Exergy Analysis of a Cogeneration Plant

Derya Burcu Ozkan, Onur Kiziler, Duriye Bilge

***Abstract*—**Cogeneration may be defined as a system which contains electricity production and regain of the thermo value of exhaust gases simultaneously. The examination is based on the data's of an active cogeneration plant. This study, it is aimed to determine which component of the system should be revised first to raise the efficiency and decrease the loss of exergy. For this purpose, second law analysis of thermodynamics is applied to each component due to consider the effects of environmental conditions and take the quality of energy into consideration as well as the quantity of it. The exergy balance equations are produced and exergy loss is calculated for each component. 44,44 % loss of exergy in heat exchanger, 29,59 % in combustion chamber, 18,68 % in steam boiler, 5,25 % in gas turbine and 2,03 % in compressor is calculated.

***Keywords*—**Cogeneration, Exergy loss, Second law analysis

I. Introduction

EFFICENT usage of energy becomes more important in our world where the fossil fuels are limited. [1] Companies are paying attention to use energy efficiently by investing cogeneration plants where electricity and heat energy are used simultaneously.

Cogeneration system reduces the cost of energy in industries such as textile, folio, ceramic, chemistry, food and metal. Moreover, cogeneration applications on residential and industrial areas are giving promising results.

There are two kinds of approaches to design the plant; according to the need of electricity or to the need of heat energy of the factory. Establishing cogeneration system in a way meeting all the heat energy requirements, more electricity power is generated than needed by factory and this method is preferred in countries where selling excessive electricity to the electric grid is more profitable.

In countries where selling generated electricity to the electric grid is not profitable like Turkey, where cogeneration plant that is examined is located, factory designs plants according to the needed electricity capacity and use heat energy as a supporter to the central heat station. The advantages obtained by corporations by using cogeneration system are given below.

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1. Due to usage of electricity where it is actually generated, there is no loss of transfer and by regaining the heat energy, the cost of energy is kept low.
2. Factories are not concerned by harm given to the regarding machines because of voltage and frequency fluctuation.
3. Saving from the primary fuel in proportion to regained heat energy, the limited sources are used efficiently furthermore emission harm is reduced to minimum.
4. Corporations are not affected by blackouts caused by power grid and electricity can be received from electric grid when maintenance and breakdown happens.
5. National electricity generation is supported.

Optimization of thermal systems is generally based on thermodynamic analysis. However, the systems thus optimized are often not available due to economic constraints. The theory of exergy cost, a thermoeconomic optimization technique, combines the thermodynamic analysis with that of economic constraints to obtain an optimum configuration of a thermal system [2].

Huan et al. performed an exergy analysis on a cogeneration system with steam-injected gas turbine. By specifying the balance equations of mass, energy, and exergy of the components, they determined the exergy loss. By taking the compressor pressure ratio, ratio of the vapour injected, temperature of the vapour, and amount of the feed water as parameters, they wrote down the outputs of the first and second law and calculated the heat–power ratios. They also stated that while the highest exergy loss occurred in the combustion chamber, the highest exergy leakage occurred through the waste gases [3]. Bandyapadhyay et al. realized the thermo-economic optimization of the cogeneration facility through parameters such as the magnitude of the facility, investment costs, and power generation required for designing and operating the facilities. Furthermore, this study was also examined by taking surface areas, heat conveyance, flow directions, and laws on heat transfer into account to increase the productivity of heat exchangers. By adopting a flexible approach as to the choice of fluid, besides determining the operational pressure, the optimum design and the operational requirements of the cogeneration facility were determined [4]. Kwon et al. stated that it was hard to determine the separate unit costs of the products for facilities such as cogeneration plants and combined cycle plants in which two products were obtained by harnessing from a single fuel. Besides adding that such a determination of the above mentioned facilities was of importance. Furthermore, they performed an exergy economic analysis of a 1000-kW gas turbine cogeneration facility. By calculating the exergy costs for a unit product, they wrote down the exergy balance for each point during the flow process and they formed an exergy economic balance equation for each component based on these exergy values. They employed a specific energy cost method developed by Tsatsaronis and the method of Modified Productive Structure Analysis of Thermal System developed by Kim and later compared the cost of the products. According to the result of the study mentioned above, when the specific exergy cost method was analyzed, although employing a waste heat boiler did not cause a change in the exergy cost of unit electricity, they observed that the costs are decreased when the Modified Productive Structure Analysis of Thermal System was employed. They also determined that no change occurred in the unit exergy cost of steam. In this study, the costs of the components of the gas turbine cogeneration facility were calculated and the ratios of such costs to the total cost were determined. Finances were levelized and thus levelized costs were employed in these calculations. They showed that when the specific exergy cost method was employed, it had an impact on the cost of electricity and especially on the cost of the turbine and compressor. Thus they indicated that the cost of all the components was affected by both the methods [5]. Valdes et al. introduced a thermo economic optimization model into the cogeneration facility based on their studies. This optimization process was generally applied to a cogeneration system composed of a single pressure by employing a genetic algorithm. This system once applied was also utilized in the optimization of more complex facilities, such as the heat recovery steam generators which had two to three pressure levels. The variables taken into consideration for the optimization were the thermodynamic parameters to be determined for designing the HRSG. Two different functions were proposed when the study was performed. While one of the functions helped to minimize the production cost, the other gave rise to maximizing the yearly cash flow. The results helped in determining the best optimization strategy by comparing these two functions [6]. Siveira and Tuna performed a thermo economic analysis of the cogeneration plants. Air and combustion products were regarded as ideal gases for this study and all the components outside the combustion chamber were thought to be adiabatic. On the basis of the second law of thermodynamics, they tried to minimize the exergy production costs. The values related to the processed vapor and electricity production were taken as fixed values for this calculation. The variables in the optimization process were as follows: in the case of steam turbine the pressure of the steam and the outlet of the boiler were considered as variables and in the case of gas turbine the ratio of pressure, the outlet pressure of turbine exhaust gas, and the mass flow rate were taken as variables. The model was first applied to a simple Rankine cycle and then to a cogeneration system with regenerator gas turbine. While the calculations were being made, first the outlet cost of each component was found and thus the value determined was considered as the inlet cost of the next component. In conclusion, the exergy production costs of steam, electricity, and the products of combustion, all of which form the object function and the conditions leading to the minimal cost for the simple rankine cycle, and the cogeneration system with regenerator gas turbine were realized. Also, the application of the model was shown by employing the real data of a facility in a chemical industry in Sao Paulo [7].

Temir and Bilge analyzed the trigeneration system in terms of thermoeconomic aspects. An electrical generator fed by natural gas and a trigeneration system composed of a cooling system with absorption harnessed from the heat energy of the exhaust gases of the aforementioned generator were examined [2].

In the system examined, a cogeneration plant is established to meet the electricity requirements of a milk, a seed and a beer factory and to bring saturated steam to the milk and seed factory as well as superheated water to the beer factory. 55000 MW/year electricity, 75000 ton/year saturated steam at 205°C and 16 bar is produced and 125.109 kJ/year energy is transferred. In the study, energy balance equations are applied to each component through the second law of thermodynamics and exergy loss is calculated. Evaporative cooling, compressor, combustion chamber, gas turbine, heat exchanger and steam boiler are the components of the system. In results of the analyses, it is seen that 0 kW of exergy is lost in evaporative cooling meanwhile 111 kW in compressor, 3226 kW in combustion chamber, 286 kW in gas turbine, 4845 kW in heat exchanger and 2037 kW in steam boiler is lost. When percentage of exergy destyroyed by component is taken into consideration, 39,30 % of loss of exergy in heat exchanger, 37,75 % in combustion chamber, 16,52 % in steam boiler, 4,64 % in gas turbine and 1,80 % in compressor is calculated. In this consequence, exergy loss that is seen as a potential lost of work, is seen in heat exchanger at most. According to these results, heat exchanger is the component to be paid attention when considering a new amendment.

II. SYSTEM DESCRIPTION

The system process flow of the cogeneration system where 55000 MW/year electricity, 75000 ton/year saturated steam and is given below 125.109 kJ/year heat energy of overheated water is produced, is given in the figure 1 below.

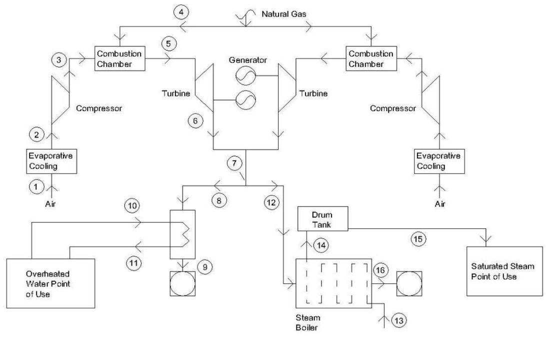


Fig. 1 System Process Flow

The operating method of the system was examined on the basis of the parameters of a cogeneration system producing electricity, superheated water and saturated water. Thus efficiency of components was calculated through exergy and exergy loss by each component in the system by means of the thermodynamic analysis. The atmospheric air is cooled in evaporative cooler, capacity of 60000 m3/h air inlet. Designed to run by natural gas, twin gas turbines capacity of 10000 kW in total are used for generating electricity to use in a milk factory, beer factory, feed factory and the cogeneration system itself. Exhaust gas, temperature of 764,44 K and pressure of 0,1 MPa leaves the turbines and is used in two different systems; heat exchanger where superheated water is produced and steam boiler where saturated steam is produced. 17,44 kg/s of exhaust gas (44,35%) is used to heat 128,34 kg/s water, temperature of 419 K and pressure of 1,1 MPa. Water's temperature is raised to 430 K while exhaust gas's temperature decreases to 421,60 K from 764,44 K before being thrown out to atmosphere. The superheated water circulates to be used in beer factory and returns in a closed circuit system. 21,88 kg/s of exhaust gas (55,65%) is used in steam boiler. Steam boiler's pressure is 1,6 MPa causing water's saturation temperature is 478 K. 2,36 kg/s water is taken into boiler at 325 K and leaves the boiler at 478K in gas phase to be used in milk and feed factory. Transferring its heat to water, exhaust gas is thrown out to atmosphere at 397,30 K.

The following definitions are accepted for analysis calculations of the cogeneration system:

- Equipments are systems having continuous flow.
- Boiler, pipes and components of other installations are insulted against heat losses.
- The fuel enters into boiler under environmental conditions.
- Dead state is environment state. (T_0 = 303 K and P_0 = 0,1 MPa)
- The boiler is run by natural gas.
- Natural gas is Methane.
- Air and natural gases are ideal gases.
- Exhaust gas behaves like air and is an ideal gas.
- Evaporative cooling is a process that enthalpy is stable during.

III. Exergy Analysis

According to Bejan [8], the exergetic balance applied to a fixed control volume is given by the following equation:

$$\sum \dot{m}_{in} e_{in} - \sum \dot{m}_{out} e_{out} + \dot{Q}\left(1 - \frac{T_0}{T}\right) - \dot{W} - \dot{E}_D = 0 \qquad (1)$$

The second law analysis, i.e. the exergy analysis, calculates the system performance based on exergy, which is defined as the maximum possible reversible work obtainable in bringing the state of the system to equilibrium with that of environment. In the absence of magnetic, electrical, nuclear, surface tension effects, and considering that the system is at rest relative to the environment, the total exergy of a system can be divided into two components: physical exergy and chemical exergy;

$$E = \dot{E}_{Ph} + \dot{E}_{Ch} \qquad (2)$$

The physical exergy component is associated with the work obtainable in bringing a stream of matter from its initial state to a state that is in thermal and mechanical equilibrium with the environment. Mathematically,

$$\dot{E}_{Ph} = \dot{m} e_{Ph} \qquad (3)$$

The physical and the chemical exergies of current in the cogeneration system will be calculated. The physical exergies in the calculations were obtained from the following formula.

$$e_{Ph} = (h - h_0) - T_0 (s - s_0) \qquad (4)$$

The chemical exergy of fuel,

$$e_F^{ch} = \left[1.0401 + 0.1728\frac{h}{c} + 0.0432\frac{o}{c} + 0.2169\frac{s}{c}\left(1 - 2.0628\frac{h}{c}\right)\right] \times LHV \qquad (5)$$

h,c,o,s are the mass fractions of H,C,O and S respectively.

$$CH_4 + 3(O_2 + 3{,}76N_2) \rightarrow CO_2 + 2H_2O + O_2 + 11{,}28N_2 \qquad (6)$$

Since the combustion air entering the control volume is very close to the reference state, both its thermo-mechanical and chemical exergies are equal to almost zero. Similarly, the thermo-mechanical exergy of the fuel is also zero.

In gas turbines, more air than needed is used and it is usual that air fuel ratio according to mass is 50 or more. Therefore accepting exhaust gas as air does not lead to an important miscalculation. [9]

The mass flow rate, temperature and pressure values in specified points are the values of measurement in cogeneration plant. Environmental conditions refer to temperature and pressure of the air and gas behaviors in dead state conditions of where the plant is located.

Entropy change (s - s0) equation for gases,

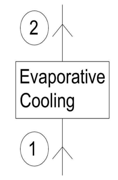
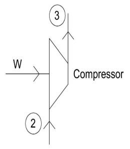
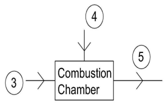
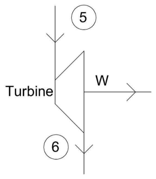
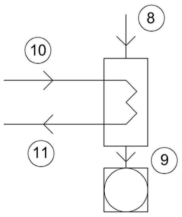
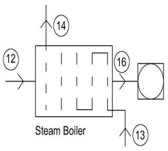
$$s - s_0 = s_1^{\,0} - s_0^{\,0} - R \ln \frac{p_1}{p_0} \qquad (7)$$

Entropy change (s - s0) equation for liquids, is calculated with

$$s - s_0 = \int_0^1 c(T)\frac{dT}{T} = c_{ort} \ln \frac{T_1}{T_0} \qquad (8)$$

the (8) equations. In table 1, energy equations and exergy destruction equations are shown for each component.

TABLE I
ENERGY AND EXERGY DESTRUCTION EQUATIONS

Name	Figures	Energy Equations	Exergy Destruction Equations
Evaporative cooling		$-Q=m_2(h_2-h_1)$	$E_1=E_2+E_d$
Compressor		$W=m_2(h_3-h_2)$	$E_2+E_W=E_3+E_d$
Combustion chamber		$Q=(m_5h_5)-(m_3h_3+m_4h_4)$	$E_Q+E_3+E_4=E_5+E_d$
Turbine		$W=m_5(h_5-h_6)$	$E_5=E_6+E_W+E_d$
Heat Exchanger		$m_8h_8+m_{10}h_{10}=m_9h_9+m_{11}h_{11}$	$E_8+E_{10}=E_9+E_{11}+E_d$
Steam Boiler		$m_{12}h_{12}+m_{13}h_{13}=m_{14}h_{14}+m_{16}h_{16}$	$E_{12}+E_{13}=E_{14}+E_{16}+E_d$

IV. RESULTS AND DISCUSSION

In this study, exergy analysis is done by taking the values of measurements of a cogeneration system located in Izmir, Turkey in to consideration. Second law of thermodynamics is applied to all components, concerning the evaporative cooling, combustion chamber, gas turbine, heat exchanger and steam boiler and each component is evaluated in the context of second law efficiency and exergy loss.

In Table II, quantity of the components and exergy loss by component accordingly are given.

TABLE II
EXERGY LOSS BY COMPONENT

Component	Quantity	Exergy Loss (kW)
Compressor	2	221,56
Combustion Chamber	2	3226,00
Turbine	2	572,32
Heat Exchanger	1	4845,14
Steam Boiler	1	2036,86

In figure 2, percentage of exergy loss by component is given by taking the amount of the destroyed exergy in table ll.

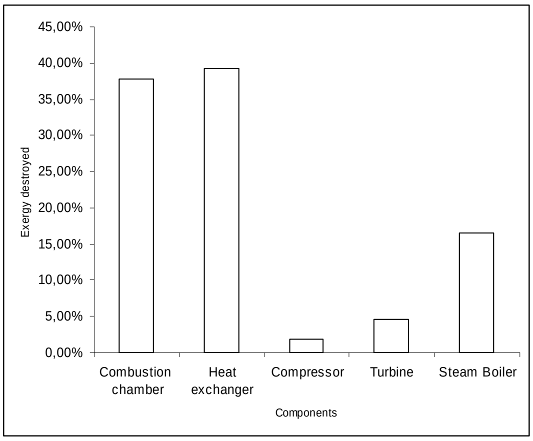


Fig. 2 Percentage of exergy loss by component

In figure 3, second law efficiencies of the components as a graphic. In engineering systems, causes of irreversibility's are examined and by reducing the irreversibility's, the efficiency is tried to be increased as much as possible. [9] In this cogeneration system, efficiency should be increased by increasing the second law efficiencies of the steam boiler, combustion chamber and heat exchanger.

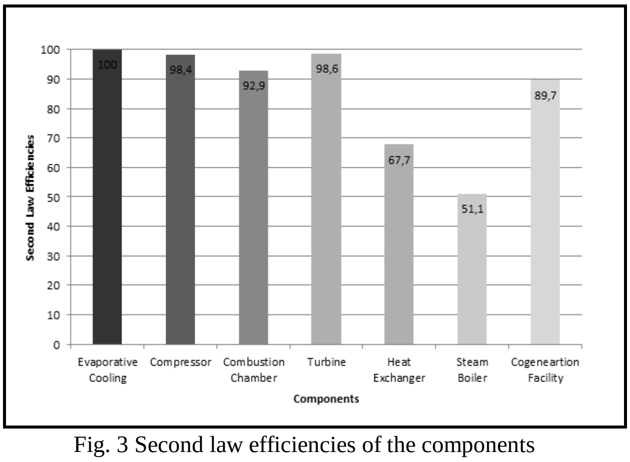


Fig. 3 Second law efficiencies of the components

Evaluating the results, exergy loss that is seen as a lost potential of work is seen at most in heat exchanger by 44,44%. According to this result, a possible amendment should be made to the heat exchanger. In order to increase the efficiency of the entire plant, following amendment should be made to combustion chamber than, steam boiler.

TABLE III
UNITS

Symbol	Quantity	Unit
c	specific heat	kj/kg.K
c	mass fraction of carbon	
e	specific exergy	kj/kg
h	entalphy	kj/kg
h	mass fraction of hydrogen	
$\dot{m}$	mass flow	kg/s
P	pressure	mPa
R	gas constant	kj/kg.K
Q	heat	kW
s	entropy	kj/kg.K
s	mass fraction of sulphur	
T	temperature	K
W	work	kW
E	exergy	kW

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