Exergy Assessments by Using Real-Time Measurements in a Factory

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***Abstract*—Trigeneration electric production can be defined as a power system in which heating and cooling are simultaneously produced. In this study, we attempted to decrease the energy consumption of a pharmaceutical factory. For this purpose, a trigeneration application was carried out based on the data from a currently active pharmaceutical factory in Istanbul, Turkey. The costs of exergy and exergy losses, the ratios of exergy losses, and the exergy economic factor parameters of the equipment were determined. The exergy economic factors were found and in view of these parameters, assessments were made to determine the improvements that could be made in the system equipments.**

***Index Terms*—energy, factory, exergy analysis, exergy economic factor**

I. Introduction

A trigeneration system is one that can generate three different types of energy (electric, heating, and cooling) from a single source of energy. Although the investment cost of a trigeneration systems is high, these systems are more economical compared to systems from which power, heating, and cooling are individually obtained [1].

Reference [2] emphasized that the initial investment costs of cogeneration systems were more than the costs required for conventional systems; however, the payback period was less for the cogeneration systems. To assess and determine the minimum cost of electricity generation, they examined the use of a cogeneration system to generate heat and electricity and compared it with a conventional system generating an equal amount of heat by harnessing energy from the same source. Ref. [3] performed an exergy analysis on a cogeneration system with a steam-injected gas turbine. By applying the balance equations of mass, energy, and exergy of the components, the exergy loss was determined. By taking the compressor pressure ratio, vapor injected ratio, vapor temperature, and feed water quantity as parameters, the outputs of the first and second law were recorded, and the heat to power ratios were calculated. Additionally, while the highest exergy loss occurred in the combustion chamber, the highest exergy leakage occurred through the waste gases (flue gases). Ref. [4] accomplished the thermoeconomic optimization of a cogeneration facility through parameters such as the magnitude of the facility, the investment costs, and the power generation required to design and operate the facilities. They compared the efficiency of a multistage cogeneration system aimed at either obtaining maximum power generation or minimal operational costs to the efficiency of a single reversible heat machine. Furthermore, the studied case was also examined by taking surface areas, heat transfers, and flow directions into account to increase the efficiency of the heat exchangers. By determining the operational pressure and selecting the fluid, the optimum design and the operational requirements of the cogeneration facility were established.

Ref. [5] conducted studies comparing a cogeneration system with a trigeneration system. Thermoeconomic analyses of the cogeneration and the trigeneration systems were performed in their studies. Ref. [6] analyzed the trigeneration system in terms of the thermoeconomic aspect. Ref. [7] focused on trigeneration schemes in which a gas turbine was used as a prime mover for power production while cooling was generated by a typical compression-refrigeration system. Ref. [8] aimed at keeping the production costs to a minimum by approaching the issue within the thermoeconomic research adopted for the water–ammonia absorption cooling system. Ref. [9] studied a conceptual trigeneration system based on a high temperature gas turbine cycle, which used a heat-recovery steam generator for heat processing and a vapor-absorption refrigeration system. Maximum energy is lost during the combustion and steam-generation processes. These processes account for over 80% of the total energy destruction in the overall system. Ref. [10] examined the thermodynamic and thermoeconomic methodology of a trigeneration system with a 6.5 MW gas-diesel engine. The system has been installed in the Eskisehir Industry Estate Zone in Turkey. The thermodynamic methodology includes the relations and performance parameters for energy and exergy analysis, while the thermoeconomic methodology covers the cost balance relations, cost of products and thermodynamic inefficiencies, relative cost difference, and the exergonic economic factor. The application of the methodology is presented in another Ref. [11]. The energy, exergy, and equivalent electrical efficiencies of the entire system are found to be 58.97%, 36.13%, and 48.53%, respectively. Ref. [12] developed an annual analysis of an engine trigeneration system as an integrated thermal system through a computational simulation program. Seasonal loads and exergy

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efficiences are calculated for both weekdays and weekends. Ref. [13] investigated the effects of various thermodynamic factors on the performance of a trigeneration cycle based on endogenous/exogenous exergy destruction. The results indicated that, increasing compressor pressure ratio, pre-heater outlet temperature and excess air lead to better combustion and lower exergy loss and fuel consumption. Increasing the mass flow rate of steamgenerator, while keeping the cycle outlet temperature constant and considering cooling capacity variable, leads to increase the first and second law efficiencies of the cycle. Ref. [14] analyzed the the tri-generation cycle by using conventional exergy and exergoeconomic calculations. Also, a new definition for the exergoeconomic factor is introduced which suggests that the components of refrigeration cycle and combustion chamber have the lowest values of the exergoeconomic factor, therefore, the corresponding exergy destruction cost rates should be reduced. It is concluded that employing the new exergetic and exergoeconomic concepts provide valuable information for improving the overall system. Ref. [15] have implemented energy level and exergy analysis on energy conversion processes to reveal the energy variation in amount and quality during the operation of combined cooling, heating and power system. Ref. [16] proposes a simple linear programming model to minimize the total annual variable operation and maintenance costs of a generic tri-generation system. Their results show that, tri-generation is more cost effective than the separate production for all studied scenarios. The proposed model helps to determine the right operational strategy.

The parameters for setting up a trigeneration system in the factory were determined by considering the minimization of the cost of energy when the operational costs of the current system and the trigeneration systems were compared. Real operating parameters such as the temperature, pressure, flow rates and electricity consumption values of the devices are measured and recorded for all steam lines over a course of a year in the system.

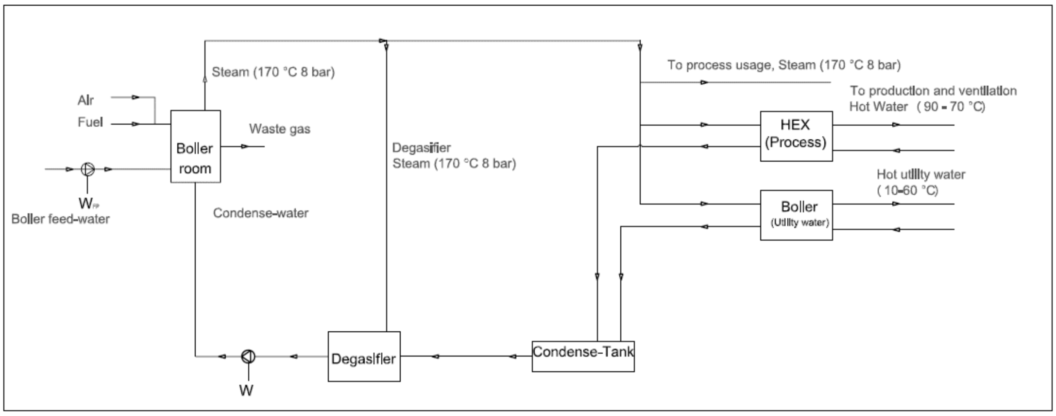


Figure 1. The current flow scheme of the facility

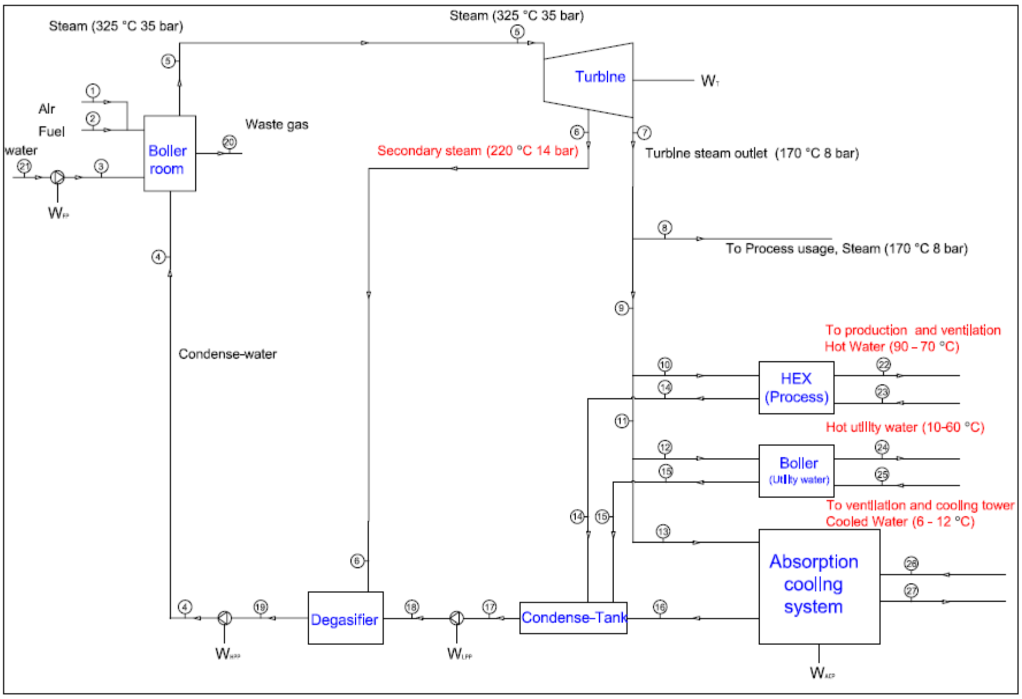


Figure 2. The flow scheme of the trigeneration system

II. System Description

The energy balance and energy consumption values of a pharmaceutical factory generating energy 24 hours a day, 360 days a year, were examined to determine the trigeneration system parameters. The steam-flow scheme in the plant is specified in Fig. 1. Steam (4200 kg/h) at a temperature of 170 ℃ and subjected to a pressure of 8 bar is used to meet the process usage. A 4000 kW capacity of hot water is required for production and ventilation at the factory and is met through a heat exchanger; hot water used for the routine needs of the factory is met by a boiler with a capacity of 120 kW. Additionally, there are cooling units in the factory supplying a total cooling capacity of 5148 kW.

A trigeneration system was designed with a turbine to meet the electricity requirement in the factory, in addition to an absorption-cooling unit to meet the cooling needs. A condenser tank, a degasifier, pumps, and a steam boiler were also used. The flow scheme of this system is presented in Fig. 2.

The electricity requirement for the factory was calculated to determine the capacity of the turbine. It was assumed that the units running for 24 hours were at a fixed capacity.

The following definitions are assumed for the analysis calculations of the trigeneration system:

- The equipment is an open system having steady flow.
- The boiler, pipes and components of other installations are insulated against heat losses.
- The fuel enters into the boiler under environmental conditions.
- The dead state is the environment state (To: 298.15 K and P_o: 1.013 bar).
- The performance coefficient value of the absorption-cooling unit is assumed to be 1.2.
- The temperature of the flue gas is fixed at 500 K.
- The boiler is run by natural gas
- Air and natural gas are ideal gases.
- Air molar composition (%) is 77.48 N_2, 20.59 O_2, 0.03 CO_2, and 1.90 H_2O (g).
- The gain and loss of heat, pressure, and exergy in the pipe connections are negligible.
- The molar composition of natural gas used (%) is 98.52 CH_4, 0.41 C_2H_6, 0.14 C_3H_8, 0.06 C_4H_{10}, 0.03 CO_2, 0.81 N_2, and 0.03 other hydrocarbons.

III. Exergy Analysis

According to Ref. [17], the exergy balance applied to a fixed control volume is given by the following equation:

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

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 its environment. In the absence of magnetic, electrical, nuclear, and 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,

$$\dot{E} = \dot{E}^{Ph} + \dot{E}^{Ch} \quad (2)$$

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,

$$\dot{E}^{Ph} = \dot{m} e^{Ph} \quad (3)$$

The physical and chemical exergies of the current in the trigeneration system will be calculated. Only the chemical exergies of the fuel, combustion air, and flue gas apply to this system. The physical exergies of the flows under environmental conditions are zero and are obtained from the following formula.

$$e^{Ph} = (h - h_o) - T_o(s - s_o) \quad (4)$$

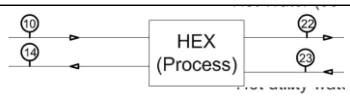
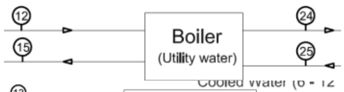
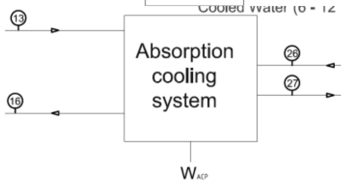
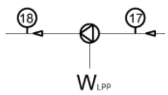
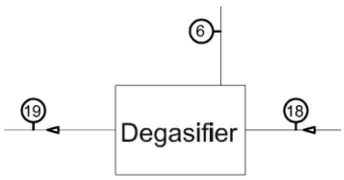
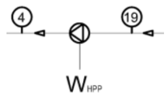
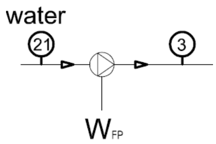
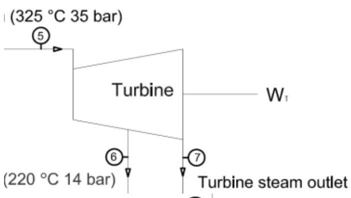
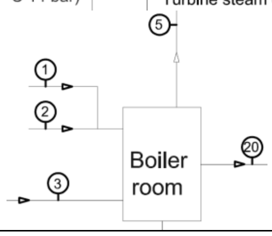
The parameters to be used in the physical exergy calculations are presented in Table I. Additionally, the physical exergy value of each component is calculated using (3), and the chemical exergy values are presented in Table I. The energy balance of each of the system components and the equation of exergy balance are shown in Table II.

TABLE I. Physical Exergy and Chemical Exergy Values

No	$\dot{m}$ (kg/h)	P (bar)	T (K)	h (kj/kg)	s (kj/kgK)	e^{ph} (kj/kg)	e^{ch} (kj/kg)	∑e (kj/kg)	E (kj/h)
1	19557	1.0	298.2	-	-	0	4.4	4.4	86050
2	952	1.0	298.2	-	-	0	51485.4	51485.4	49014100
3	4200	35.0	286.7	56.7	0.2	3.9	0	3.9	16380
4	13822	35.0	469.1	833.7	2.3	156.3	0	156.3	2160378
5	18022	35.0	598.2	3040.7	6.5	1091.8	0	1091.8	19676419
6	702	14.0	493.2	2853.9	6.5	890.6	0	890.6	625201
7	17320	8.0	443.6	2769.1	6.6	787.2	0	787.2	13634304
8	4200	8.0	443.6	2769.1	6.6	787.2	0	787.2	3306240
9	13120	8.0	443.6	2769.1	6.6	787.2	0	787.2	10328064
10	7030	8.0	443.6	2769.1	6.6	787.2	0	787.2	5534016
11	6090	8.0	443.6	2769.1	6.6	787.2	0	787.2	4794048
12	210	8.0	443.6	2769.1	6.6	787.2	0	787.2	165312
13	5880	8.0	443.6	2769.1	6.6	787.2	0	787.2	4628736
14	7030	8.0	443.6	721.1	2.1	115.6	0	115.6	812668

15	210	8.0	443.6	721.1	2.1	115.6	0	115.6	24276
16	5880	8.0	443.6	721.1	2.1	115.6	0	115.6	679728
17	13120	8.0	443.6	721.1	2.1	115.6	0	115.6	1516672
18	13120	14.0	443.9	722.1	2.1	116.3	0	116.3	1525856
19	13822	14.0	468.3	830.3	2.3	153.9	0	153.9	2127205
20	20529	1.0	500.0	-	-	53.6	61.1	114.7	2354676
21	4200	5.5	283.2	42.01	0.2	1.6	0	1.6	6720
22	171551	5.0	363.2	376.9	1.2	26	0	26	4460326
23	171551	5.0	343.2	292.9	0.9	12.9	0	12.9	2213007
24	2065	5.0	333.2	251.1	0.8	7.9	0	7.9	16313
25	2065	5.0	283.2	42	0.1	1.6	0	1.6	3304
26	73513	5.0	285.2	50.4	0.2	1.2	0	1.2	882156
27	73513	5.0	279.2	25.2	0.1	2.7	0	2.7	198485.1

TABLE II. ENERGY AND EXERGY DESTRUCTION EQUATIONS

Name	Figures	Energy Equations	Exergy destruction equations
HEX (Process)		$Q=\dot{m}_{10}(h_{10}-h_{14})$ $Q=\dot{m}_{22}(h_{22}-h_{23})$	$\dot{E}_{10}+\dot{E}_{23}=\dot{E}_{14}+\dot{E}_{22}+\dot{E}_d$
Hot water boiler		$Q=\dot{m}_{12}(h_{12}-h_{15})$ $Q=\dot{m}_{24}(h_{24}-h_{25})$	$\dot{E}_{12}+\dot{E}_{25}=\dot{E}_{15}+\dot{E}_{24}+\dot{E}_d$
Absorption cooling system		$Q_{steam}=\dfrac{Q_c}{COP}$ $Q_{steam}=\dot{m}_{13}(h_{13}-h_{16})$ $Q=\dot{m}_{26}(h_{26}-h_{27})$	$\dot{E}_{W,ASP}+\dot{E}_{13}+\dot{E}_{26}=$ $\dot{E}_{16}+\dot{E}_{27}+\dot{E}_d$
Pump (Low pressure)		$W_{LPP}=\upsilon(P_{18}-P_{17})$ $=h_{18s}-h_{17}$	$\dot{E}_{W,LPP}+\dot{E}_{17}=\dot{E}_{18}+\dot{E}_d$
Degasifier		$\dot{m}_{18}h_{18}-\dot{m}_6h_6=\dot{m}_{19}h_{19}$	$\dot{E}_{18}+\dot{E}_6=\dot{E}_{19}+\dot{E}_d$
Pump (High pressure)		$W_{HPP}=\upsilon(P_4-P_{19})$ $=h_{4s}-h_{19}$	$\dot{E}_{W,HPP}+\dot{E}_{19}=\dot{E}_4+\dot{E}_d$
Boiler feed-pump		$W_{FP}=\upsilon(P_3-P_{21})$ $=h_{3s}-h_{21}$	$\dot{E}_{W,FP}+\dot{E}_{21}=\dot{E}_3+\dot{E}_d$
Turbine		$W_t=\dot{m}_5h_5-\dot{m}_6h_6-\dot{m}_7h_7$	$\dot{E}_5=\dot{E}_6+\dot{E}_7+\dot{E}_{W,t}+\dot{E}_d$
Steam boiler		$Q=\dot{m}_5h_5-\dot{m}_3h_3-\dot{m}_4h_4$	$\dot{E}_1+\dot{E}_2+\dot{E}_3+\dot{E}_4=$ $\dot{E}_5+\dot{E}_{20}+\dot{E}_d$

The chemical exergy per mole of natural gas undergoing a combustion reaction has been calculated using (5) and (7). Assuming that the products and the reactants are ideal gases,

$$e_f^{-CH} = g_f + \sum_{i=1}^{n} x_{p,i} g_{p,i} + \sum_{i=1}^{n} x_{p,i} e_{p,i}^{-CH} \qquad (5)$$

$$g_f = \sum_i x_{r,i} g_{r,i} \qquad (6)$$

$$\sum_{i=1}^{n} x_{p,i} e_f^{-CH} = -RT_0 \sum_{i=1}^{n} x_{p,i} \ln \frac{x_{o,i}}{x_{p,i}} \qquad (7)$$

$$C = cE \qquad (8)$$

In the above equation, c is the cost of the unit exergy flux; C is the cost of the lost exergy flux; and E is the exergy flux. One of the most important objectives in the thermodynamic analysis of plants is to reduce costs. Monetary expenditures may be classified into two groups. One group consists of expenditures such as investment, operation, maintenance, and repair, while the other group involves expenses incurred due to energy loss. While evaluating any unit, knowing which exergy current cost is more dominant helps to determine where to improve the unit. The criteria for this evaluation, the thermoeconomic (exergoeconomic) factor (f), is described as follows:

$$f = \frac{Z}{Z + c_p E_D} \qquad (9)$$

A relatively high value of f shows that most of the monetary expenditures of the evaluated unit are caused by investment and operational costs. Trying to increase the productiveness of the component (for example, by increasing its surface or using equipment that is more expensive with a high efficiency) will not be realistic for the purpose of reducing the difference of the temperature in the heat transfer. On the other hand, a low *f* value shows the opposite result. In the latter case, units with high efficiency must be used, despite the risk of increasing investment and operational cost [18]

Here, Z is the levelized monetary expenditure, which includes the investment and yearly operational costs of any component.

$$Z = \left[\frac{Co_{inv}}{L_{yr} \times 8640h} + \frac{Co_{op,yr}}{8640h} \right] * A \qquad (10)$$

The value (Z) is a function of economic parameters, such as yearly operating time, life of the system, interest, and escalation. The energy lost in the whole system is the sum of the exergy lost in each unit.

$$\sum_{x=1}^{n} E_{D_x} = E_{D_1} + E_{D_2} + E_{D_3} + \ldots + E_{D_n} \qquad (11)$$

On the other hand, the ratio of exergy destruction in any unit or part to the exergy destruction in the whole system (y_n) shows the extent of energy destruction that is caused by the component [18]

$$y_n = \frac{E_{D,n}}{\sum E_D} \qquad (12)$$

The y values for the system components were calculated using (12).

IV. Results

Thermoeconomic values, such as the ratio of exergy loss, are calculated for the components, along with the exergy economic factor within any trigeneration system. These values are presented in Fig. 3.

The steam boiler is the component in which maximum exergy loss occurs. Furthermore, the exergy factor parameter is much higher for the steam boiler than it is for the other components. Although difficult, enhancing the performance of the steam boiler will have a great impact on the overall performance of the system. It shows that the output of the boilers is high, thus playing a vital role in the performance of the system.

Though the exergy loss in the steam turbine is lower than that in the steam boiler, its exergy economic factor is much higher than that of the steam boiler. While any improvement made in this component to increase its performance will lead to an increase in the cost of investment, it will have less of an effect on the performance of the system compared to the steam boiler; thus, it is not preferred. The heat exchanger has a rather low exergy economic parameter, and at the same time it has a 6.97% rate of exergy loss in the system, which shows that the performance of this component may be improved more easily than that of the others. When this result is taken into account, it is possible to state that the heat exchanger (HEX) may be considered a high priority component when carrying out improvements to the system.

Although the absorption-cooling system also contributes to 8.25% of the exergy loss in the system, its exergy economic factor parameter is much higher than of the process exchanger. This distinction shows that making improvements to the absorption-cooling system will prove to be difficult and more expensive. For these reasons, there is a mid-level priority for improving the absorption-cooling system.

V. Conclusion

A trigeneration system was designed based on the energy consumption data of a drug-producing factory; the equipment used in the system was evaluated by the thermoeconomic analysis method.

The ratios of the exergy loss of the components of the system to the exergy economic factors were calculated, and improvements were thus evaluated. According to the data obtained, improvements made to the steam boiler and heat exchanger would have the greatest impact on the performance of the system.

APPENDIX A NOMENCLATURE

A	Levelized value factor
B	Annual consumption
c	Cost of unit exergy flux (US$/kJ)
C	Hourly cost of the total exergy (US$/h)
Co	Cost (US$)
e	Specific exergy (kJ/kg)
E	Exergy (kJ/h)
El	Consumed electricity (kWh)
f	Exergy economic factor
h	Specific enthalpy (kJ/kg)
H_u	Low heat value (kJ/kg)
i_{eff}	Rate of payback (%)
L	System life (year)
$\dot{m}$	Mass flow rate (kg/h)
$\dot{Q}$	Heat (kJ/h)
P	Purchase price (US$/kWh or US$/m^3)
s	Specific entropy (kJ/kg K)
T	Temperature (^{o}C)
W	Work (kJ)
x	Stoichiometric coefficients
X	Mole fraction (kmol/kmol)
y	Exergy destruction ratio (%)
Z_g	Daily working time (hour)
Z_y	Annual working time (day)
Z	Levelized monetary expenditure (US$/h)

Greek letters

η_{th}	Thermal efficiency
η_{II}	Second law efficiency
ρ	Density (kg/m^3)
υ	Specific volume (m^3/kg)
Δ	Difference

Subscripts

ACP	Absorption cooling system pump
b	Boiler
c	Cooling load
conv	Conventional system
Ch	Chemical
d	Destruction, day
el	Electricity
f	Fuel
FP	Feed pump
HEX	Heat exchanger
HPP	High-pressure pump
in	Inlet
inv	Investment
LPP	Low-pressure pump
o	Dead state
op	Operational
ou	Outlet
p	Product
Ph	Physical
r	Reactant
trig	Trigeneration system
yr	Year

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