Exergoeconomic Analysis of 600 MW Thermal Power Plant

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Abstract

In this paper, Exergy and Exergoeconomic analysis of 600MW Thermal Power Plant is carried out. The energy and exergy at input and output of each component is calculated and specified with the help of data taken from the plant. The first and second law efficiency for each and every component of thermal power plant is calculated separately. The analysis shows that maximum amount of exergy destruction occurs in the boiler, which is around 42% of the total exergy produced and maximum energy loss occurs in the condenser which is 68.79%. The exergoeconomic factor is calculated for steam generator, turbine and condenser and it is found out to be 0.45, 0.81 and 0.41 respectively. A low value of the exergoeconomic factor and large percentage of exergy destruction i.e. (42%) in boiler implies that it is worth investing in boiler in terms of design or technical changes. Finally, the components are found where there is scope of improvement or having high exergy destruction with the help of Improvement Potential and maximum Improvement Potential is found out for the boiler which is around 92% of the overall improvement potential of the plant.

Keywords: *Energy, Exergy, Exergoeconomic, Exergy Destruction, Efficiency*

I. INTRODUCTION

Due to the continuously growing demand for the natural resources by the current energy conversion technologies and the serious concern for the impact on environment due to global warming, waste emission, disposal etc. have brought about the need of creation of new method that helps to understand that how to improve the design and operation of energy system and prevent the residues from damaging the environment. So the exergoeconomic is the science of the natural resources saving that connects the physics and economics by means of second law of thermodynamics.

The topic of analysis of power generation system is of scientific interest and also essential for efficient utilization of energy resources. The most commonly used method for the analysis of energy conversion system is the first law of thermodynamics or energy analysis. The energy analysis based on first law of thermodynamics cannot provide the true measure of efficiency and losses. So there is increasing interest in the combined effective utilization of first and second law of thermodynamics. Exergy analysis based on second law of thermodynamics provides the clear understanding between energy loss to environment and internal irreversibilities in the process. It is a methodology for the performance evaluation of devices and process and involving the exergy at different point in series of energy conversion steps. Exergy of any thermodynamic process shows efficiency or inefficiency of that process. Exergy is the phenomenon provides us with a better understanding of processes for qualifying energy. Therefore, it would better to use exergy to identify, qualify and quantify energy destruction. For this reasons, modern approach to process analysis uses exergy analysis which provides more distinct and clear view of a process.

The saving of energy or exergy is the prime objective of the conventional thermodynamic optimization process. This kind of optimization has benefits like an increase in energy or exergy efficiency or decrease of irreversibility of the system but this increase in efficiency is achieved at the cost of increase of capital investment. Thus it is difficult to reach the balance between thermodynamics and economics. It is well known fact that same amount of energy in different thermal devices may have quite different amount of exer5y and thus different economic values. So the conventional thermodynamic optimization is not able to differentiate the complex relationship among energy, exergy and cost. In order to overcome this problem, the combination of economic and thermodynamic optimization is done which is called exergoeconomis. In exergoeconomic analysis, combination of concept of cost which is an economic property and exergy which is an energetic property is done in order to achieve the best balance between thermodynamics and economics. The production process of complex energy system can be evaluated on the basis of its economic profitability and efficiency with respect to resource consumption. So the economic analysis can calculate the cost of fuel, operation and maintenance of the total plant or individual component etc. but provide no measure of how to allocate the cost among them and its product. On the other hand, thermodynamic analysis provides efficiency of individual component or overall plant and locates and quantifies the irreversibilities but cannot evaluate their significance in terms of overall production process. So the shortcoming of thermodynamics and economic analysis is overcome by exergoeconomic analysis.

II. LITERATURE SURVEY

Bejan et. al. 1996 [1] has explained the fundamentals of exergy analysis and entropy generation minimization, economic analysis and exergoeconomic analysis. This reviews the many concepts, like irreversibility, entropy generation or exergy destruction. Examples illustrate the exergy flows and accumulation in closed system, open system heat transfer processes and power and refrigeration plants. Rashad et. al. 2009 [2] has performed the energy and exergy analysis steam power plant in Egypt. The primary aim of the paper is to analyze each and every component of the system separately and identify the components which having the highest energy losses and exergy destruction. The maximum energy loss was found in the condenser where 56.4%, 55.2% and 54.4% of the input energy was lost to the surroundings at 50%, 75%, and full load respectively. In addition, the calculated overall thermal efficiency based on specific heat input to the steam was 41.9%, 41.7% and 43.9% at 50%, 75%, and 100% respectively.

Adibhatla et. al. 2014 [3] has explained the energy and exergy analysis of thermal power plant at different loads under constant and pure sliding pressure. In this paper, analysis is done at 100%, 80%, 60% load under constant and pure sliding pressure. The study shows that boiler has highest rate of exergy destruction than any other component in the plant. The study also reveals that there is a reduction in the rate of exergy destruction at part load conditions for the turbine in case of sliding pressure operation as compared to constant pressure operation. So the sliding pressure operation of the unit at part loads provides several benefits. So sliding pressure operation is suitable for once through units and thus a better way of operating at part load conditions. Rosen & Dincer 2003 [4] has performed the exergoeconomic analysis of power plant operating on various fuels. The definite relation is identified between the thermodynamic losses to capital cost ratios for all the devices. This relation is identified when the ratio is based on total exergy losses not on energy loss. This correlation may be successfully utilized in power plant component so as to achieve the optimal design by balancing the thermodynamic particularly exergy and economic characteristics. The result of analysis is helpful for both general and for electrical generating stations to provide insights into the relation between thermodynamics and economics.

Aljundi [5] has performed the exergy and energy analysis in Jordan. In his paper, each and every component of plant is analysed separately and an energy and exergy loss in each component is quantified. The identification is done for the component having the highest energy loss and exergy destruction. The largest energy loss is found to be condenser where 134MW is lost to the surroundings and only13MW is lost in boiler subsystem. On the other hand, maximum exergy destruction is found to be in boiler. Boiler has maximum percentage ratio of exergy destruction to total exergy destruction in plant which is about 77%. It is concluded that major source of irreversibility in plant is boiler. In boiler, major cause of exergy destruction is chemical reaction in combustion chamber. In order to reduce the exergy destruction in combustion chamber preheating of combustion air is done and air fuel ratio is maintained properly.

Bolatturk 2015 [6] has performed the thermodynamic and exergoeconomic analysis of cayirhan thermal power plant. In this paper, the author finds out the thermodynamic property at each and every point of steam flow cycle using the engineering equation solver package program. With the help of obtained thermodynamic properties, thermal and second law efficiency found to be 38% and 53% respectively. The exergy destruction, improvement potential, exergoeconomic factor is find out for each one of the component in the plant. The maximum exergy destruction occurs in boilers, so the improvement potential is largest for the boiler. The exergoeconomic factor which is always less than one is maximum for turbine group, after that boiler and followed by condenser. The low value of exergoeconomic factor for boiler shows that there is more exergy destruction and improvement can be done by reducing the exergy destruction or increasing the investment on boiler.

Gupta & Kumar 2015 [7] has performed the thermoeconomic optimization of a boiler used in a coal fired thermal power plant based on hot air temperature. The power plant under analysis is 55MW coal fired plant. The results are shown with the help of graph for the effect of hot air temperature on unit product cost of boiler, unit product cost of air pre heater, exergetic efficiency of the boiler system. Finally the optimization is done for unit product cost of air pre heater and unit product cost of boiler with reference to hot air temperature. Vuckovic et. al. 2014 [8] has performed the advanced exergy analysis and exergoeconomic evaluation of thermal processes in an existing industrial plant. In this paper, the advanced exergy analysis is used to identify performance of critical components and the potential for exergy efficiency improvement of industrial energy supply plant. With the advance exergy

analysis, overall system efficiency increased by 7.44% but this would require huge investment costs.
Selbas et. al. 2010 [9] has performed thermoeconomic optimization of the steam power plant with the help of levelized cost method. The optimization is done with Matlab. The stated design parameters are 20˚C ambient temperatures and 0.1 MPa atmospheric pressure, 12.5 MPa pump pressure. The optimum operating values for a 500 MW steam power within the specified design parameters has been defined as 900 ˚C boiler temperature and 250 kg/s steam flow. After the calculation, the unit cost of steam is 0.538 $/MW and the unit cost of electricity is 1.18 $/MW. The results show that due to increase in boiler temperature, unit cost of steam and unit cost of electricity also increases. Also with increase in boiler temperature, power output increases as well as total irreversibility also increases. So the optimization is done in order to achieve the maximum power with minimum possible irreversibilities.

III. MATHEMATICAL MODELING

Exergy is the maximum theoretical useful work obtained as the system interacts with the environment. If we neglect the nuclear, magnetic, electrical, and surface tension effects, the total exergy of a system (**E_x**) can be divided into four components: physical exergy $E_{X(PH)}$, kinetic exergy $E_{x(KN)}$, potential exergy $E_{x(PT)}$, and chemical exergy $E_{x(CH)}$.

$$E_x = E_{x(PH)} + E_{x(KN)} + E_{x(PT)} + E_{x(CH)} \quad (1)$$

If the kinetic, potential and chemical exergy are considered to be negligible then exergy can be written as by equation (2).

$$E_x = m[(h_1 - h_0)-T_0(s_1-s_0)] \quad (2)$$

Exergy can be transferred to or from a system by heat, work, and mass. Work can be obtained from a heat source at temperature (T), which is above the environment temperature (T_0), by transferring heat (Q) to a heat engine and rejecting the waste heat to the environment. Hence, every time heat transfer is accompanied by exergy transfer.
The maximum work that can be obtained from a heat source at temperature T is the work produced from a Carnot heat engine which works between this heat source and the environment. The efficiency of Carnot heat engine is,

$$\eta = 1 - \frac{T_0}{T} \quad (3)$$

Therefore, the exergy of heat Q is,

$$E_{x(heat)} = (1-T_0/T)Q \quad (4)$$

When the temperature at the location where heat transfer occurs is not a constant, the exergy transfer accompanying heat transfer is determined by integration.

$$E_{x(heat)} = \int (1 - T0/T)\, \delta Q \quad (5)$$

Exergy is the useful work potential. For boundary work, such as the work of a piston-cylinder device, a portion of work is used to push the atmosphere air away and it cannot be utilized and thus, the exergy transfer by the expansion work equals the difference between the expansion work and the surroundings work, that is,

$$E_{x(work)} = W - W_{surr} \quad (6)$$

Where $W_{surr} = P_0 (V_2 - V_1)$ and P_0 is the atmospheric pressure. Mass contains exergy as well as energy and entropy. The rate of exergy transfers to or from a system is directly proportional to the flow rate. When a mass (m) enters or exit the system, exergy (m Ψ) enters or leaves a system as well, where Ψ is the flow exergy.

$$E_{x(mass)} = m\psi \quad (7)$$

Or

$$E_{x(mass)} = m[(h - h_0) - T_0(s - s_0) + v^2/2 + g z]$$

A. *Exergy Balance for Closed System*

The exergy balance for a closed system is shown by combining the energy and entropy balances:

$$(U_2 - U_1) + (KE_2 - KE_1) + (PE_2 - PE_1) = \int_1^2 \delta Q - W \quad (9)$$

And entropy balance

$$S_2 - S_1 = \int_1^2 \frac{\delta Q}{T} + S_{gen} \quad (10)$$

Where W and Q represent, respectively, energy transfer by work and heat between the system under study and its surroundings, T denotes the temperature on the boundary where transfer of energy by heat occurs, and the term (S_{gen}) accounts for entropy generation causes internal irreversibilities. Multiplying the entropy balance by the temperature (T_o) which is temperature of surrounding and minus the resulting expression from the energy balance gives

$$(U_2 - U_1) + (KE_2 - KE_1) + (PE_2 - PE_1) - T_0 (S_2 - S_1) = \int_1^2 \delta Q - T_0 \int_1^2 \frac{\delta Q}{T} - W - T_0 S_{gen}$$

Rearranging, the closed system exergy balance results:

$$E_{x2} - E_{x1} = \int_1^2 (1 - To/T)\, \delta Q - [W - P_0 (V_2 - V_1)] - T_0 S_{gen} \quad (11)$$

B. Exergy Balance for Open System

Like mass, energy, and entropy, exergy is an extensive property, so it can be transferred into or out of a control volume where streams of matter enter and exit. Exergy balance is given as:

$$\frac{dE_x}{dt} = \sum_j \left(1 - \frac{T_0}{T_j}\right) Q_j - \left(W_{cv} - P_0 \frac{dV_{cv}}{dt}\right) + \sum_i m_i e_i - \sum_e m_e e_e - E_{xd}$$

(12)

Where subscript 'i' and 'e' represents inlet and exit streams respectively, 'm' is the mass flow rate and 'P_0' is the atmospheric pressure.

C. Exergoeconomic Factor

Exergoeconomic factor is denoted by f and is given by mathematical relation as:

$$f = \frac{Z}{Z + C_f(E_{xd})} \quad (13)$$

The exergoeconomic factor can be defined as the ratio of non-exergy-related costs i.e. capital investment and operating and maintenance expenses (Z) to the sum of non exergy and exergy related cost i.e. sum of investment and maintenance cost and exergy destruction cost (c_f*$E_{x,d}$) . In evaluating the performance of a component, we want to know the relative importance of each category and this is provided by the exergoeconomic factor (f).

D. Improvement Potential

Improvement potential is denoted by IP and is given by

$$IP = (1 - \eta_{Ex}) I \quad (14)$$

Where I is the irreversibility or exergy destruction in the component where η_{Ex} is exergy efficiency of the specific component.

IV. POWER PLANT UNDER CONSIDERATION

Power plant under consideration is Rajiv Gandhi Thermal Power Plant located in Hisar, Haryana. The total capacity of the plant is 1200MW with two 600 MW units. The work for implementation of 1200 MW Hisar Thermal Power Project was awarded during January, 07. The cost of Rs. 3.19 crore per MW for this project is the lowest in the Country. The thermodynamic model of the plant which shows the steam flow is shown in figure (1)

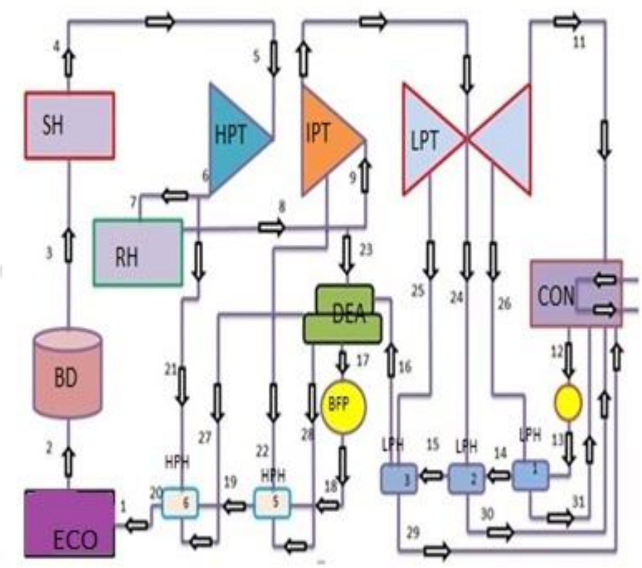

Fig. 1 Thermodynamic Model Of The Plant

V. EXERGY AND EXERGOECONOMIC ANALYSIS

Before exergoeconomic analysis, we will perform exergy analysis. The crucial steps to perform energy and exergy analysis are listed below:

1. First of all, the thermodynamic model of the overall plant is prepared showing the steam flow in the plant as shown in figure (1). The various channels connecting different components are numbered as 1, 2 etc.
2. The data is taken from the plant related to the mass flow rate, pressure and temperature of steam flow at each channel of thermodynamic model of the plant. All the data taken is real time data.
3. With the values of pressure and temperature at each point of thermodynamic model, the values of enthalpy and entropy can be find out at each point with the help of Mollier chart.
4. With the exergy and energy formula, the values of energy and exergy can be calculated at different point of the thermodynamic model of the plant.

Table 1 shows the data for energy and exergy analysis of the plant. It shows the value of pressure, temperature and mass flow rate of the steam flow which is taken from the plant and also the value of energy and exergy in kW calculated with the help of equation (2). One thing should be noted that all the data is taken at full load. Figure (2) shows the first law efficiency of different component.

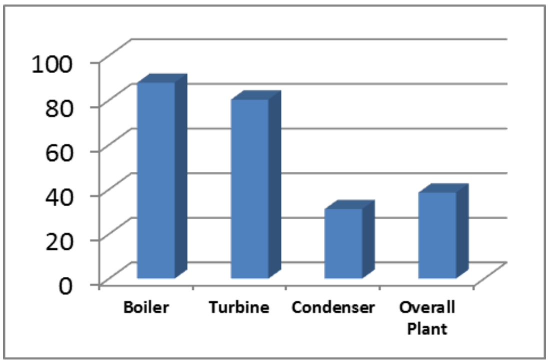

Fig. 2 First Law Efficiency of Different Components and Overall Plant

The maximum energy loss occurs in condenser. Approximately 70% of energy is lost in the condenser which is very share of energy supplied in the steam generator. The overall plant efficiency is 38.29%. Figure (3) shows the exergy efficiency of different components of the plant. The lowest exergetic efficiency is 58% for the boiler which means 42% of the exergy supplied is lost in the boiler itself. Percentage exergy destruction of different components is shown in figure (4). The value in figure (4) for exergy destruction plot is in absolute term and is shown in percentage in pie chart.

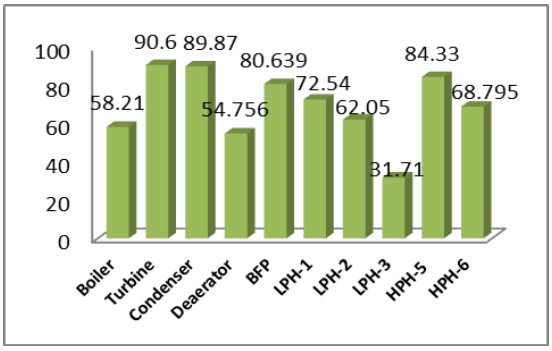

Fig. 3 Exergy Efficiency of Different Components

Table 2 shows the calculation for exergoeconomic factor and improvement potential. The improvement potential is related to exergy efficiency in the sense that more the exergy efficiency, less be the improvement potential and vice versa. The one thing should be noted that all the data taken is real time data taken from Hisar Thermal Power Plant.

Table 1.Energy and Exergy Analysis Data

S.N	(m) (kg/s)	P (bar)	T (˚C)	h (kj/kg)	s (kJ/kg K)	Energy (KW)	Exergy (KW)
0	-----	1.0332	27	113.32	0.395	0.00	0.00
1	547.5	182.4	278	1221.52	3.012	6068800.09	177037.84
2	547.5	177.5	349	1641.51	3.743	842174..35	292265.35
3	547.5	170.8	374	2792.45	5.562	1466839.00	618159.25
4	547.5	165.2	537	3397.83	6.418	1798284.63	809006.80
5	547.5	161.42	531	3385.22	6.419	1791380.58	803088.33
6	515.83	40.30	336	3057.17	6.522	1518540.58	570393.46
7	506.93	39.30	335	3057.18	6.533	1492345.14	558884.24
8	506.93	36.67	535	3529.90	7.236	1731626.24	691253.80
9	488.93	34.29	533	3527.59	7.263	1669069.14	661677.76
11	435.62	0.247	75	2637.18	7.259	1099456.96	119573.33
12	446.66	28	44.7	189.623	0.633	34094.28	2202.48
13	446.66	32.63	46.6	197.953	0.6581	37814.96	2573.20
14	446.66	27.92	56.2	237.28	0.781	55527.87	3804.64
15	446.66	22.60	85	357.97	1.132	109153.87	10397.35
16	446.66	19.22	156	662.44	1.9101	245492.37	42485.40
17	446.66	10.19	183	758.792	2.196	288319.03	55966.498
18	446.66	192.01	188	807.474	2.191	310063.66	69402.92
19	446.66	188.21	213	917.456	2.49	383307.53	87305.95
20	446.66	182.4	278	1221.74	3.09	495103.40	144430.63
21	35.02	39.52	330	3043.99	6.508	102623.93	38400.76
22	22.02	21.37	455	3368.57	7.270	71681.22	26265.12
23	22.02	10.39	424	3316.62	7.525	70538.91	23438.13
24	8.233	5.58	325	3114.96	7.58	24707.56	7168.80
25	9.466	1.27	232	2937.80	7.69	26730.84	5551.61
26	1.466	0.632	160	2798.83	7.85	3936.07	645.49
27	35.02	39.52	328	3038.63	6.94	102422.29	38293.66
28	22.02	21.37	451	3358.93	7.256	71457.93	26134.17
29	8.233	10.39	323	3099.88	7.29	24588.579	7808.07
30	9.466	5.58	216	2887.66	7.076	26258.66	7285.96
31	1.466	0.632	142	2764.49	7.796	3887.155	632.189

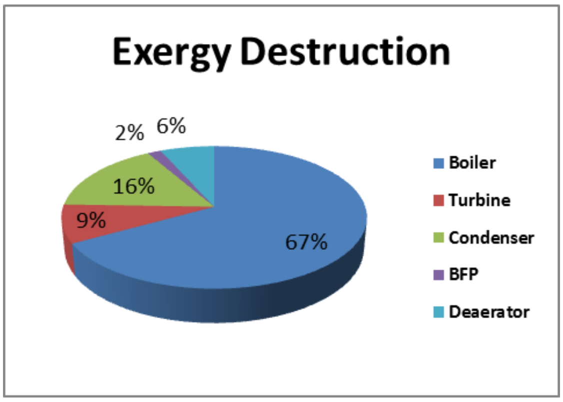

Fig.4 Exergy Destruction in Different Components

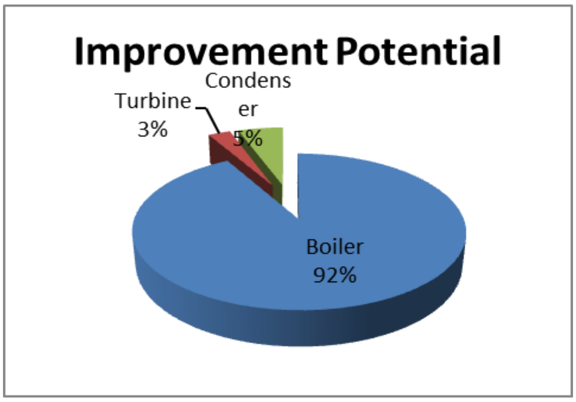

Fig.5 Improvement Potential in Different Components

Figure (5) shows the improvement potential for boiler, turbine and condenser. The value used in pie chart is in absolute term and is shown in percentage. The maximum improvement potential is for boiler which is around 92% of the overall improvement potential.

Table 2.Exergoeconomic Factor and Improvement Potential for different Components

Component	C	Z	f	IP
Boiler System	1246.41	1039.2	0.45	229282.26
Turbine System	161.68	715.8	0.81	6640.44
Condenser System	302.36	214.2	0.41	13482.733

In the table 2, C denotes the cost of exergy loss in core, Z shows the cost of investment in crore, f is the exergoeconomic factor and IP is the improvement Potential.

VI. CONCLUSION

The boiler has the highest amount of exergy destruction, so the greater attention should be paid towards boiler in terms of design and technical change. Around 42% of exergy supplied is lost in the steam generator itself, so efforts should be made for positive results. For the boiler exergoeconomic factor is 0.45. A low value of the exergoeconomic factor and large percentage of exergy destruction i.e. (42%) implies that it is worth investing in boiler in terms of design or technical changes. In condenser, the exergoeconomic factor is minimum and it is 0.41. The low exergoeconomic factor means more exergy destruction but in condenser the exergy destruction is only 10.13%. The reason for that is cost (investment cost + operating & maintenance cost) for the condenser is very less as compared to cost of exergy destruction, i.e. exergoeconomic factor is very low. The investment cost of condenser can be increased by some changes in design of condenser at the cost of exergy efficiency.

Maximum Improvement Potential is find out for the boiler. In percentage term, from the overall plant, the improvement potential for the boiler is 92%. Which means boiler is the components which has the major scope of improvement. The maximum amount of irreversibilities occurs in the boiler. Around 42% of the exergy is lost in the boiler itself. So the reason should be find out the overall low exergy efficiency for the boiler. It is well known that steam generator consists of super heater, evaporator, furnace, economizer, fan etc. The exergy efficiency of individual component in the boiler should be found out to investigate the components which are responsible for the low exergy efficiency of the boiler. The major technical changes should be made in the design of boiler in order to increase the exergy efficiency of the boiler after find out the cause of overall lower exergy efficiency of the boiler. The future work must concern itself on how to improve the exergy transferred to the steam in boiler.

NOMENCLATURE

BD	Boiler Drum
BFP	Boiler Feed Pump
CON	Condenser
DEA	Deaerator
E_x	Exergy
E_n	Energy
ECO	Economiser
f	Exergoeconomic Factor
HPT	High Pressure Turbine
HPH	High Pressure Heater
h	Enthalpy
IPT	Intermediate Pressure Turbine
I.P	Improvement Potential
K.E	Kinetic Energy
LPT	Low Pressure Turbine
LPH	Low Pressure Heater
m	mass flow rate of steam flow
P.E	Potential Energy
P	Pressure of Steam Flow
RH	Reheater
SH	Super Heater
s	Entropy
T	Temperature of Steam Flow
V	Velocity of Mass
W	Work Done

Z Height of Mass

Subscripts

ad	adiabadic
CH	Chemical
d	Destruction
e	Exit
f	Fuel
gen	Generation
i	Inlet
KN	Kinetic
l	Loss
PT	Potential
p	Product
PH	Physical
surr	Surrounding

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