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Exergy Analysis of Thermal Systems in a Paper Production Factory

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Abstract

Combined cycle power plants have an important effect in the energy production sector today. In this study, the natural gas cycle power plant that meets the electrical and thermal energy needs of Hayat Paper Factory established in Çorum is discussed from a thermodynamic perspective. The facility consists of a gas turbine, a heat recovery steam generator (HRSG) directly connected to the gas turbine exhaust, and units used in paper production.

In the study, energy and exergy analyzes of gas turbine, HRSG and pulp cylinders were examined. As a result of these energy analyses, waste energy was determined. This is calculated to reuse waste energy and increase the energy efficiency of industrial production facilities. Outdoor air temperatures, pressure ratio of the gas turbine compressor and electrical energy efficiency were determined as 9.1 °C, 14.7% and 30%, respectively. In the production facility, the saturated steam need of the process is met by HRSG and the overall efficiency of the system is approximately 42.6%. The resulting steam is used in paper production systems. The 3094.85 kW exergy coming out of the HRSG is lost in total in the pipes and connection valves until it reaches the paper drying cylinders. Preventing these energy losses will increase the energy efficiency of the facility.

Keywords

combined power, cycle, irreversibility, exergy analysis, waste heat

1 Introduction

Energy, the healthiest basic input for social and economic development, is needed more and more every day.

Energy conservation is not using less energy without compromising economic improvement and modern living conditions. Energy conservation is to realize energy production and consumption with the maximum efficiency and increase efficiency due to minimize energy losses.

Especially in large plants, for using energy efficiently, loss energy is regained to system or additional facilities are built; thus, energy costs are decreased. In addition, during the transformation in plants which uses fossil fuel, harmful emissions are reduced that are being thrown environment. Installation of combined power plants has increased, in recent years. For more than twenty years, the most efficient energy production way in the world is combined power plants with successfully implemented and supported with ongoing technical developments. However, to meet today's electrical energy needs with the reduction of fuel reserves and increasing global competition, to improve quality, reduce costs and expenses, it is a major problem to benefit with the maximum rate of industrial facilities. Therefore, usage of combined heat and power plants has gained weight in industrial plants.

According to energy consumption data for 2022 in Turkey, 31.2% of total consumption is industry, 27.1% is transportation, 30.7% is household and 11% is other sectors [1].

In many countries around the world, electricity is generated from combined power cycle plants. In Turkey, according to December 2024 data, 21.3% of its total electrical energy production is generated from combined power cycle plants. Therefore, even small improvements in thermal efficiency will provide significant fuel savings [2].

Huang [3] applied the second law approach for the thermodynamic analysis of combustion gas turbine cogeneration system and examined the effects of pinch point temperature and process steam pressure on the energetic and exergetic performance of the system. Oh et al. [4]

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implemented the exergy analysis of cogeneration system and tested the effect of the inlet air temperature and the relative humidity of the inlet air temperature on the performance of the system.

The production and use of electricity generation systems and thermal energy production together from a single fuel source is defined as cogeneration [5, 6]. The demand for this type of energy both in homes and in industry is of great importance in terms of economical use of energy [7]. Kakaras et al. [8] explained in his study that the ambient air temperature entering the gas turbine directly affects the turbine efficiency. They stated that, depending on the model of the turbine, for every 10 K increase in the ambient air temperature, the nominal power at 288 K decreases by 5 to 10% according to the standards. On the other hand, they stated that the specific consumption of fuel increased by 1.5% to 4% [8].

In Shamet et al.'s [9] study, they examined the energy and exergy analysis of the Garri 4 power plant in Sudan. They tried to determine the cause of irreversibility of the units in the plant. They determined that the energy loss in the condenser was approximately 67% and the exergy destruction of the boiler was approximately 84.36% [9].

Kumar [10] mentions that there are many researchers on the determination of energy and exergy of thermal power plants. He recommends the development of the concept of 4-E analysis in order to obtain more efficient results [10].

In this paper energy and exergy analyses are presented for gas turbine, heat recovery steam generator and production processes with aim of regaining waste heat in industry and increasing energy efficiency in production facilities. It is observed that parameters such as ambient temperature, pressure ratio of gas turbine's compressor affect electrical energy efficiency.

2 System description

Total installed capacity 7500 kWe cogeneration system in Hayat paper mill started up in 2005. While 33% of obtained energy after combustion in gas turbine is used for producing electricity from gas turbine generator, 43.6% of remaining energy is sent to HRSG Fig. 1 shows the schematic diagram of cogeneration system. Ambient air

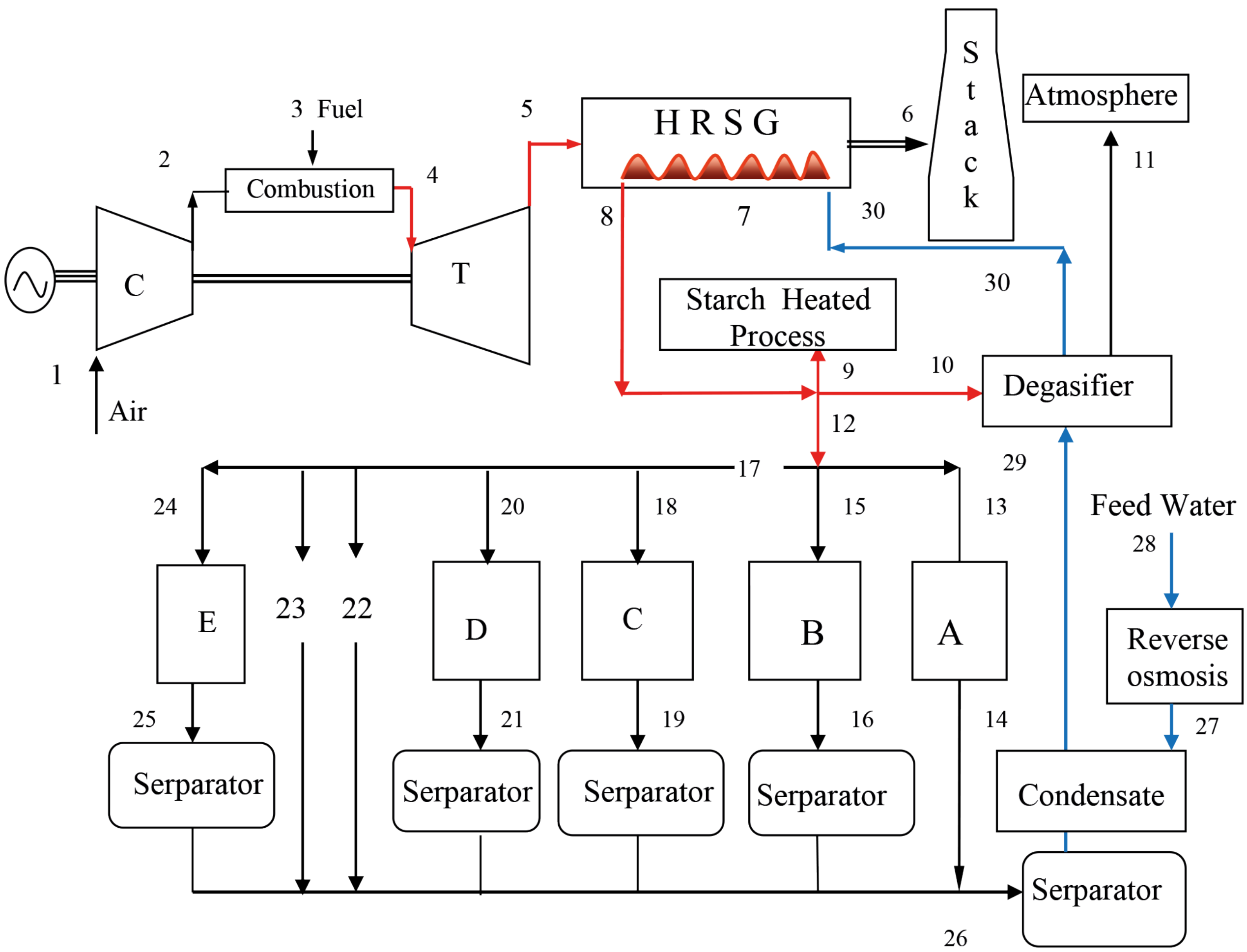

Fig. 1 Schematic of combined gas turbine power plant

is compressed in the turbine and supplied to the combustion chamber. Fuel is burned in chamber and hot gas produced. The hot gas is expanded in turbine to a lower temperature and pressure. This expanded gas is utilized in heat recovery steam generator and steam is obtained. A significant part of obtained steam (77.3%) is used in drying process, beginning from paper pulp to the end of the dehumidification section. 26.94% of remaining energy is used in degasifier and 2.84% in starch mixture. 10.3% of total combustion energy (2.394 MWe) is used in drying process. After that, flash steam coming from drying cylinders is condensed in condenser section to regain to waste heat steam generator system. After heat recovery steam generator, approximately at 110 °C stack energy constitutes 3.1% of total energy. Keeping energy high is to prevent condensation within the chimney. This way is more economical.

3 Technical properties of cycle plant

Hayat paper factory uses the Turbomach TBM-T70 model gas engine. Pressure ratio is 14.7. Internal combustion turbines have advanced design for heavy industry applications and only natural gas combustion type is appropriate. Internal combustion turbine has air compressor that is multi-stage horizontal-axis and air flow control is done with air routing fins. Air cooled structured generator is directly connected to the turbine shaft. Approximately 1612.8 kg of natural gas is consumed per hour in the gas turbine system. The natural gas, which has a mass flow rate of 0.448 kg/s, is at 85 °C and is sent to the combustion chamber through a filter. Air enters the compressor at ambient temperature and the outlet temperature increases as a result of the compression of the compressor. The air with increased temperature mixes with the fuel in the combustion chamber.

Exergy change and irreversibility were determined according to the excess air condition entering the gas turbine combustion chamber. It was seen that the majority of irreversibility occurs in the combustion chamber. Approximately 60% of the electrical energy produced is sent to the electrical switchgear facility and 40% is consumed in the paper production facility.

4 Theoretical information

4.1 Energy analysis of steady flow systems

Exergy which accompanies to a steady flow of matter is determined with the maximum amount of work obtainable when the stream substance is brought from its initial state to the dead state, for the case of adiabatic stream.

The exergy of a closed system is

$$E_{phys} = \left(U - U_0\right) + P_0\left(v - v_0\right) - T_0\left(s - s_0\right) + KE + PE \; . \tag{1}$$

The specific exergy of the flow is given by

$$\varepsilon = \varepsilon_{phys} + \varepsilon_{chem} + \varepsilon_{pot} \; . \tag{2}$$

When environment temperature is T_0, exergy balance in steady flow systems [11] is

$$\begin{aligned} \frac{d\dot{E}}{dt} &= \sum_j \left(1 - \frac{T_0}{T_j}\right)\dot{Q} - \left(\dot{W} - P_0\frac{dV}{dt}\right) - \dot{E}_D \\ &+ \sum_{\text{in}} \dot{m}_{\text{in}} - \varepsilon_{\text{in}} - \sum_{\text{out}} \dot{m}_{\text{out}} - \varepsilon_{\text{out}} . \end{aligned} \tag{3}$$

Where the subscripts "in" and "out" represent inlet and exit states, $\dot{m}$ is the mass flow rate.

4.2 Chemical exergy

To calculate chemical exergy, it is not enough to know only the temperature and pressure. The chemical composition of the environment must also be determined. Since the environment is not in thermodynamic equilibrium, it is necessary to model an exergy reference environment.

Chemical exergy can be applied to all gas mixtures as follows [12]:

$$E_{chem} = n\left[\sum x_i \;\; \varepsilon_{chem} + \bar{R}T_0 \sum x_i \;\; \ln x_i\right] . \tag{4}$$

Where n is sum of moles, x_i is the mole fraction of the i component in the mixture [11, 13, 14]. The Gibbs function of the substance is considered as the enthalpy value. The Gibbs functions of certain materials are zero in environmental conditions. To determine chemical exergy of each gas in mole, Eq. (5) is used.

$$\varepsilon_{chem} = \bar{R}T_0 \ln\frac{P_0}{P_{00}} \tag{5}$$

P_{00} is the partial pressure of the gas. After combustion of natural gas, the specific exergy of each gas component is determined and multiplied by the mole ratio (x_i) of each gas to determine the total chemical exergy. The total specific exergy is determined in Eq. (6).

$$\begin{aligned} \varepsilon_{chem} &= \sum x_i \;\; \varepsilon_{\mathrm{N_2}} + x_i\varepsilon_{\mathrm{O_2}} + x_i\varepsilon_{\mathrm{CO_2}} + x_i\varepsilon_{\mathrm{H_2O}} \\ &+ \bar{R}T_0 \sum x_i \;\; \ln x_i \end{aligned} \tag{6}$$

In Eq. (7), the total exergy is determined by multiplying with the fuel mass.

$$E_{chem} = m_{\text{fuel}} \times \varepsilon_{chem} \tag{7}$$

4.3 Physical exergy

Until a system reaches physical equilibrium with its environment, the power taken from the system is defined as physical exergy [15]. The total exergy of the system in the mass flow [11–14] is

$$E_{phys} = m_{\text{fuel}} \left[\frac{h_{\text{mixture}} - h^0 - T_0 \left(s_{\text{mixture}} - s^0 \right)}{M} \right] . \tag{8}$$

The weight of the combustion efficiency per kmol is defined by *M*.

The physical exergy of the gas formed in the combustion chamber is determined from Eq. (8). The enthalpy and entropy values of the total mixture are determined from Eqs. (9) and (10).

$$h_{\text{mixture}} = x_1 h_{N_2} + x_2 h_{O_2} + x_3 h_{CO_2} + x_4 h_{H_2O} \tag{9}$$

$$s_{\text{mixture}} = x_1 s_{N_2} + x_2 s_{O_2} + x_3 s_{CO_2} + x_4 s_{H_2O} \tag{10}$$

The enthalpy and entropy values of N_2, O_2, CO_2, H_2O gases are determined by Eqs. (2) and (3).

The properties of the gases at T_0 temperature and the entropy (h^0) and enthalpy (s^0) values in Eq. (6) according to the T_0 Gibbs function are accepted as in Table 1 [11].

Based on the values in Table 1, the enthalpy (h^0) and entropy (s^0) values of the combustion efficiency of the mixture depending on the mole fractions in Eqs. (11) and (12) are found.

$$h^0 = x_1 \mathrm{N}_2 + x_2 \mathrm{O}_2 + x_3 \mathrm{CO}_2 + x_4 \mathrm{H}_2\mathrm{O} \tag{11}$$

$$s^0 = x_1 \mathrm{N}_2 + x_2 \mathrm{O}_2 + x_3 \mathrm{CO}_2 + x_4 \mathrm{H}_2\mathrm{O} \tag{12}$$

The total exergy of the gas consumed in the combustion chamber of the gas turbine is determined by Eq. (13).

$$E_{\text{combustion}} = E_{phys} + E_{chem} \tag{13}$$

5 Gas turbine cycle

5.1 Compressor work

The environment air is pressurized by the compressor and sent to the combustion chamber. In this case, the compressor work is determined by Eq. (14).

$$W_{comp} = m_{\text{air}} \left(h_{\text{out}} - h_{\text{in}} \right) = m_{\text{air}} c_{p,\text{air}} \left(T_{\text{out}} - T_{\text{in}} \right) \tag{14}$$

Table 1 Enthalpy and entropy specifications of gases in atmospheric conditions

	N_2	O_2	CO_2	H_2O
h^0 (kJ/kmol)	0	0	−393954.44	−242122.27
s^0 (kJ/kmol K)	190	203.6	212	187

Irreversibility occurs in the power generation in compressors. With these irreversibility, the compressor power is equal to Eq. (15).

$$W_{comp} = \dot{I}_{comp} - m_{\text{air}} \left(\varepsilon_{\text{in}} - \varepsilon_{\text{out}} \right) \tag{15}$$

And the efficiency according to exergy exchange is

$$\psi_{comp} = \frac{m_{\text{air}} \left(\varepsilon_{\text{in}} - \varepsilon_{\text{out}} \right)}{W_{comp}} . \tag{16}$$

In Eq. (17), an isentropic compressor outlet temperature is T_2 and varies with the compressor pressure ratio (*PR*).

$$T_2 = T_1 \left[1 + \frac{PR^{(k-1)/k} - 1}{\eta} \right] \tag{17}$$

5.2 Fuel exergy

95% of the gas turbine fuel consists of methane (CH_4) and other gases [16]. In order to determine the exergy of the system, the exergy of the fuel used (E_{fuel}) must be calculated.

The fuel consists of methane gas, therefore the physical and chemical specific exergies of methane gas are calculated and determined from Eq. (18) [10].

$$\varepsilon_{\text{fuel}} = \varepsilon_{phys} + \varepsilon_{chem} \tag{18}$$

Equation (19) gives chemical

$$\varepsilon_{chem} = \varepsilon_{chem}^{st} \frac{T_0}{T_n} - \Delta H \frac{T_n - T_0}{T_n} \tag{19}$$

and Eq. (20) physical exergy

$$\varepsilon_{phys} = R T_0 \ln \frac{P_{\text{fuel}}}{P_0} . \tag{20}$$

5.3 Combustion chamber exergy

Combustion chamber exergy is determined by the sum of the input and output exergy values, including all irreversibility, considering a control volume. The exergy equation is Eq. (21).

$$\sum \Delta \dot{E}_{\text{in}} = \sum \Delta \dot{E}_{\text{out}} + \dot{I} \tag{21}$$

The exergy balance of a system is expressed by the exergy entering and exiting the system and irreversibility.

The combustion chamber exergy is determined by the sum of the chemical and physical exergies of the burned gas.

$$E_{egas} = E_{phys} + E_{chem} \tag{22}$$

5.4 Gas turbine

The exhaust gases from the combustion chamber expand in the turbine with high pressure and are thrown into the HRSG section. The high pressure gas produces power in the turbine. Some of this power is transferred to the compressor. The net power produced in the turbine is equal to the turbine exergy.

Compressor work is determined from Eq. (23).

$$W_{GT} = m_{egas}\left(h_{\text{in}} - h_{\text{out}}\right) = m_{egas} c_{pegas}\left(T_{\text{in}} - T_{\text{out}}\right) \tag{23}$$

Here h_{in} and h_{out} are the compressor inlet and outlet enthalpies. The irreversibility ($\dot{I}_{GT}$) of the compressor is determined by Eq. (24).

$$\dot{I}_{GT} = m_{egas}\left(\varepsilon_{\text{in}} - \varepsilon_{\text{out}}\right) - \dot{W}_{GT} \tag{24}$$

Compressor exergetic efficiency according to the inlet and outlet exergy value change is determined from Eq. (25).

$$\psi_{GT} = \frac{\dot{W}_{GT}}{m_{egas}\left(\varepsilon_{\text{in}} - \varepsilon_{\text{out}}\right)} \tag{25}$$

6 Heat recovery steam generator

Combined gas turbine cycles work at high temperatures. Gas turbine exhaust constitutes heat output of combustion gases. Evaluating this waste hot gas as a source of heat in thermal processes is a requirement of engineering approach. Ongoing effort to provide higher heat efficiency in common power plant has led to new regulations.

It is observed that the irreversibility in exhaust gases is low which indicates effective utilization of heat energy, but the specific work output of the turbine decreases. Generally with increase in turbine inlet temperature the specific work output of a gas turbine increases. But increase in turbine inlet temperature has strictmetallurgical limitations in terms of maximum temperature that the turbine stage could withstand.

Gas turbine compressor inlet temperature is ambient temperature; gas turbine waste gas temperature, flow rate and fuel quantity varies according to environmental conditions. Under the assumption of being adiabatic heat recovery steam generator (HRSG) is manufactured in size $6 \times 2 \times 5$ m^3 and is directly connected to the gas turbine output. As shown in Fig. 1 to meet the steam needs of the plant; in the heat recovery steam generator, economizer and heat exchangers are placed gradually at the beginning.

When inlet and outlet exergy formulize for the heat recovery steam generator (HRSG) shown in Fig. 1, exergy flow balance is

$$\left(E_5 - E_6 + \dot{I}_{\text{HRSG}}\right) = \left(E_8 - E_{30}\right). \tag{26}$$

7 Exergy analysis of drying cylinders

Steam coming from HRSG with 1200 kPa pressure, 192 °C temperature and 3.26 kg/s mass flow is sent to drying cylinders. The pressure in the entrance of cylinders is reduced to 530 kPa. Paper, starting from the paper pulp process until being dry-paper is passed through 40 cylinders which have different diameters. These cylinders are collected in five groups according to the paper consistency. In each group, cylinders have same diameters and connections, so energy flow is obtained as a group.

Steam coming from cylinders is decreased to condensation state and collected in separators which are made for each group.

Collected hot waters in separators are collected in the main separator and sent to condenser with 87 °C temperature.

With additional energy output line, steam exhaust of HRSG is used in starch heating process and degasifier-section. Therefore, system water dwindles through working and water with 0.7 kg mass flow added to condenser. Cylinders specific exergies are calculated by

$$\varepsilon_{\text{in}} = \left(h_{\text{in}} - h^0\right) - T_0\left(s_{\text{in}} - s^0\right). \tag{27}$$

In Eq. (27), thermodynamic properties of the environment are; enthalpy h^0 = 104 kJ/kg, entropy s^0 = 0.3624 kJ/kg K. Environment temperature and pressure are taken as T_0 = 282.25 K, P_0 = 1.013 bar, respectively. During the gas turbine operation, the necessary inlet, outlet, combustion chamber, nozzle outlet, HRSG inlet and outlet pressure, temperature values are seen on the electronic digital screen. These values obtained in the study were used in the calculations. In addition, since these values were recorded in the system, long-term value examinations were made. The purpose of exergy analyses in combined cycle system is to determine net amount of exergy flow and available energy in the plant. Calculated node points are shown in Table 2.

8 The electrical power profile and heating load profile

The electrical power profile and heating load profile were compared to insure that the heat from power production could be utilized. A typical winter profile indicates there is a good match between thermal heating and electrical power requirements. In the spring and fall, electrical and heating load profiles are similarly shaped, however, there is a 25% reduction in electrical and a 40% reduction in heating requirements. During the summer there is minimal heating load, thus requiring a separate condenser since conditions are unsuitable for cogeneration. Seasonal and daily variations in power and heating requirements dictate the

Table 2 Thermodynamic properties, energy and exergy rates of HRSG and gas turbine at various locations

No.	Temperature T (°C)	Pressure P (kPa)	Mass flow m (kg/s)	Enthalpy h (kJ/kg)	Entropy s (kJ/kg K)	Specific exergy ε (kJ/kg)	Exergy E (kJ)
1	15	93	23.800	285.00	1.650	0.000	0.000
2	330	1000	23.800	330.00	1.797	30.190	718.280
3	85	1200	0.448	–	–	51790.000	23201.920
4	1247	909	24.240	–	–	1091.800	26465.232
5	490	110	24.240	–	–	417.300	10115.352
6	110	104	24.240	–	–	29.830	723.079
7	120	1200	3.470	504.48	1.526	74.180	257.420
8	191	1200	3.264	2792.20	6.539	948.240	3094.850
9	192	1200	0.100	2794.90	6.546	949.270	94.930
10	192	122	0.600	2858.00	7.708	684.630	410.780
11	25	105	0.600	104.93	0.367	1.670	1.000
12	192	530	2.770	2836.00	6.995	863.810	2392.760
13	185	126	0.208	2844.70	7.663	684.020	142.500
14	90	126	0.208	377	1.193	40.980	8.540
15	185	126	0.398	2844.7	7.663	684.020	272.680
16	90	126	0.398	377.00	1.193	40.860	16.290
17	185	408	1.853	2828.84	7.094	828.510	1535.480
18	185	295	0.703	2835.30	7.255	789.690	555.810
19	90	295	0.703	377.14	1.193	41.150	28.960
20	185	408	0.332	2828.80	7.094	828.510	275.230
21	90	408	0.332	377.23	1.192	41.260	13.710
22	185	41	0.010	2840.60	8.666	397.220	3.970
23	185	41	0.010	2840.60	8.666	397.220	3.970
24	185	300	0.797	2849.50	7.278	797.350	635.710
25	90	300	0.797	377.14	1.193	41.150	32.800
26	87	200	2.770	377.07	1.193	41.050	113.700
27	83	150	2.770	356.02	1.134	36.437	100.930
28	25	120	0.700	104.94	0.367	1.679	1.175
29	70	120	3.470	335.00	1.075	32.055	111.232
30	103	150	3.470	440.20	1.363	56.095	194.652

need for an hourly computer simulation to optimize energy use; however, even without hourly analysis, the potential for cogeneration is apparent.

9 Conclusions

The results presented in this paper are energy and exergy analyses for the gas turbine, HRSG and production states. The results also show loss exergy in the components. Energy and exergy values of system's components are calculated, consumption rate and irreversibility relation and exergy factor are shown in flow diagram. The highest exergy is 26465,232 kW respectively at 909 kPa and 1247 °C steam inlet conditions.

Ambient environment temperature, pressure and system's overall efficiency are defined T_0 = 282.25 K, P_0 = 1.013 kPa, 31% respectively. Gas turbine exhaust temperature is 490 °C, and constitutes 43.6% of combustion energy. This waste heat is used in paper production system as process heat by utilizing. The thermodynamic values and exergy flow of each unit of the facility are shown in Table 2. The energy flow of the plant is shown as a Grassmann diagram in Fig. 2.

When the energy flow analysis of the HRSG system is performed, there is an energy input of 10310.00 kW, whereas there is an energy output of 3817.95 kW. In this case, an irreversible energy of 6492 kW is formed. It is seen

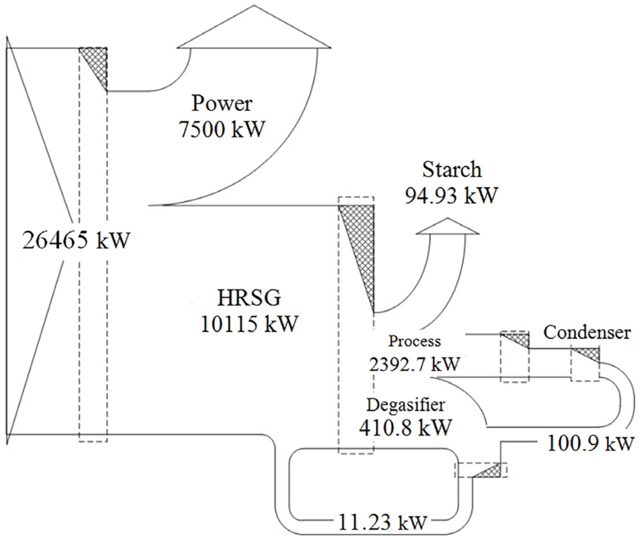

Fig. 2 Flow diagram

that 3094.85 kW of energy taken from HRSG for process operations creates a loss of 196.38 kW in Degasifier, Starch Heated Process and internal installation connections. Only 1254.167 kW of the 2392.76 kW of energy intended to be transferred to the paper production cylinders is transferred. There is an energy loss of 1138.60 kW in the cylinder unit installation lines. Preventing these energy losses will increase the energy efficiency of the facility.

The effect of the turbine inlet temperature on the cycle has been also investigated and selected results are depicted in Fig. 3. For both energetic efficiency and power configuration reach their maximum efficiencies at low ambient temperatures.

In Fig. 4, it is observed that as the ambient temperature, which is the turbine inlet temperature, increases, the exhaust outlet temperature increases. In contrast, it is seen that the second law efficiency of the turbine decreases.

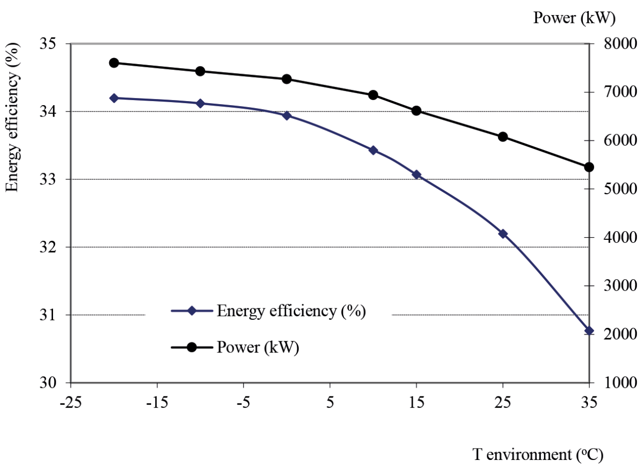

Fig. 3 Exergy efficiency and cycle power depending on turbine inlet temperature change

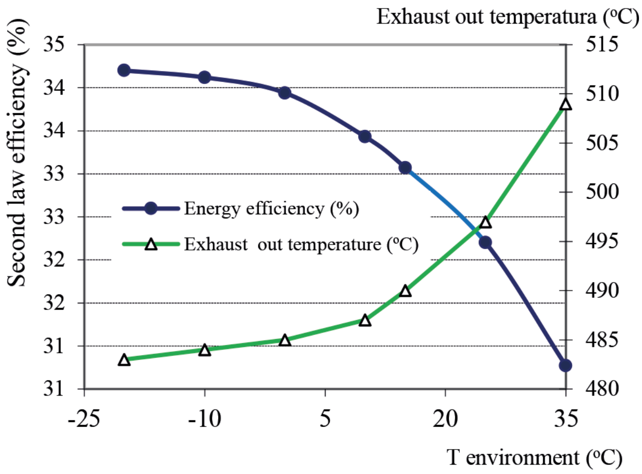

Fig. 4 The effect of the turbine inlet temperature and exhaust out temperature on the cycle

The daily average electricity and heating load profile of the facility in October was determined. As seen in Fig. 5, energy use is higher at noon. In parallel, the heat load also increases.

Nomenclature

E	Exergy (kJ)
I	Irreversibility (kJ)
T	Temperature (K)
T_n	Reaction temperature (K)
W	Power (kW)
h	Enthalpy (kJ/kg)
s	Entropy (kJ/kg K)
R	Universal gas constant (kJ/Kmol K)
P_0	Environmental pressure (kPa)
P_{00}	Partial pressure of the gas
PR	Pressure rate
M	Weight of combustion efficiency per kmole (kg/kmol)
n	Sum of moles (kmol)

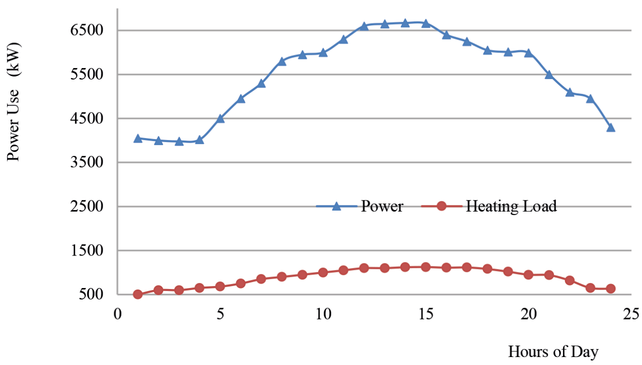

Fig. 5 Electrical and heating load profile for October

m	Measure of mass flow (kg/s)
H_u	Fuel under heat value
c_p	Specific heat (kJ/kg K)
k	Specific heat ratio
x_i	Mole ratio of the mixture
ε	Specific exergy (kJ/kg)
ψ	Exergy efficiency
ΔH	Standard combustion enthalpy (kJ/kmol)
η	Efficiency

Abbreviations

chem	Chemical
phys	Physical
pot	Potential
HRSG	Heat recovery steam generator
st	Standard
comp	Compressor
egas	Exhaust gas

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