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First Law and Second Law Analysis of a Lignite Fired Boiler Used in a 30 MWe Thermal Power Plant

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Abstract*— The aim of this paper is to find out the amount and the sources of irriversibilities generated in the boiler of a 30 MWe thermal power plant so that any process in the system that having the largest exergy destruction can be identified that in turns helps the designer to redesign the system's components and the processes. The useful concept of energy and exergy utilization is analyzed, and applied to the boiler system. Energy and exergy flows in a boiler have been calculated in this paper. The energy and exergy efficiencies have been determined as well. In a boiler, the energy and exergy efficiencies are found to be 84.524 % and 33.73 % respectively. Irriversibilities (exergy destruction) for boiler is also calculated and found to be 93.355 MW. It has been found that the boiler is the major contributor for exergy destruction.

***Keywords* — First Law of Thermodynamics, Second Law of Thermodynamics, Energy, Exergy, Irriversibilities, Boiler, Lignite Coal, Exergy destruction**

I. INTRODUCTION

Energy consumption is the most important problem in the today's era. In the present scenario per capita energy consumption determines the level of development of the nation. With the increased awareness that the world's energy resources are limited has caused many countries to reassess their energy policies and take measures for eliminating the waste. It has also ignite the interest in the scientists and researchers to take a close look at the energy conversion devices and to develop new techniques for better utilization of the available resources. The First Law of Thermodynamics is conventionally used to analyze the energy utilization, but it is unable to account the quality aspect of energy. That is where exergy analysis becomes relevant. Exergy is the consequent of Second Law of Thermo- dynamics. It is a property that enables us to determine the useful work potential of a given amount of energy at some specified state. Exergy analysis has been widely used in design, simulation and performance evaluation of thermal and thermo-chemical systems. The energy use of a country has been assessed using exergy analysis to gain insight of its efficiency and potential for further improvement in the performance of a thermodynamic system. Energy and exergy analysis provides insight into losses in various components of a power generating system. Unlike energy, exergy is not generally conserved but is destroyed. So, the majority of the causes of irreversibilities like heat transfer through a finite temperature difference, chemical reactions, friction, and mixing are accounted by exergy analysis [1]. Researchers all around the world are carrying out exergy studies and have evaluated the performance of power plants to assess the main locations of the losses, in order to optimize the performance of the power plants. The exergy method of analysis has been developed and has been used in Russia, Europe, Germany and Poland from the year 1960 [2-3]. Horlock et al. [4] estimated the rational efficiencies of three modern fossil-fuel power plants using the exergy calculations They analyzed the effect of water or steam injection on the rational efficiency of the plant. The relation between the irreversibility in combustion and the loss of exergy due to mixing in the exhaust was also considered in their analysis Rosen [5] has compared the performance of operating coal-fired and nuclear steam power plant located in Canada of unit size of approximately 500 MWe using a process-simulator, Aspen Plus. Verkhivker and Kosoy [6] performed an exergy analysis on a power plant. In another study, Dinçer and Muslim [7] performed a thermodynamic analysis of a reheat cycle power plant. Kwak et al. [8] studied a 500 MW combined cycle plant in exergetic and thermo-economic point of view. The quantitative balance of the exergy and exergetic cost for each component and for the whole system was considered in the investigation. A computer program was developed to determine the production costs of power plants, such as gas and steam plants and gas turbines cogeneration plants. Kopac and Hilalci [9] presented energy and exergy analysis of the Çatalağzı power plant and investigated the effect of ambient temperature on the power plant performance. Sengupta et. al. [10] conducted an exergy analysis of a 210 MW thermal power plant. Aljundi [11] quantified the exergy loss in the components as well as the overall exergy loss of a thermal power plant and concluded that the maximum exergy destruction occurs in the boiler system by as much as 77% of the total exergy destruction of the power plant. Oktay [12] analyzed a modern coal-fuel power plant in Turkey using the exergy calculation. Ganapathy et. al. [13] performed an exergy analysis on an operating 50 MWe unit of lignite fired steam power plant, aiming to find the energy efficiency and exergy efficiency of the power plant. The results revealed that maximum energy loss of 39% occurs in the condenser, whereas the maximum exergy loss of 42.73% occurs in the combustor. Ozdemir et. al. [14] performed an exergo economic analysis of fluidized bed coal combustor power plants.

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II. FIRST LAW (ENERGY) ANALYSIS OF BOILER

The First law efficiency of the boiler can be calculated by two methods, direct and indirect method. Direct method of efficiency calculation includes only the input and the out put energies but does not include the various heat losses occurring in the boiler. The efficiency can be measured easily by measuring all the losses occurring in the boilers. The disadvantages of the direct method can be overcome by this method, which calculates the various heat losses associated with boiler. The efficiency can be arrived at, by subtracting the heat loss fractions from 100.

The losses from the boiler include the following:

- Dry flue gas loss (L_1)
- Heat loss due to moisture and hydrogen in fuel.(L_2)
- Losses due to the combustibles.(L_3)
- Losses due to sensible heat in ash(L_4)
- Radiation losses.(L_5)
- Unaccounted losses(L6)
- **Boiler Efficiency** = 100 – Total losses
  = 100 – (L_1+L_2+L_3+L_4+L_5) (1)

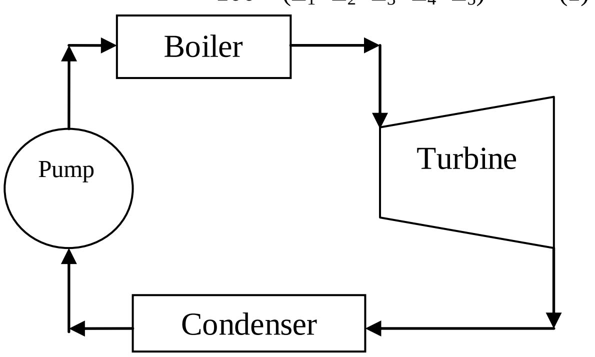

Fig: - 1 schematic diagram of simple steam power plant.

A. *Dry flue gas loss (L_1) can be calculated by*

$$Theoretical\ Air\ required = \frac{1}{23}\left[2.67C + 8\left(H_2 - \frac{O_2}{8}\right) + S\right] \quad (2)$$

$$kg/kg\ of\ coal$$

$$Excess\ Air = \frac{O_2\%}{21 - O_2\%} \quad (3)$$

Actual mass of air supplied = (1+ Excess air/100) * Theoretical Air in kg/kg of coal (4)

Total mass of flue gas = (Actual mass of air supplied +1) kg (5)

$$FlueGasLoss = \frac{mass \times C_p \times (T_{Flue} - T_{Air})}{C.V.} \quad (6)$$

B. *Loss due to % moisture and % hydrogen in fuel (L_2):*

Losses due to % moisture & Hydrogen in fuel =

$$\frac{total\ moisture \times heat\ per\ kg\ of\ moisture}{gross\ C.V.} \quad (7)$$

$$Total\ moisture = \frac{\%\ moisture}{100} + \frac{9 \times \%H}{100} \quad (8)$$

C. *Losses due to combustible (L_3):*

Losses due to combustible =

$$\frac{(\%U\ Total\ combustible) \times (C.V.\ of\ carbon) \times 100}{gross\ C.V.} \quad (9)$$

D. *Losses due to sensible heat in ash (L_4):*

Losses due to sensible heat in ash = (Losses due to sensible heat of fly ash) + (losses due to sensible heat ash in grate) (10)

E. *Radiation losses (L_5):*

Radiation loss = as per design the loss due to radiation taken from American boiler

Manufacturer's association graph is = 0.41%

F. *Unaccounted losses (L_6):*

These are taken as 1.5 %.

Table 1 Parameters Used For Efficiency Calculation

Parameters	Unit	Quantity
Steam temperature	°C	482
Steam pressure	kg/cm^2	61.1
Steam flow	TPH	73
F.G. Air heater outlet temp.	°C	165
Rejected coal	%	28.76

The proximate analysis and ultimate analysis of lignite coal are given in Table

Table 2 Ultimate analysis of coal

Coal constituents	Unit	Coal sample
C	%	51.95
H	%	3.46
N	%	1.378
O.	%	11.63
S	%	0.5
Ash	%	10.14
Moisture	%	20.63

Table 3 Proximate Analysis of Coal

Coal constituents	Unit	Coal sample
Fixed Carbon	**%**	**32.62**
Volatile matter	**%**	**36.1**
Moisture	**%**	**20.63**
Ash	**%**	**10.14**
Calorific value	**Kcal/kg**	**4619.44**

Summary of boiler losses

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Total ($L_1+L_2+L_3+L_4+L_5+L_6$) = 15.476
Boiler Efficiency = 100 – Total losses
= 100 – 15.476 = 84.524 %

III. SECOND LAW (EXERGY) ANALYSIS OF BOILER

Table 4 Data for exergy calculation of the boiler are as follows: -

Substance	Mass flow rate (Kg/Sec)	Temperature(^{0}C)
Air	57.220	160^{0}C
Fuel	06.945	946^{0}C
Water	34.720	126^{0}C
Steam	34.300	480^{0}C
Hot Products	64.165	165^{0}C

Exergy of fuel: -Exergy of the fuel is given by the equation proposed by Shieh and Fan [15] for calculating the exergy of a fuel

$$\varepsilon_f = 34183.16(C) + 21.95(N) + 11659.9(H) + 18242.90(S) + 13265.9(O)$$

In which: the values in parentheses are the percentage in mass of the carbon (C), nitrogen (N), hydrogen (H), sulfur (S), oxygen (O), that can compose a fuel. on substituting the values of C, N, H, S and O from Ultimate analysis we get,Exergy of the fuel = 19795.9 KJ/Kg While the calorific value of the fuel is = 19401 KJ/Kg The exergy value of the coal is very close to its calorific value Thus it is clear that the exergy of the fuel is accurate. Kotas (1985) suggests that the ratio (exergy of fuel / calorific value) should stay between 1.15 and 1.30; in this analysis, such value is 1.020.

Total Exergy of the fuel = 137482.5255 KW

= 137.4825255 MW

Exergy of feed water: -

Exergy of the feed water can be calculated by the relation

$$\varepsilon_{w_=} = (C_p)_w\left[(T_w - T_0) - T_0 l_n\left(\frac{T_w}{T_0}\right)\right] \quad (11)$$

Where,

$T_{w=}$ Temperature of feed water = 126 ^{0}C=399 K

T_0 = Reference temperature = 25 ^{0}C = 298 K

$(C_p)_w$ = Specific heat of water at constant temperature =4.187 KJ/KgK

On putting these values in above equation we get ,

Exergy of the feed water = 58.71 KJ/Kg

Total Exergy of the feed water = 2038.41 KW = 2.03841 MW

Exergy of air supplied: -

Exergy of the air supplied can be calculated by the relation

$$\varepsilon_a = (C_p)_a\left[(T_a - T_0) - T_0 l_n\left(\frac{T_a}{T_0}\right)\right] \quad (12)$$

Where,

T_a = Temperature of feed water = 160 ^{0}C = 433 K

T_0 = Reference temperature = 25 ^{0}C = 298 K

$(C_p)_a$ = Specific heat of air at constant temperature = 1.005 KJ/KgK

On putting these values in above equation we get ,

Exergy of the feed water = 58.71 KJ/Kg

on putting these values in above equation we get ,

Exergy of the air supplied ε_a = 23.77 KJ/Kg

Total Exergy of air supplied = 1360.25 KW

= 1.36025 MW

Exergy of steam formed: -

Exergy of steam formed can be calculated by the relation

= $(h - h_0) - T_0 (S - S_0)$

Where,

h = enthalpy of Steam formed = 3330.2 KJ/Kg

h_0 = enthalpy of feed water = 104.9 KJ/Kg

T_0 = Reference temperature = 25 ^{0}C = 298 K

S = Entropy of Steam formed = 6.750 KJ/Kg K

S = Entropy of feed water at Reference temperature

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= .367 KJ/Kg K

On putting these values in above equation we get

Exergy of steam formed = 1323.166 KJ/Kg

Ideal Eff. (%)	First law Eff. (%)	Deviation (%)	Second law Eff. (%)	Deviation (%)	Irreversibility's (MW)
85	84.524	.476	33.73	51.27	93.355

Total Exergy of steam formed = 45384.59 KW

Exergy of the flue gasses: -

$$\varepsilon_g = (C_p)_g \left[\left(T_g - T_0\right) - T_0 l_n \left(\frac{T_g}{T_0} \right) \right] \quad (13)$$

Where,

T_g = Temperature of feed water = 165^0C = 438 K

T_0 = Reference temperature = 25 ^{0}C = 298 K

$(C_p)_w$ = Specific heat of water at constant temperature =1.321 KJ/KgK

On putting these values in above equation we get ,

Exergy of the flue gasses = 33.33 KJ/Kg

Total Exergy of the flue gasses = 2138.76 KW

= 2.13876 MW

Total Irriversibilieties in the steam Boiler: -

Total Irriversibilieties in the steam boiler are given by ,

I_b = Total exergy entering the boiler - Total exergy leaving the boiler

$$I_{b} = \left(\varepsilon_a + \varepsilon_w + \varepsilon_f\right) - \left(\varepsilon_s + \varepsilon_g\right) \quad (14)$$

On putting the respected values in above equation we get

Total Irriversibilieties in the steam boiler = 93.366 MW

Second Law efficiency (Exergetic efficiency) of the Boiler: -

Second Law efficiency (Exergetic efficiency) of the Boiler is given by

η_{II} = Total Exergy leaving the boiler / Total Exergy entering the boiler

On putting the respected values in above equation we get

Second Law efficiency (Exergetic efficiency) of the Boiler η_{II} = 33.73 %

IV. RESULTS AND DISCUSSIONS

The First Law and Second Law analysis is performed and the results are summarized in table 4.
Percentage deviations are calculated from the actual and ideal efficiencies, this deviation is an important factor since it gives us a measure of performance of the equipments. More the deviation poorer will be the performance of the equipments and vice versa. The total Exergy input to the boiler is 140.877 MW, while the Exergy output is 47.522 MW due to the irriversibilities of the system 93.355 MW of energy has been lost. The result of energy analysis shows that the energy input of the boiler is 137.483 MW**.** First Law (Energy) efficiency and Second law (Exergy) efficiency are found to be 84.524% and 33.73%. The deviation of first law and second law efficiency from actual efficiency provided by the manufacturer is also shown in table 3.1. The value of efficiency deviation from first law is not very much while the efficiency deviation from second law is of significant amount, that's why exergy analysis is very important and plays a vital role in exact energy assessment. The factors contributing to the higher irriversibilities are irreversible chemical reaction in the combustion chamber, tube fouling, defective burners, fuel quality, use of inefficient soot blower, steam traps and air heater fouling.

IV. CONCLUSION

This paper represents the results of energy and exergy analysis performed on a 30 MW coal fired thermal power plant. The analysis was performed on the unit with running load of 25.5 MW. Exergy destruction on the boiler combustion chamber is also discussed in this paper. The result of exergy analysis indicates that the boiler has the energy destruction of 93.355 MW, which is the 67.90 % of the total exergy input to the boiler. By optimizing the factors (as discussed above) which are responsible for irriversibilities the performance of the boiler can be improved and the irreversibility losses can be reduce. This study can help the designer to redesign the system's components and the processes

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