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PERFORMANCE ASSESSMENT OF A COGENERATION SYSTEM IN FOOD INDUSTRY

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ABSTRACT

Extensive analysis of the thermodynamics first and second laws is performed on a 14.25 MW cogeneration plant in Adana, Turkey. In this study, the most important parts of the system is observed and thermodynamic performance assessments are evaluated. The obtained outcomes indicate that major exergy destruction happens in boiler, which is 42% of the whole system irreversibility. Moreover, the economizer and chimney have also considerable irreversibilities which are 29% and 25%, respectively. The energy efficiencies of the chimney, economizer and boiler are calculated as 61.68%, 66.03%, 79.91%, respectively. On the other hand, the exergy efficiencies of chimney, economizer and boiler are calculated as 96.56%, 30.27% and 71.94%, respectively.

Keywords: *Cogeneration, Energy, Exergy, Thermodynamic Analysis, Food Industry.*

INTRODUCTION

Most of the emerging technologies in the world is related to energy consumption based on non-renewable fossil fuels, since they limited resources and they also cause severe environmental pollution. The fossil fuels are an important reason for the environmental pollution while natural gas is more environmental friendly. On the other hand, reuse of the waste heat is one of the important source to produce energy due to high amount of fossil fuel consumption and consequent global warming.

Cogeneration generates heat and work using single fuel to develop energy usage in the system. Energy efficiency increases while the environmental pollution decreases thanks to the cogeneration systems. Improving the efficiency of systems is a cheap, fast and easy way to accomplish. For these reasons, performance analysis, especially the effectiveness analysis of the losses and irreversibilities is the heart of the improvement actions. The obtained information is used to determine the operation costs. With the help of the exergy analysis, exergy destructions of the system can be exposed, while potential can be introduced to improve the system efficiency [1-22].

There are a number of studies on thermodynamic analysis for the cogeneration systems in the literature. Neseli et al. [15] analyzed amount of the waste energy that could be recovered by applying law of thermodynamic during the pressure reducing process in a natural gas pressure reduction station in Izmir, Turkey. They used turbo-expanders in place of throttle valves and regulators to produce energy from the natural gas. They calculated the highest energy and exergy efficiencies of the system as 94.96% and 70.61%, respectively. The mean value of CO_2 emission factor was found as 295.45 kg/MW h. Kamate and Gangavati [8] examined the exergy analysis for the cogeneration plants in sugar industries. The exergy analyses were implemented for each part of the system to evaluate the system efficiencies. They concluded that the most exergy destruction occurred in boiler while the least exergy destruction occurred in turbine. Acıkkalp et al. [1] examined the exergetic performance evaluation of an electricity production plant in Eskisehir, Turkey. They used an advanced exergy analysis method for this evaluation. The exergy efficiency was found as 40.2%. On the other hand, they calculated exergy destruction rate as 78.242 MW. They observed that condenser, combustion chamber and the high pressure steam turbine could develop the system efficiency.

An exergy analysis is implemented for a cogeneration system producing electricity and steam in a food plant. On the basis of the data obtained from running plant, the exergy analysis and the exergetic performance assessment are exerted for each part of the cogeneration plant. Moreover, the Grassmann diagrams, which yields information concerned with the amount of exergy input to the system for each part, were presented. Although exergetic performance evaluation of the cogeneration plants are broadly taken into account, investigation concerned with real case data achieved from running plant is still necessary, essentially. Furthermore, as can be understood from the limited number of studies available in the literature, there is an important gap in performance

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studies regarding cogeneration systems in the food industry. This study is carried out to fill this void in literature about performance analyses on cogeneration system in food industry.

SYSTEM DESCRIPTION

The plant has 14.25 MW capacity and its major components are a boiler (B), an economizer (ECO), a turbine (TE), four ventilation fans (VF), a chimney (CH) and two pumps (P). The diagrammatic representation of the investigated cogeneration plant is illustrated in Figure 1.

The boiler, which is one of the major parts of the cogeneration plant, is steam capacity of 22 t/h. Moreover, pressure of steam is 12 bar. Four ventilation fans provide the combustion air for the burner in order to achieve combustion in the system. Total capacities of them are 46000 m^3/h (30 kW). The boiler and economizer components have vertical and horizontal heat exchangers in which heat transfer occurs. The data for operating conditions of the cogeneration system are given in Table 1. The capacities of the feed water pump, which is used in the system, are 83 kW (22 t/h) and the chimney which is made of steel has no insulation material. In the system, the feed water is first pumped into the economizer and then this feed water reaches the boiler. Water is transformed into steam by the help of heat exchangers, located in boiler. A number of assumptions are made in this work which are:

- the plant operation is in a steady state,
- vicissitudes in potential and kinetic energy are not taken into account,
- conventional boiler is used in the system,
- physical exergy of natural gas is ignored,
- turbine is accepted as adiabatic.

Table 1. Operating conditions of the system

Air flow rate	46000 m^3/h
Comb. gas flow rate	40.21 kg/s
Natural gas flow rate	0.5179 kg/s
Steam flow rate	22 t/h
Steam pressure	12 bar
Steam temperature	190°C
Water flow rate	22 t/h

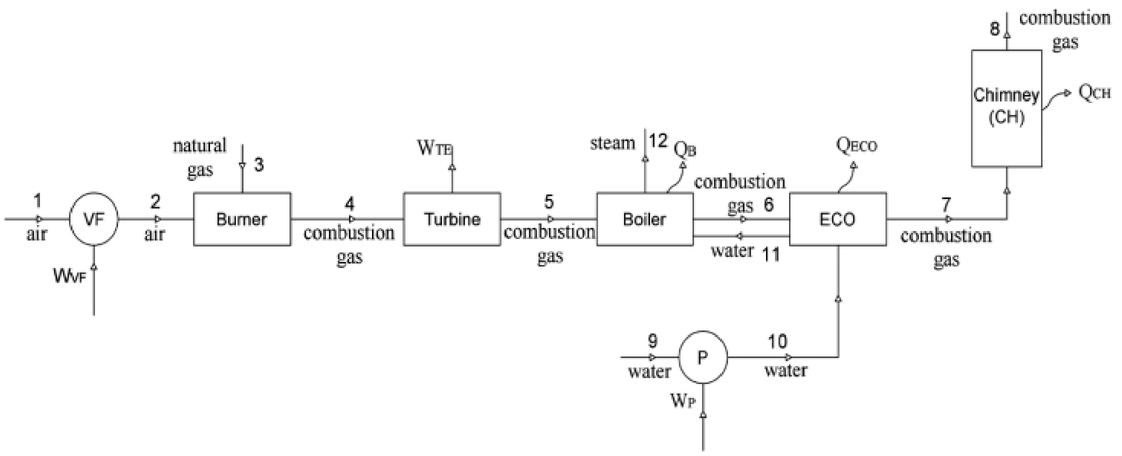

Figure 1. Diagrammatic representation of the cogeneration plant [21]

ANALYSIS

The purpose of the present study is to perform thermodynamic analyses in belief that grasping and showing the most and the least effective parts of the cogeneration plant. The thermodynamic efficiencies of the cogeneration system are described as efficiencies of energy and exergy based on the thermodynamics first and second laws. Schematic diagram of components for cogeneration system are represented in Figure 2. For the calculations, the thermodynamic characteristics of the water, steam and combustion gases are obtained from the tables of thermodynamics. Moreover, in order to take into account exergetic performance of the cogeneration plant, the reference environment are assumed as T_0 = 35°C, P_0 = 101.3 kPa.

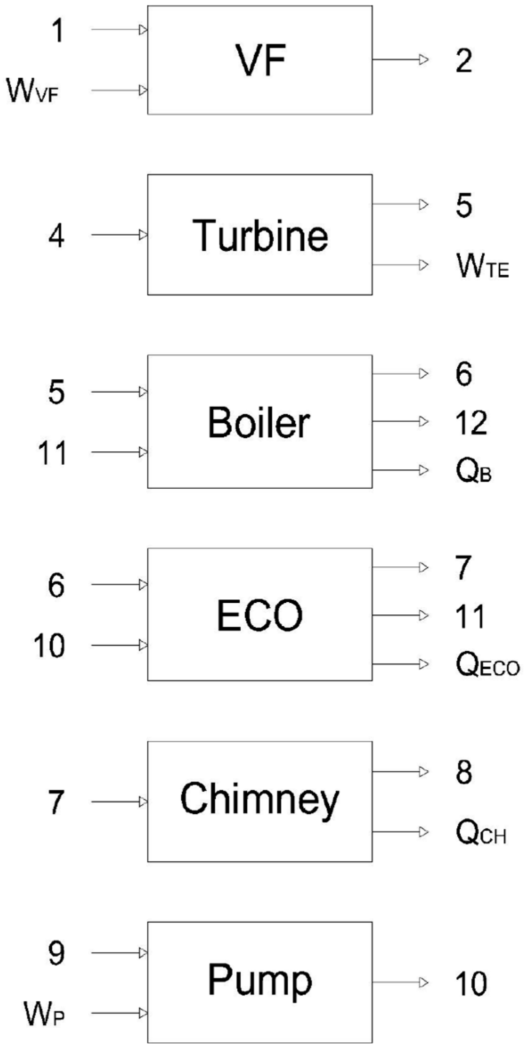

Figure 2. Diagrammatic representation of the parts [21]

The analysis of first law is employed with the help of balance equations of mass and energy, as can be shown in Equations (1) and (2):

$$Mass\ Input = Mass\ Output\ (\Sigma \dot{m}_{in} = \Sigma \dot{m}_{out}) \tag{1}$$

$$Energy\ Input - Energy\ Output = Net\ Energy\ (Q + W) = \Sigma \dot{m}_{out} h_{out} - \Sigma \dot{m}_{in} h_{in} \tag{2}$$

Energy balance equation for the conventional boiler can be described as Equation (3):

$$E5 + E11 = E12 + El \tag{3}$$

$$El = Ecg + Qloss \tag{4}$$

$$Ecg = \dot{m}fuel\dot{m}cgCp{-}cg(Tcomb - T0) \tag{5}$$

where E_l, E_{cg}, and Q_{loss} represent the energy loss, the energy of combustion gas and heat loss on the boiler surface via radiation transmission, respectively. The balance equation of energy for the economizer can be calculated as in Equation (6):

$$\dot{m}_6h_6 + \dot{m}_{10}h_{10} = \dot{m}_7h_7 + \dot{m}_{11}h_{11} + Q_{loss} \quad (6)$$

Exergy balance equations can be asserted as Equation (7):

$$Exergy\ Input - Exergy\ Output - Exergy\ Consumed = Net\ Exergy \quad (7)$$

The general formula required to calculate the physical exergy is given as Equation (8):

$$ex^{ph} = (h - h_0) - T_0(s - s_0) \quad (8)$$

Exergy balance equation for the conventional boiler can be calculated with Equation (9):

$$Ex_5 + Ex_{11} = Ex_6 + Ex_{12} + Q_B(1 - T_0 / T_S) + \dot{E}x_D \quad (9)$$

Exergy balance equation for the economizer can be calculated with Equation (10):

$$Ex6 + Ex10 = Ex7 + Ex11 + QECO(1 - T0 / TS) + \dot{E}xD \quad (10)$$

The energy efficiency, which is described as the ratio of energy output to energy input, can be written as Equation (11):

$$\eta 1 = energy\ output/energy\ input = 1 - (energy\ loss/energy\ input) \quad (11)$$

The energy efficiency for the boiler can be given by Equation (12):

$$\eta_{I,B} = (\dot{m}_5h_5 - \dot{m}_6h_6) / (\dot{m}_{12}h_{12} - \dot{m}_{11}h_{11}) \quad (12)$$

The energy efficiency for the economizer is written as Equation (13):

$$\eta_{I,ECO} = (\dot{m}_{11}h_{11} - \dot{m}_{10}h_{10}) / (\dot{m}_6h_6 - \dot{m}_7h_7) \quad (13)$$

The energy efficiency for the chimney is written as Equation (14):

$$\eta_{I,CH} = (\dot{m}_8h_8) / (\dot{m}_7h_7) \quad (14)$$

The general exergy efficiency formula is asserted as Equation (15):

$$\eta_{II} = exergy\ output/exergy\ input = 1 - (exergy\ loss/exergy\ input) \quad (15)$$

The exergy efficiency of the boiler is written as Equation (16):

$$\eta_{II,B} = (\dot{m}_{12}ex_{12} - \dot{m}_{11}ex_{11}) / (\dot{m}_5ex_5 - \dot{m}_6ex_6) \quad (16)$$

The exergy efficiency for the economizer is written as Equation (17):

$$\eta_{II,ECO} = (\dot{m}_{11}ex_{11} - \dot{m}_{10}ex_{10}) / (\dot{m}_6ex_6 - \dot{m}_7ex_7) \quad (17)$$

The exergy efficiency for the chimney is written as Equation (18):

$$\eta_{II,CH} = (\dot{m}_8ex_8) / (\dot{m}_7ex_7) \quad (18)$$

RESULTS AND DISCUSSION

In the scope of the research, the thermodynamic analyses are employed in consequence of the thermodynamics first and second laws to calculate the effectiveness of the cogeneration system. As a result of the thermodynamic analyses, the exergy destruction, efficiencies of energy and exergy of the major parts for the cogeneration system can be shown in Figures 3–4–5, respectively. Besides, the dispersion of the exergy destruction can be illustrated in Fig. 6. In terms of using the balance equations described above, the exergy destructions, energy and exergy efficiencies of the major parts are reckoned and represented in Table 2.

As understood from Table 2, the energy efficiencies of the chimney, economizer and boiler are around 61.68%, 66.03%, 79.91%, respectively. On the other hand, the exergy efficiencies of chimney, economizer and boiler are calculated as 96.56%, 30.27% and 71.94%, respectively. Figure 4 shows that the energy efficiencies of the major components are over 0.6. The large amount of excess air causes decrement of overall efficiency resulting increase in the heat losses by virtue of enhancement of the flue gas mass flow rate, for this study. Furthermore, one another reason of irreversibility is low heat transfer from combustion gas to the water through the heat exchanger tubes in boiler. The irreversibility can be decreased by effective array of the heat exchanger tubes located inside both boiler and economizer. The irreversibility of the economizer can also be decreased with effective insulation. On the other hand, it is observed that combustion efficiency is convincing for this system but it can be also improved by decreasing the amount of the excess air.

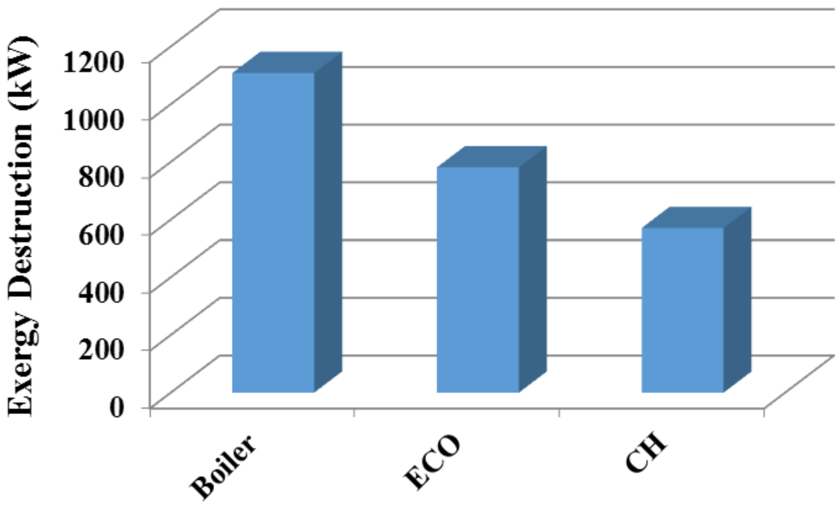

Figure 3. Exergy destruction rates for the major parts

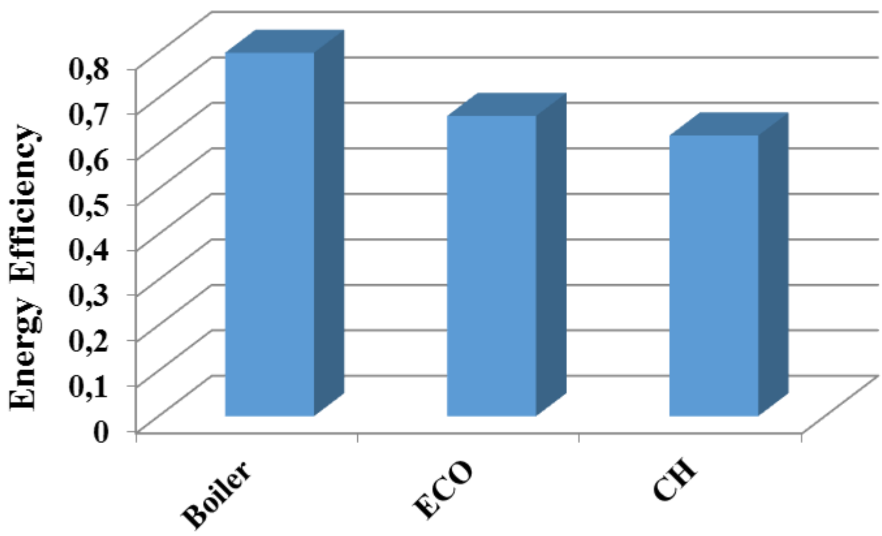

Figure 4. Energetic efficiency for the major parts

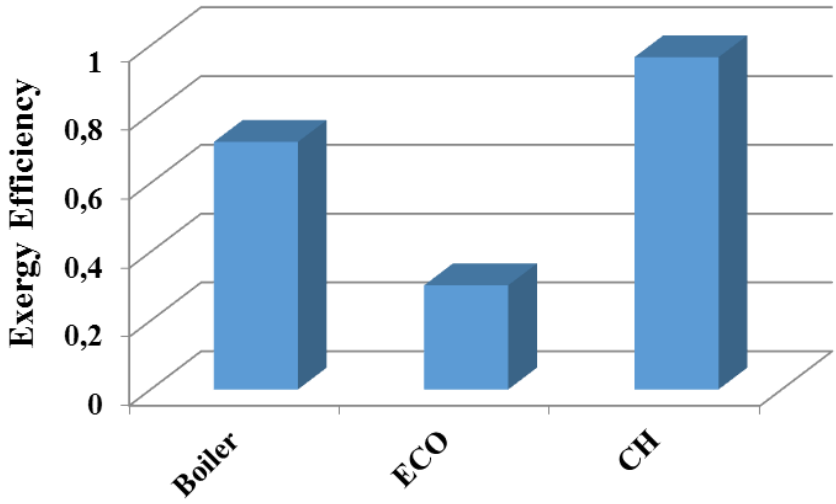

Figure 5. Exergetic efficiency for the major parts

Table 2. The outcomes of exergetic analysis

Components	$\dot{E}x_D$ (kW)	η_I (%)	η_{II} (%)
Boiler	1107.85	79.91	14.60
ECO	781.17	66.03	39.38
CH	570.93	61.68	8.60

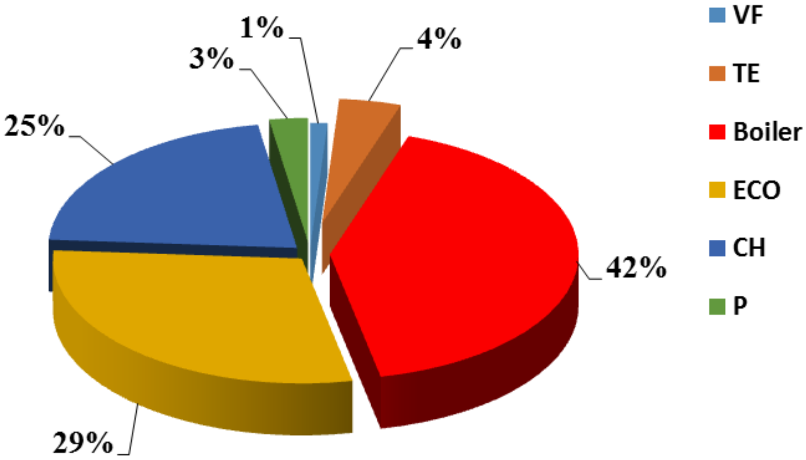

Figure 6. Distribution of exergy destruction rates

CONCLUSION

Thermodynamic analyses are employed based on the first and second laws of thermodynamics in a running cogeneration plant for food industry. The major exergy destruction occurs in the boiler which is around 1107.85 kW with 42% of the overall system irreversibility. The economizer and chimney follows it with 29% and 25%, respectively. The exergy destructions of economizer and chimney are observed as 781.17 kW and 570.93 kW, respectively. Moreover, the energy efficiencies of chimney, economizer and boiler are around 61.68%, 66.03%, 79.91%, respectively. On the other hand, the exergy efficiencies of chimney, economizer and boiler are calculated as 96.56%, 30.27% and 71.94%, respectively. The suggestions to improve the system performance can be listed as below:

• One of the system output is the steam of which pressure and temperature are effective parameters on the boiler performance. Increasing the steam pressure and temperature results in higher heat transfer to the water, so that overall system efficiency increases.

• Economizer has the second largest irreversibility after the boiler. On account of the decrement in the temperature of the combustion gas, the temperature at the boiler output also decreases and hereby, irreversibility of the economizer dwindles. The irreversibility of the economizer can also be decreased with effective insulation.

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NOMENCLATURE

E	Energy rate (kJ/sn)
$\dot{E}xD$	Exergy Destruction (kW)
LHV	Lower heating value of fuel (kJ/kg)
$\dot{m}$	Mass flow rate (kg/s)
P	Pressure (Pa)
Q	Rate of heat transfer (W)
W	Rate of work (W)
h	Specific enthalpy (kJ/kg)
s	Specific entropy (kJ/kg K)
Ex	Specific exergy (kJ/kg)
Cp	Specific heat capacity (kJ/kmol K)
T	Temperature (K)

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