ENERGY AND EXERGY ANALYSIS OF STEAM GENERATION AND UTILIZATION FOR ELECTRIC POWER GENERATION (CASE STUDY OF AJAOKUTA STEEL POWER PLANT, NIGERIA)

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Abstract

Steam power generation is one of the major power generations in the world which needs to be enhanced in order to reduce greenhouse effect while improving the power generation. The efficiency of energy utilization can be obtained from exergy analysis which involves showing the use of energy and material resources and thereby establishing how efficient the energy is used in the process. This paper presents the energy and exergy analysis of steam generation and utilization of Steam Power Plant in Ajaokuta Steel Plant in Nigeria. The method adopted include data collection and analysis on first and second laws of thermodynamics based on the present operational performance of the steam power plant under study. The energy and exergy from fuel was much higher than the energy and exergy gained by feedwater. The average energy generated in fuel being 107799.3kJ/s while that absorbed by the feedwater or generated by steam is 89454.3kJ/s. The percentage of steam generated to sensible heat from fuel is 83% while that of steam utilized to steam generated is 60%. The average exergy generated in fuel combustion is 67728kJ/s, while that of steam generated is 43245.1kJ/s and the steam exergy utilization is 43161.5kJ/s. The percentage exergy generated in the boiler is 64%, meaning exergy is lost through boiler and its accessories, while the exergy of steam generated to steam utilized is 99.8%, invariably no useful energy in steam that is lost in pipelines and connections. The exergy destroyed in steam generation and utilization equipment were also analysed. The first law energy generation and utilization are 83% and 60% while that of second law are 64% and 99.8% respectively. Hence, the first law analysis shows that the entire steel plant need urgent rehabilitation, but the exergy analysis has practically shown that steam generation is approximately equal to steam utilization of the plant.

Keywords: Exergy, energy, steam, feedwater, heat-regeneration

Introduction

Industrialization and urbanization increase population and technological development, invariably increase energy consumption which is one of the most important indicators of development in society or country and living standard of communities. Environmental problems such as contamination and greenhouse effect are caused by rapid growth development in energy consumption. Presently, about 80% of the electricity generation in the world is produced from fossil fuels such as coal, petroleum, fuel-oil, natural gas which fired thermal power plants while the remaining 20% of electricity generation are hydraulic, nuclear, wind, solar geothermal and biogas (Kaushik, Siva, & Tyagi, 2011). Although Nigeria is relatively endowed with abundant fossil fuels and other renewable sources of energy, the energy situation in the country is to be managed in such a way as to ensure sustainable energy development which brings about the research analyses of energy and exergy steam generation and utilization in a steam power plant. The energy generation and end use efficiency in developing countries are still only two-thirds to half of what would be considered best practice in the industrialized world.

It is imminent to reduce energy consumption of any process and to control the quantity of energy as well as the degradation of energy quality that occurs. Energy analysis based on the first law, unfortunately does not give any indication of energy quality degradation. The solution to measuring this quality degradation lies in a quantity based on the second law of thermodynamics, exergy which quantifies not only the energy transformation but also the energy destruction leaving the energy quality (Sanober, Richard, & Neil, 2012). Exergy analysis is based on second law of thermodynamics which is a useful method in evaluation, optimization and improvement heat generation and utilization equipment of steam power plant. Exergy overcomes the shortcoming of energy analysis which quantifies irreversibility through entropy generation in a process.

According to Mahdi and Yasar (2016) the mechanical relationship between entropy-exergy together with the thermal aspect usually leads to the formulation of physical exergy based on both useful work and heat which are the outcomes of available energy of a thermodynamic systems with respect to reserviour while the concepts of vaporising liquefied natural gas (LNG) as developed and for generating electricity have some thermodynamic and economic advantages over systems proposed in the past (Tatiana, George, Alicia and Camilo (2012) as cited in Morusuk *et al* (2012).

Rosen and Dinser (2004) compared exergy analysis method on low temperature air flow dehumidification systems. In their research analysis, three different air condition systems were experimented, namely; the rotary wheel system, liquid desiccant system and low temperature air –flow with ice storage system. The three systems have the same cooling load (11.8kW) but with different energy consumption for cooling and heating. The exergy efficiency of rotary wheel and liquid desiccant systems being 34.7% and 48.5% respectively while the low temperature air-flow and ice storage system has 68.1%. They concluded that, the new type low temperature air-flow and ice system has shown obviously the advantage of eliminating heat and moisture load with low energy consumption and high exergy efficiency. Eike, Andreas, and George (2016) used mixed integer linear programs (MILP) to evaluate a combined heat and power plants on energy and exergy balances for different operating conditions. Taner and Sivrioglu (2015) used regression analysis methods and SPSS 17.0 software to analyse the effect of solid oxide fuel cell (SOFC) in a sugar ethanol factory while (Zahra & Iman, 2018) analysed the fuel composition of SOFC with optimised differential evolution algorithm while varying the operating parameters of the of the cell. Mahdi and Yasar (2016) used exergy analysis to reduce the energy utilization and carbon emission by feed location modification and (Diana, Alexandar, Benjamin, Michele & Jens, 2016) compare the energy efficiency of different polymer processing methods in two different climatic conditions (temperate and Mediterranean). While Xueli, Niaping, and Jie, 2015) conducted exergy analysis on low temperature system with different working fluid and found that air flow with ice system has the highest exergy and best suitable for the system. Sarang, and Amit (2013) researched on industrial boiler to ascertained the metallurgical status by operating the plant at 50%, 75% and 100% capacity as designed. It was discovered that, the plant wassafer and economical to operate between 50% and 75% capacity. This paper presents the energy and exergy analysis of steam generation and utilization in a steam power plant in Nigeria. The Figures1 and Figure 2 present the external features and steam generating equipment of the Ajaokuta steam power plant.

Figure 1:External feature of the power plant (Ajaokuta Steam Power Plant)

Figure 2: Boiler Drum (Ajaokuta Steel Power Plant)

Methodology

Steam Generation Section

The Parametric data of the steam generating section was recorded and analysed using first law and second laws of thermodynamics with steam table. The evaluated data was recorded as the plant operated during this period. The equipment involved in steam generation section were waste- heat recovery equipment, heat regeneration equipment and boiler. According to Figure 3, M_{11} is the mass flow rate of the fluid circulating in the drum, which is much higher than the steam mass flow rate M_1. Figure 3 also present the schematic diagram of the steam power plant.

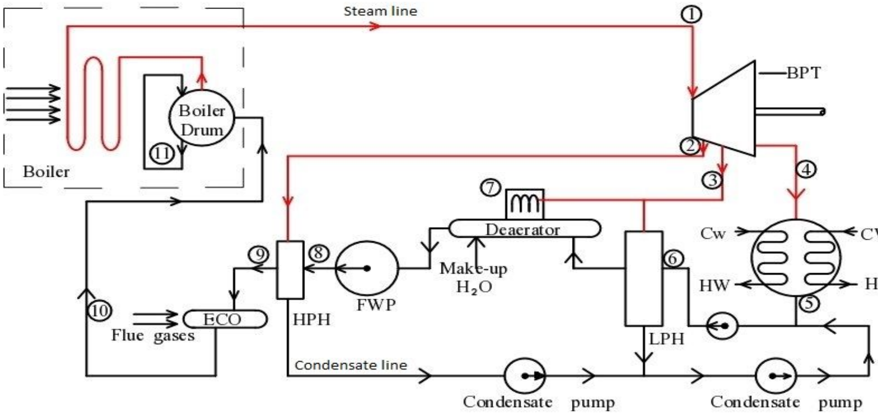

Figure 3: Schematic Diagram of the Steam Power Plant

Energy and Exergy of Steam Generation

According to Goran, Mica, Mirko, and Dragan (2012) and Cengel (2006), the equation for energy balance in an open system of steam generator is expressed below.

$$Q_{fi} \quad M \quad _i \quad \frac{i}{} \quad _i \quad W \quad M \quad _o \quad — \quad _o \tag{1}$$

According to Equation (1), W is the work produced by the system.
Neglecting kinetic energy and potential energy, the equation becomes;

a. Furnace Heat Analysis

$$Q_{fi} \quad M \ _i \quad W \quad M \ _o$$

$$Q_{fi} \quad \frac{}{3600} \tag{2}$$

$$Q_{fi} \quad \frac{0.72 \quad 8900 \quad 55.53}{3600}$$

$$Q_{fi} \quad 98.84M \ /s$$

Heat Analysis of the Boiler Drum and its Accessory (Energy Transfer in Boiler)

The energy transferred in steam generation was best analyzed using modified Rankine cycle. The following equation is used to calculate the heat gained by water in steam generator.

Furthermore, the exhaust gas, and consequently the fuel, gives thermal energy also to the water passing through the economizer. Thus, the energy gained by the water that becomes steam is written as follows:

$$E \quad M \quad _0 \quad M \tag{3}$$

$$E \quad 36.67 \ 1397.96 \quad 1013.71 \quad 26.39 \ 3411.86 \quad 1397.96$$

$$67.27M \ /s$$

a. Energy loss in boiler (E_{LB})

$$E_{LB} \quad Q_{fi} \quad E \tag{4}$$

$$E_{LB} \quad 98.84 \quad 67.27$$

$$31.57M \ /s$$

b. Boiler Energy efficiency (Eff_{BE})

The equation for boiler efficiency is $[1 \quad \frac{LB}{} \; X\,100\%$ (5)

$Eff_B \quad \frac{6\ .}{.\ \ 4} X\,100\%$ = 68.1%.

c. Exergy of the boiler

The exergy generation in furnace and the exergy gained by the working fluid in boiler was analyzed. Equation (6) gives the exergy gained by the working fluid in the boiler and that T is the temperature of the furnace. It is given: T = 833.15 K = 560°C. The formula for furnace exergy is,

$Ex_f \quad Q_f[1 \quad \frac{T}{T}$ (6)

T_0 = 303.15k T = temp. of furnace

$$Ex_f \quad 98.84 \;\; 1 \quad \frac{303.15}{833.15}$$

$$62.44M\;\;/s$$

d. Exergy gained by water.

The equation for calculating exergy gained by water is

$Ex \quad M \qquad {}_0 \quad M \;\; {}_o S \quad S\;{}_0 \quad M \qquad M \;\; {}_o S \quad S$ (7)

$$Ex \quad 32.72M\;\;/s$$

e. Exergy Destroyed in Boiler (I_{oB})

This is the unavailable energy in boiler as specified in second law of thermodynamics and the equation for calculating it is;

$I_{oB} \quad M \;\; {}_o S \quad S\;{}_0 \quad M \;\; {}_o S \quad S$ (8)

f. Exergy efficiency of the boiler (Eff_{BEx})

$Eff_B \quad [\frac{M \qquad M\;T \qquad M \qquad M\;T}{\_\_} \quad 100$ (9)

Steam Utilization Section

This is the section where steam was applied in steam power systems. The equipment involved was majorly back pressure turbine. The steam generated in boiler was discharged into turbine assembly and from the part of the steam was used for the regenerative heaters (Low Pressure Heater, High Pressure Heater and Deaerator). The energy and exergy analysis of the steam utilized in this section was analysed as follows.

Energy and Exergy of Steam Utilization.

a. Energy analysis in back Pressure turbine. The equation required for the calculation of energy in turbine is

$M \qquad M \qquad M_3 \;\; {}_3 \quad M_4 \;\; {}_4 \quad W_{TB}$ (10)

b. *Mass of Steam for Regenerative Heaters*. M_2 and M_3 are masses of steam required for regenerative heaters (LPH and HPH). The equation for calculating the mass flow rates were stated below according to Nag, (2011).

$M \quad \frac{M}{\qquad}$ (11)

$M_3 \quad \frac{M \quad M}{\quad}$ (12)

The Table 1 presents the requirement for the calculation of turbine first and second law analysis.

Table 1: Information required for energy and exergy analysis for turbine

	h_2 kJ/kg	h_3 kJ/kg	h_6 kJ/kg	h_7 kJ/kg	M_1 kg/s	M_2 kg/s	M_3 kg/s	M_4 kg/s
1.	3024.18	2245.07	610.63	1013.62	26.39	4.41	1.57	20.41
2.	3024.18	2257.61	636.53	1013.62	38.33	6.05	2.57	29.71
3.	3024.18	2249.25	636.53	1013.62	40.00	6.32	2.56	31.12
4.	3018.62	2226.57	610.63	1013.62	38.33	6.41	2.20	29.72
5.	3006.08	2269.55	614.94	966.76	39.44	5.80	2.32	31.32
6.	3057.98	2298.19	602.03	990.12	39.44	6.23	2.34	30.87
7.	3081.34	2285.41	610.63	1013.62	31.94	5.21	1.83	24.90
8.	2919.95	2244.06	614.94	897.76	32.50	3.99	2.04	26.47
9.	2974.36	2248.83	593.43	943.62	36.11	5.31	2.14	28.66
10.	2920.94	2222.19	602.03	920.62	38.33	5.27	2.28	30.78
11.	2936.03	2268.60	623.57	897.76	36.11	4.28	2.43	29.40
12.	3017.03	2252.96	658.18	990.12	27.22	3.83	1.64	21.75
13.	2908.42	2205.49	630.18	920.62	34.72	4.43	2.05	28.24
14.	2970.53	2269.78	610.63	943.62	36.11	5.10	2.39	28.62
15.	2961.41	2248.12	658.18	943.62	36.67	4.54	2.32	29.81

c. Steam Dryness Fraction in BPT. To calculate the dryness fraction of the steam exiting from turbine, the following equation was applied at 52^{0}C

$h_4 \quad h_f \quad x h_{fg}$ at 52^{0}C (13)

$$X \quad \frac{h_4 - h_f}{h_{fg}}$$

$$X \quad 0.82$$

$$W_{TB} \quad 26.39 \quad 3411.86 - 4.41 \quad 3024.18 - 1.57 \quad 2554.12 - 20.41 \quad 2167.6$$
$$28451.7 \quad /s$$
$$28.5M \quad /s$$

d. Turbine Energy Efficiency (Eff_{TB})

$$Eff_{TB} \quad \frac{A \quad tu \ wor \quad of \ turbine}{Isentro \quad i \ wor \quad of \ turbine.}$$

$$\frac{M \qquad M \ - M \quad - \quad M \ - M \ - M \quad -}{M \qquad M \ - M \quad - \quad M \ - M \ - M \quad -} \quad (14)$$

e. Turbine Exergy Analysis.

The total exergy generated in the turbine is expressed as the exergy generated through process 1-4. Therefore, the total exergy from process 1 – 4 is

$M \quad h - h - {}_o S \quad S \qquad M - M \quad h - h_3 - {}_o S - S_3 \qquad M_4 \ h_3 - h_4 - {}_o S_3 - S_4$ (15)

f. *Exergy Destroyed in Turbine (I_{oBPT})*. The equation for calculating turbine exergy is stated as $I_{oTB} \quad {}_o M S - M S - M_3 S_3 - M_4 S_4$ (16)

Energy and Exergy analysis in Condenser

The energy and exergy in condenser is analysed below.

i. Energy utilisation in Condenser. Energy utilisation in condenser is the energy dissipated from steam to the cooling water and is expressed as below.

$$.E_{co\ \ d}\quad M_4\ ?_4 - ?\ . \qquad (17)$$

ii. Exergy utilisation in condenser (Ex_{cond}) and is expressed as below.

$$Ex_{co\ \ d}\quad M_4[?_4 - ? - \ _o S\ - S_4 \qquad (18)$$

iii. Exergy destroyed in Condenser (I_{ocond}) is expressed as

$$I_{oco\ \ d}\quad M_4\ _oS_g \qquad (19)$$
$$S_g\quad S_4 - S$$

Energy and Exergy Utilisation in Regenerative Heaters

This was the energy and exergy contained in steam used in heating Low pressure heater and high-pressure heater

i*. Energy utilisation in Low and High-Pressure Heaters* and is expressed as below

$$E_{LP}\quad M_3\ ?_3 - ?_6 \qquad (20)$$
$$E\ _P\quad M\ \ ? - ? \qquad (21)$$

ii. Exergy utilisation in Low and High Pressure Heaters. The equation for the exergy evaluation in regenerative heaters is expressed below

$$Ex_{LP}\quad M_3[?_3 - ?_6 - \ _o S\ - S_6 \qquad (22)$$

$$Ex\ _P\quad M\ [? - ? - \ _o S\ - S \qquad (23)$$

Results and Discussion

The energy and exergy analysis of steam generation and utilization of steam power plant was analysed base on the present performance of the steam plant and the result is presented in Table 2 below;

Table 2: Parametric Data of steam power plant in kW/s

15.1. E_i	15.2. E_{gen}	15.3. E_{uti}	15.4. Ex_i	15.5. Ex_{gen}	15.6. Ex_{uti}
15.7. 98843.4	15.8. 67274.9	15.9. 43119.5	15.10. 62439.4	15.11. 32722.8	15.12. 33146.5
15.13. 105507	15.14. 92893.7	15.15. 58011.6	15.16. 66648.8	15.17. 45316	15.18. 47004.8
15.19. 109283	15.20. 97449.5	15.21. 60289.7	15.22. 69034.1	15.23. 47227.7	15.24. 48603
15.25. 108283.5	15.26. 93208.8	15.27. 59340.1	15.28. 67915.4	15.29. 45598.7	15.30. 47453.1
15.31. 104396.4	15.32. 96790.2	15.33. 58062.6	15.34. 66406.6	15.35. 47158.7	15.36. 48322.3
15.37. 101064.6	15.38. 96497.2	15.39. 59051.4	15.40. 63387.7	15.41. 46993.8	15.42. 47907.5
15.43. 99954	15.44. 80450.8	15.45. 51660.9	15.46. 63580.7	15.47. 39284.8	15.48. 40233.8
15.49. 106839.7	15.50. 89301.4	15.51. 47855.7	15.52. 67009.9	15.53. 40450.1	15.54. 38628.6
15.55. 110904.5	15.56. 91172.4	15.57. 53927.9	15.58. 69559.3	15.59. 44201.8	15.60. 44810.5
15.61. 119389.5	15.62. 97377.3	15.63. 55765.1	15.64. 74881.1	15.65. 47049.6	15.66. 47234.3
15.67. 113836.5	15.68. 94707.1	15.69. 52492.8	15.70. 71136.4	15.71. 45746	15.72. 44539.9
15.73. 104396.4	15.74. 68766.4	15.75. 41542.1	15.76. 65185.1	15.77. 33488.6	15.78. 25774.1
15.79. 117168.3	15.80. 89599.5	15.81. 51951.7	15.82. 73265.3	15.83. 43176.2	15.84. 44163.3
15.85. 119389.5	15.86. 94034.7	15.87. 55581.2	15.88. 74499	15.89. 45577	15.90. 44594.1
15.91. 97732.8	15.92. 92290.1	15.93. 53923.8	15.94. 60985.3	15.95. 44684.8	15.96. 45006.6

The energy and exergy from fuel in Figures4 and Figure 5were much higher than the energy and exergy gained by feedwater. The average energy generated in fuel was 107799.3kJ/s while that absorbed by the feedwater or generated by steam was 89454.3kJ/s and the average energy utilized by BPT and process heating was 53505.1kJ/s. The percentage of steam generated to sensible heat from fuel was 83% while that of steam utilized to steam generated was 60%, the remaining energy generated from steam might be lost through flue gases in stack, pipeline leakages, boiler blowdown, furnace wall spallation, turbine bleeding and energy lost through recirculation of condensed water which has the largest value. Other reasons which may cause the high losses of energy in the steam plant were; moisture or more condensate in fuel supply line, carbon monoxide in air (CO) or surface radiation, convection high water level in the boiler drum and blockage or cracks in superheater tubes.

The average exergy generated in fuel combustion was 67728kJ/s, while that of steam generated is 43245.1kJ/s and the steam exergy utilization was 43161.5kJ/s. The percentage exergy generated in boiler is 64%, meaning exergy was lost through boiler and its accessories, while the exergy of steam generated to steam utilized was 99.8%, invariably no useful energy in steam that was lost in pipelines and connections.

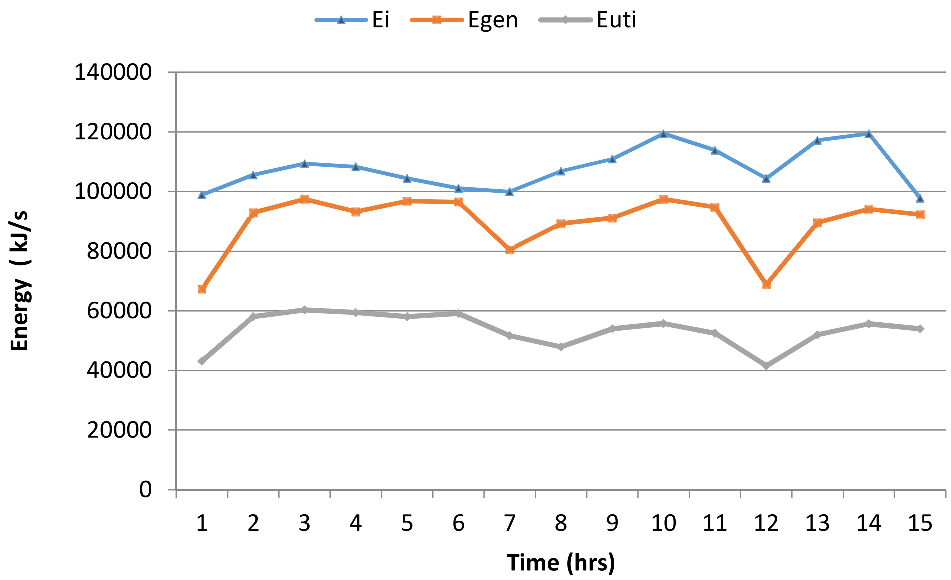

Figure 4: The relationship between Energy generation and Utilisation of steam

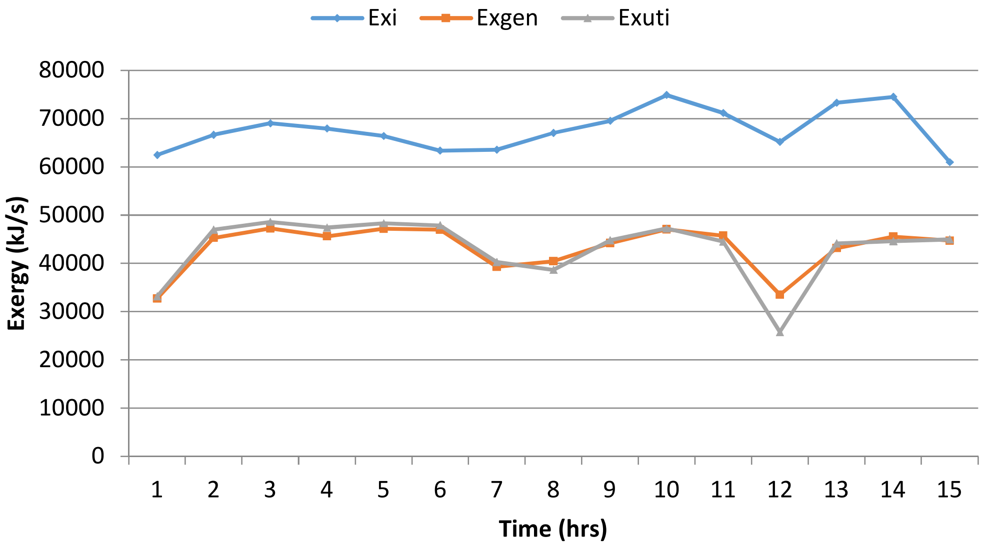

Figure 5: The relationship between Exergy generation and utilization of steam

Conclusion

In this work, energy and exergy analysis of modified Rankine cycle was carried out. The exergy analysis is a very important tool to find the actual irreversibility and actual performance of steam generating and utilisation equipment of steam power plant. The first law analysis shows that the entire steel plant need urgent rehabilitation, but the exergy analysis has practically shown that steam generation is almost equal steam utilization of the power plant.

Conflict of Interest Statement

On behalf of all authors, the corresponding author states that there is no conflict of interest.

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Nomenclature

C_i- initial velocity of fuel -m/s
C_o – velocity of steam generated m/s
CV_f– Calorific value of fuel (Natural gas) MJ
E – Energy
E_o – Energy absorbed by water in boiler kJ/s
Ex – Exergy
Ew_1 – Energy gained by feedback in boiler – kJ/s
E_{LB} – Energy loss in boiler – kJ/s
Ex_0 – Energy released by flue gasses kJ/s
Exw - Exergy gained by water kJ/s
E_{gen}– Energy generated by Steam kJ/s
E_{uti} – Energy utilisation by BPT and regenerative heaters kJ/s
E_{xi} – Exergy generated in furnace kJ/s
E_{xf}– Energy generated from fuel combustion kJ/s
Ex_{gen} – Exergy generated by steam kJ/s
Ex_{uti} – Exergy utilisation by BPT and regenerative heaters kJ/s
Ex_{TB} – Turbine exergy
g- acceleration due to gravity-m^2/s
h_i- specific enthalpy by the fuel in kJ/kg
h_1 – enthalpy of steam into back pressure turbine kJ/Kg
S - Entropy
S_{11}- Entropy generated by steam leaving boiler – kJ/KgK
S_{10} - Entropy generated by feed water into boiler – kJ/KgK
S_1- Entropy of steam into back pressure turbine
T – Temperature of furnace - K
T_0 – reference temperature - K
T_1 – Steam temperature into back pressure turbine (K)
T_{10} – Feed water temperature into boiler drum - K
T_{11} – Steam temperature from boiler drum - K
I_{OB} – Exergy destroyed in boiler
Eff_{BEx} – Boiler exergy efficiency
M_1- mass flowrate of steam into backpressure turbine
M_2 – mass flowrate of steam for high pressure heater
M_3 - mass flowrate of steam for low pressure heater
M_4 – mass flowrate of steam discharge into condenser
M_5 - mass flowrate of condense water discharge from condenser
M_6 - mass flowrate of water from low pressure heater
M_7- mass flowrate of feed water into feed pump
M_8 - mass flowrate of feed water into high pressure heater
M_9 - mass flowrate of water into Economiser
M_{10} - mass flowrate of water into boiler
M_{11} -Mass flowrate steam from the boiler drums Kg/s
M_{12} – Mass flowrate of water into boiler drums Kg/s
M_s – mass of steam generated –Kg/s
W- work done – kJ/s
W_{TBs} – Isentropic work of the turbine

W_{TB}– Real work of the turbine
Z_i- initial level of fuel-m

Subscripts
gen – generated
uti – utilisation
i – inlet
o – outlet
cond – condenser
eco –economizer