{Z}_T \tag{14}$$

$$\frac{\dot{C}_4}{\dot{E}_4} = \frac{\dot{C}_3}{\dot{E}_3} \tag{15}$$

$$\dot{C}_8 + \dot{C}_5 = \dot{C}_4 + \dot{C}_7 + \dot{Z}_{HE} \tag{16}$$

$$\frac{\dot{C}_4}{\dot{E}_4} = \frac{\dot{C}_5}{\dot{E}_5} \tag{17}$$

$$\frac{\dot{C}_7}{\dot{E}_7} = \frac{\dot{C}_8}{\dot{E}_8} \tag{18}$$

The cost of the incoming air stream $\dot{C}_1$ is assumed to be zero and the cost of the fuel stream to the system is taken as 0.176 $/kg of Diesel fuel based on market price in Iran. Additional auxiliary equations are formulated assuming the same unit cost of exergy for the work produced or supplied to the system:

$$\frac{\dot{C}_{W_{DE}}}{\dot{W}_{DE}} = \frac{\dot{C}_{W_T}}{\dot{W}_T} \tag{19}$$

$$\frac{\dot{C}_{W_T}}{\dot{W}_T} = \frac{\dot{C}_{W_C}}{\dot{W}_C} \tag{20}$$

By solving the system of 10 equations and 10 unknowns, the costs of unknown streams are obtained. Exergoeconomic assessment of systems can be performed using exergoeconomic parameters. These parameters are the average cost per exergy unit of fuel ($c_{F,k}$) and per exergy unit of product ($c_{P,k}$), the exergoeconomic factor (f_k), and the cost flow rate of the exergy destruction ($\dot{C}_D$) and exergy loss ($\dot{C}_L$). Mathematically, these variables are given as [7]:

$$c_{F,k} = \frac{\dot{C}_{F,k}}{\dot{E}_{F,k}} \tag{21}$$

$$c_{P,k} = \frac{\dot{C}_{P,k}}{\dot{E}_{P,k}} \tag{22}$$

$$\dot{C}_{D,k} = c_{F,k}\dot{E}_{D,k} \qquad (23)$$

$$\dot{C}_{L,k} = c_{F,k}\dot{E}_{L,k} \qquad (24)$$

The exergoeconomic factor f_k is defined by:

$$f_k = \frac{\dot{Z}_k}{\dot{Z}_k + \dot{C}_{D,k} + \dot{C}_{L,k}} \qquad (25)$$

This factor is an important exergoeconomic parameter that shows the relative importance of a component cost to the associated cost of exergy destruction and loss in that component.

4. Results and Discussion

The costs of unknown streams of the system are given in Table 3.

Table 3. Cost of streams in the system

State no.	$\dot{C}$ ($/h)	c ($/GJ)
1	0	0
2	4.76	38.62
3	2.93	5.99
4	1.41	5.99
5	0.50	5.99
6	4.46	40.10
7	9.45	40.10
8	12.30	40.10
Diesel fuel	8.89	3.87
$\dot{W}_{DE}$	18.38	20.39
$\dot{W}_C$	2.82	20.39
$\dot{W}_T$	4.78	20.39

The values of important exergy and exergoeconomic parameters for the system are given in Table 4.

Table 4. Exergy and exergoeconomic parameters of the system

Components	$\dot{E}_F$ (kW)	$\dot{E}_P$ (kW)	$\dot{E}_D$ (kW)	y* (%)	y (%)	ε (%)	$\dot{C}_{D,k}$ ($/h)	$\dot{Z}_k$ ($/h)	$\dot{Z}_k+\dot{C}_{D,k}+\dot{C}_{L,k}$ ($/h)	f (%)
Compressor	38.38	34.27	4.12	1.46	0.62	89.28	0.30	1.94	2.24	86.56
Diesel Engine	702.1	451.5	250.6	88.86	37.53	39.31	6.46	12.65	19.11	66.19
Turbine	70.12	65.18	4.94	1.75	0.74	92.95	0.11	3.27	3.38	96.84
Heat Exchanger	42.14	19.77	22.37	7.93	3.35	46.92	0.48	1.94	2.42	80.11
Overall System	667.8	362.5	282	100	42.24	54.28	7.35	19.8	27.15	71.61

The components having the highest value of the sum of $\dot{Z}_k+\dot{C}_{D,k}+\dot{C}_{L,k}$ are the most important components from the exergoeconomic viewpoint. The Diesel engine has the highest value of the sum $\dot{Z}_k+\dot{C}_{D,k}+\dot{C}_{L,k}$ and the lowest value of the exergoeconomic factor, *f*. This means that the cost rate of exergy destruction is noticeable for this component. Total exergy destruction in Diesel engine is 250.6 kW and it is 37.53% of the total exergy input and 88.86% of the total exergy destruction in the plant. High exergy destruction in the engine is because of the highly irreversible combustion process in the Diesel engine. Although increasing the investment cost can lead to a decrease in the cost of the exergy destruction of the engine, in any other configuration of the system, the engine will have the highest cost of the exergy destruction due to the combustion process.

The turbine has the highest value of the exergoeconomic factor, *f*. Also this value is 86.56% for the compressor. This means that the owning and operating cost of the turbocharger unit is significantly higher than the cost of the exergy destruction in it. High value of the exergy efficiency for the turbine and compressor confirms this. Exergoeconomic improvement of this unit can be achieved by decreasing the capital investment of the unit.

Also relatively high *f* value for the heat exchanger shows that it can be cost effective to reduce the investment cost by decreasing the surface area.

Exergy loss from the system is equal to the exergy of stream leaving the heat exchanger and exhaust to the environment. This value is calculated to be 23.34 kW and the cost flow rate associated with this exergy is 0.5 $/h.

The energy and exergy efficiency of the overall CHP system are found to be 93.16% and 54.28%, respectively. Also work output and heating power of the system are calculated as 277.1 kW and 281.7 kW, respectively.

In the following, effect of the ambient temperature on important energy, exergy and exergoeconomic parameters of the system is investigated.

Figure 2 shows effect of ambient temperature on the work output and heating power of the system.

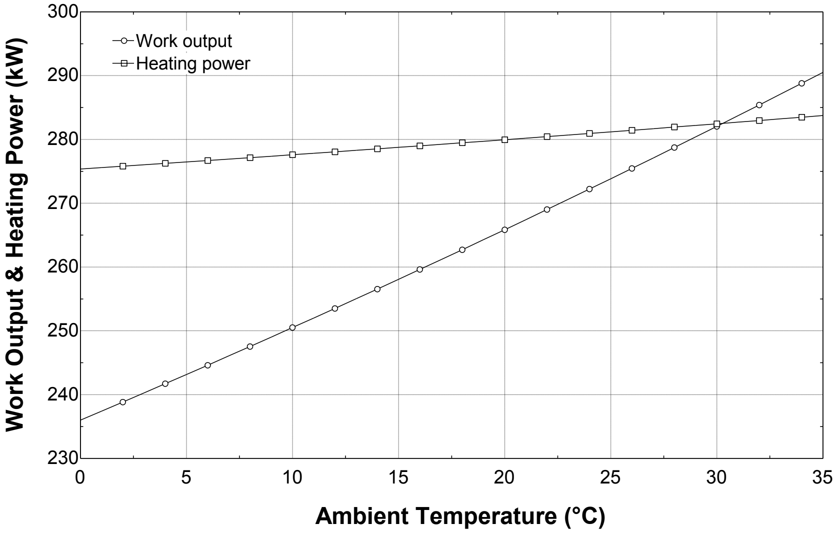

Figure 2. Effect of ambient temperature on the work output and heating power

Ambient temperature has little effect on the heating power but the work output increases with increasing ambient temperature. This is mostly due to increasing the work produced by the engine because of rising engine inlet temperature with increasing ambient temperature.

Exergetic efficiency of the system as a function of ambient temperature is given in Figure 3. Increasing ambient temperature increases the exergy destruction in the components and as a result the exergetic efficiency of the system is decreased.

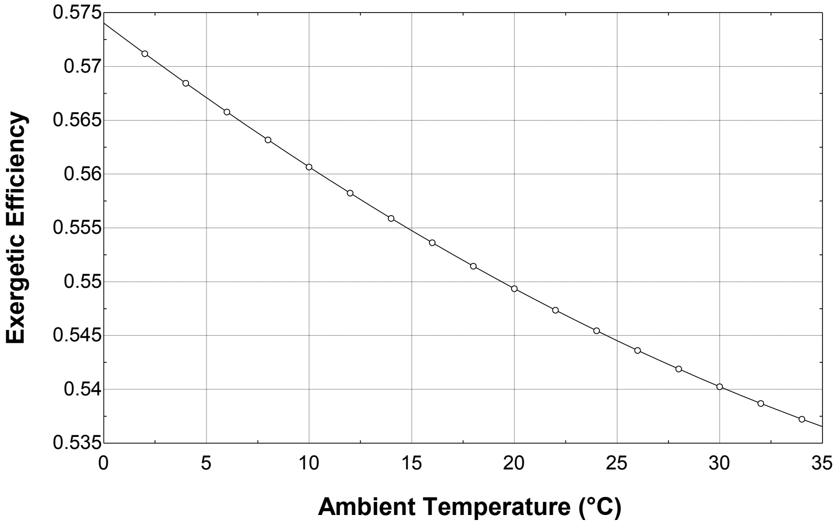

Figure 3. Exergetic efficiency of the system as a function of ambient temperature

Effects of ambient temperature on the cost of exergy destruction and exergoeconomic factor are shown in Figure 4 and Figure 5, respectively.

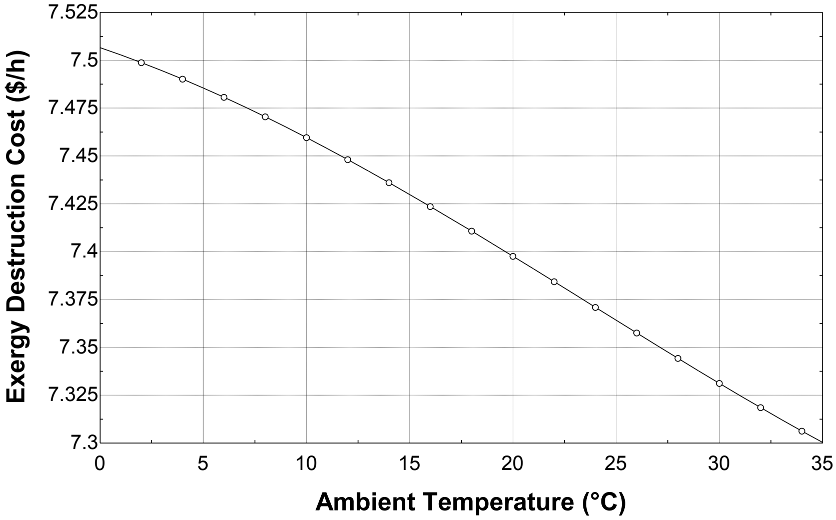

Figure 4. Effect of ambient temperature on the cost of exergy destruction

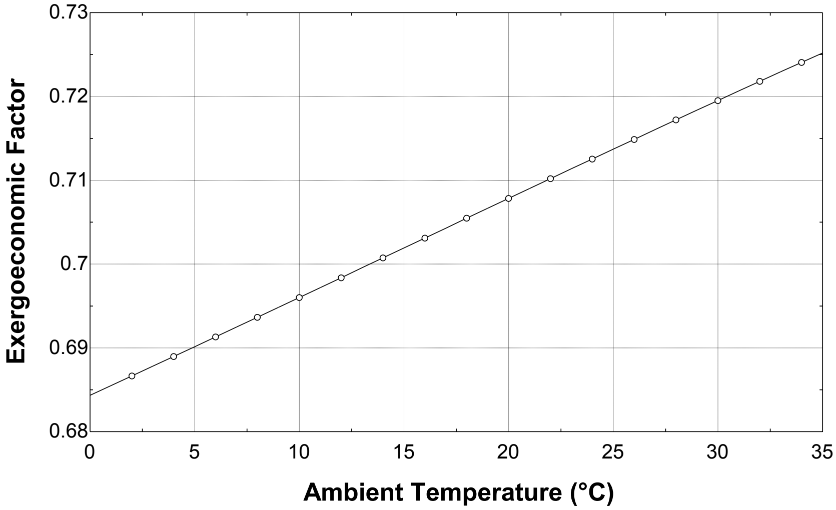

Figure 5. Effect of ambient temperature on the exergoeconomic factor

Referring to these figures, increasing ambient temperature leads to a little decrease in the cost of exergy destruction and a little increase in the exergoeconomic factor.

5. Conclusions

The detailed exergoeconomic analysis of the Diesel engine based Combined Heat and Power (CHP) system is performed. Exergy destruction within the components and exergy efficiencies are calculated and the values of exergoeconomic variables are determined for the components and entire CHP system. Moreover a parametric study is used to show effect of ambient temperature on important energy, exergy and exergoeconomic parameters of the system. The results show that increasing ambient temperature decreases the exergetic efficiency of the system but it has a positive effect on the work output, heating power and cost of exergy destruction. The results of this study help better understanding the cost formation process in the plant. Also these results can be used as a basis for exergoeconomic optimization of the system.

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