Energy Audit of a Boiler and Waste Heat Recovery System in Thermal Power Plant

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Abstract— At present the installed power generation capacity in India is 303083 MW. Based on the availability of fuel in India, approx 70% of the power generation from using pulverized coal firing in thermal power plant. In recent years, India's energy consumption has been increasing at a relatively very fast rate due to economic development and population growth. Currently world electricity demand is growing at the rate of 2.6 percent per year and it is projected to double by 2030 .the energy demand is increasing day by day, but available energy lacks in supply due to lacks of fossil fuels availability. Hence there is no option for proper and efficient utilization and conservation of energy. In this paper the main focus is given to on energy conservation opportunity by using the energy audit technique in a thermal power plant of 210MW capacity as well as use waste heat recovery system in a thermal power plant to recover the energy of exhaust gas stream with high temperature has the high potential of waste heat. Energy Audit defines the performance of each and every equipment and compared it with the base case. A well done energy audit and energy management helps to recognize the pattern of energy , form of energy consumption and amount of energy consumption so that identify possible area of energy conservation in thermal power plant.

Keywords— Energy audit, Thermal Power Plant, Boiler efficiency, Waste Heat Recovery System, Energy Conservation.

1. INTRODUCTION

Bokaro Thermal Power Station, Damodar Valley Corporation India is located at Bokaro Jharkhand. It is one of DVC's major coal fired power plants, located on the bank of the Konar River. The power plant is one of the coal based power plants of BTPS.The plant has an installed capacity of 3X210 MW. The first unit was commissioned in March, 1986. During November 1990, the second unit was commissioned and August 1993, the third unit was commissioned. Electricity is produced in BTPS by burning of pulverized coal and generates the super heated steam which is further fed to Steam Turbine to rotate the generator rotor to produce electricity at 50 Hz frequency and 15.75 kV voltages in all units. Then this 15.75 kV voltage is stepped up through individual step up transformer to 220 kV and fed to the grid. There are two other step down transformers in each unit i.e. Unit Auxiliary Transformer (UAT) which step down the voltage level to 6.6 kV and fed to the auxiliaries superheated steam is generated in steam generators at 535 ^{o}C and 130 kg/cm^2 and same is fed to steam turbine through control valve. From different stages of turbine extractions are taken and used for HP Heaters and LP Heaters. At the last stage of LP turbine the exhaust steam is taken into the condenser to maintain the vacuum or back pressure to the turbine [1]. The overall performance for all the 3 units of Plant is shown in Table 1.

Table 1: Overall Year Wise consumption history and Performance review of Thermal Plant of BTPS unit-1

Sl. No	Parameter	2008-09	2009-10	2010-11	2011-12	2012-13	2013-14	2014-15
1	Generation(MU)	3451.64	3518.16	3436.21	3356.52	3106.98	1737.68	1634.38
2	PLF(%)	62.54	63.74	62.26	60.65	56.3	31.49	29.61
3	BD (MU)	1.78	0.31	3.4	41.51	200.89	131.863	59.497
4	Deemed PLF %	62.58	63.75	62.33	61.4	56.94	33.88	30.69
5	APC %	10.57	10.75	11.54	11.68	11.19	12.5	11.96232
6	DM %	7.71	2.92	3.08	2.82	2.97	3.56	3.47
7	Availability %	76.8	75.34	78.59	85.57	75.45	42.6	37.04
8	Partial loading%	18.57	15.38	20.77	29.12	25.38	26.08	20.04
9	Outage Hr	4834.6	4568.62	4662.34	3813.42	5199.11	8675	5960.58

10	No of Outage	152	105	12	99	84	55	49
11	Heat rate	3025.27	2878.14	2815.77	3010.1	2864.52	3002	2775
12	SOC (ml/kwh)	2.799	1.68	1.39	1.547	1.429	1.47	1.3264
13	SCC (kg/Kwh)	0.754	0.785	0.851	0.909	0.907	0.907	0.822

Seven year energy consumption data at table 1 is used for calculating the average energy consumption of various sources. The power generation at various year in (MU) shown in fig 1.

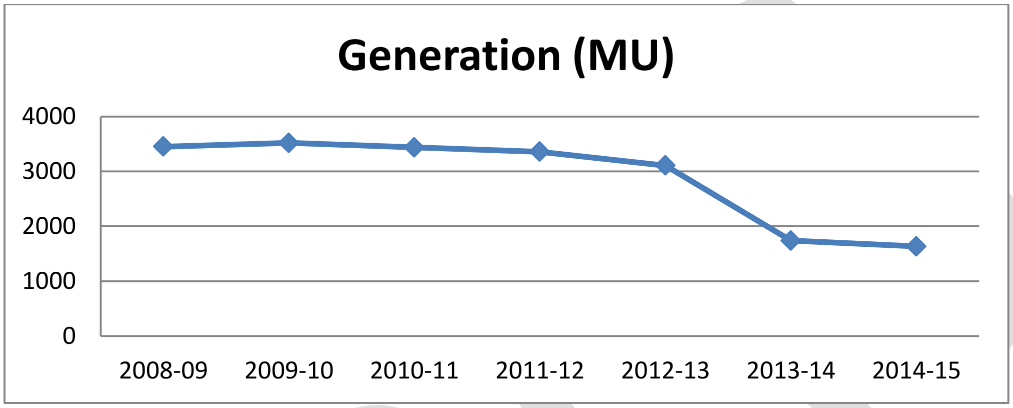

Fig.1.Graph shows power generation at various years in (MU)

1.1Need of Energy Audit

The energy audit outcome recommended energy conservation measures shall be implemented by designated consumer after technical and financial feasibility study. Main goal of energy management is to ensure effective and efficient use of ensuring to maximize profits and enhances competitive position. It also aims to minimize the environmental effects [2]. As per the energy conservation Act, 2001, energy audit is defined as "the verification, monitoring and analysis of use of energy including submission of technical report containing recommendations for improving energy efficiency with cost benefit and action plan to reduce energy consumption" [3].

1.2 Energy audit methodology

Boiler and Air preheater operational data collection were carried out with calibrated instruments. The required parameter for energy audit analysis of different system or utilities was measured and the power consumption was measured. For energy audit data collection the standard formulas as per PTC standards and CEA, BEE guidelines for Energy Auditing of power plants were used. In this project, the study is mainly targeted at identifying, sustainable and economically viable energy cost saving opportunities in boiler section of Unit-I, of Bokaro Thermal Power Station, Bokaro Jharkhand. The study shows that, there is a significant cost saving opportunities and recommendations have been made to realize this potential. It is true that there is no exact methodology, which can be its own method for conducting energy audit. It can be classified in to two types:

1.2.1 Preliminary Energy Audit or Walkthrough audit

A preliminary energy audit or walkthrough audit study typically done in three days and it can be divided into three steps:

Step-1: Identifies the quantity and cost of various energy forms used in the plant.

Step-2: Identifies energy consumption at the Boiler house and APH.

Step-3: Relates energy input to production, thereby highlighting energy wastage in major equipment like Boiler and APH/ processes.

After followed by above three steps, set of observation and recommendations for immediate low-cost action, and Identification of major areas Projects [15].

1.2.2 Detailed Energy Audit

A comprehensive audit provides a detailed energy project implementation plan for a facility, since it evaluates all major energy using systems. This type of audit offers the most accurate estimate of energy savings and cost. It considers the interactive effects of all

projects, accounts for the energy use of all major equipment, and includes detailed energy cost saving calculations and project cost. In a comprehensive audit, one of the key elements is the energy balance. This is based on an inventory of energy using systems, assumptions of current operating conditions and calculations of energy use. This estimated use is then compared to utility bill charges.
Detailed energy auditing is carried out in three phases: Phase I, II and III.
Phase I - Preparation
Phase II - Execution
Phase III –Reporting.

2. Power generation at thermal power plant

In BTPS the coal is transported from the mines by railway and is unloaded at the site by track hoppers or wagon tippler and passed through the primary crusher and the secondary crusher mill for crushing. The crushed coal is stored in the bunker and fed into coal mills for pulverization. The pulverized coal is further fed into the boiler furnace for firing and producing superheated steam. The other raw material use in the station is water which is drawn from the canal. The water after de-mineralization in DM plant is used as make up water for the power cycle. The water is also required for the cooling process and other purposes in the plant. The steam from the boiler passes through the turbine fitted with condenser for driving the generator for power generation. Power generated is evacuated /transmitted through the transmission lines to the power grid. The used steam from the turbine is taken into the condenser, where it is condensed with the help of recycled water from the cooling tower. The warm water from here is cooled in the cooling towers. the ash is produced after the burning of pulverized coal in the boilers and is collected in the bottom ash hopper, and ESP's hoppers, Air pre-heaters, economizers and chimneys of respective units (and also in the mechanical collectors). This ash is transported to the ash dykes in slurry form.

3. Boiler Efficiency Calculations (BTPS, DVC Unit-1 at 100%MCR)

In order to calculate the boiler efficiency by indirect method, all the losses that occur in the boiler must be established. These losses are conveniently related to the amount of fuel burnt. In this way it is easy to compare the performance of boiler of Bokaro Thermal Power Station unit-1 with different ratings. The purpose of the energy audit of a boiler is to determine actual performance and efficiency of the boiler and compare it with design values. It is an indicator for tracking day-to-day and season-to-season variations in boiler efficiency for energy efficiency improvements.

4. Boiler and APH parameters for efficiency calculation

Table 2 Boiler and APH Parameters

Parameter	Symbol	Unit	Values
Moisture	M	%	12.11
Ash	A	%	33.13
Volatile matter	VM	%	16.74
Fixed Carbon	FC	%	38.02
Carbon	C	%	45.189
Hydrogen	H	%	2.175
Nitrogen	N	%	1.551
Sulphur	S	%	0.628
Oxygen	O	%	5.218
Moisture	M	%	12.110
Ash	A	%	33.130
Gross Calorific Value	GCV	Kcal/Kg	4271.05
Total Combustibles	U	Kg/kg	0.03253
CV of Carbon	CVc	KJ/kg	33720.56
O_2 at AH Outlet	O_2	%	5.08

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CO_2 at AH Outlet	CO_2	%	13.77
CO at AH Outlet	CO	ppm	675.00
		%	0.0675
N_2 at AH Outlet N_2=100-O_2-CO_2-CO	N_2	%	81.083
Air heater outlet gas temp.	Tg	˚C	139.500
Carbon to Hydrogen Ratio	C/H		20.78
Instantaneous specific heat of flue gas at Tg (From fig. 7 of ASME PTC-4.1	Cp	BTU/lb/˚F	0.235
		KJ/kg/˚C	0.983945
AH secondary air inlet temp.	Ts	C	28.20
AH primary air inlet temp.	Tp	C	36.70
Secondary air flow	Qs	T/hr	603
Primary air flow	Qp	T/hr	191
Instantaneous specific heat of flue gas at Tr (From fig. 7 of ASME PTC-4.1	Cp	BTU/lb/˚F	0.23
		KJ/kg/˚C	0.963
Mean specific heat of dry flue gas	Cpg	KJ/kg/˚C	0.973
Enthalpy of vapour at partial pressure & at Tg	Htg	KJ/kg	2753.450
Enthalpy of saturated liquid at Ta	Hta	KJ/kg	111.940
Enthalpy of saturated vapour at Tr	Hsv	KJ/kg	2556.200
Ambient temp. (Dry bulb)	Ta	˚C	26.70
Ambient temp. (Wet bulb)		˚C	21.60
Weight of water vapour per kg of dry air (From psychometric chart)	Wwv	Kg/kg air	0.014
Weight of Nitrogen in dry gas WN_2=28.02*N_2*(Cb+12.01*S/(100*32.07)/(12.01*(CO2+CO))	WN2	Kg/kg coal	5.765
Nitrogen in Fuel	N	%	1.551
Weight of dry air Wa=(WN2-N/100)/.7685	Wa	Kg/kg coal	7.482
Carbon in fuel	C	%	45.189
CV of carbon monoxide	CV	KJ/kg	23627.644
Temp. of fly ash	Tfa	˚C	139.50
Specific heat of fly ash	Cpf	BTU/lb/˚F	0.206
		KJ/kg/˚C	0.8625
Temp. of Bottom ash	Tba	˚C	830.00
Specific heat of Bottom ash	Cpb	BTU/lb/˚F	0.265
		KJ/kg/˚C	1.1096
Radiation loss		%	1

Figure 2 and 3 are shown below which represent proximate and ultimate analysis of coal.

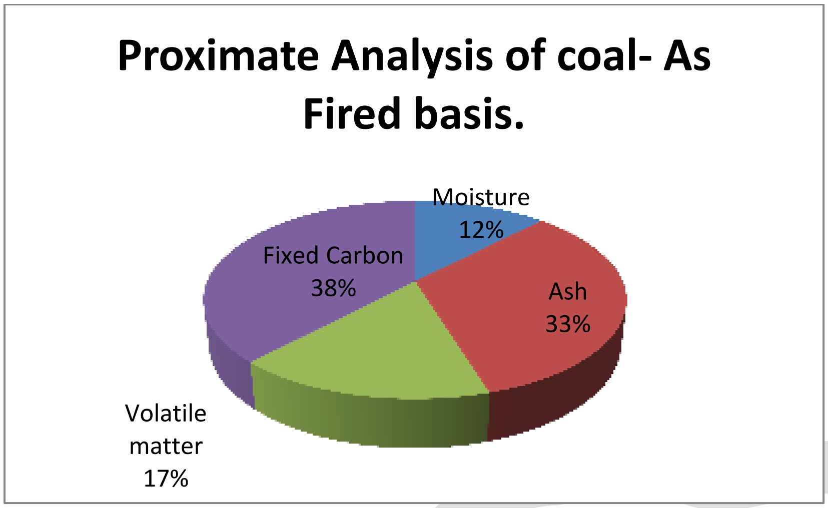

Fig.2 Pie chart of Proximate Analysis of coal - As fired basis

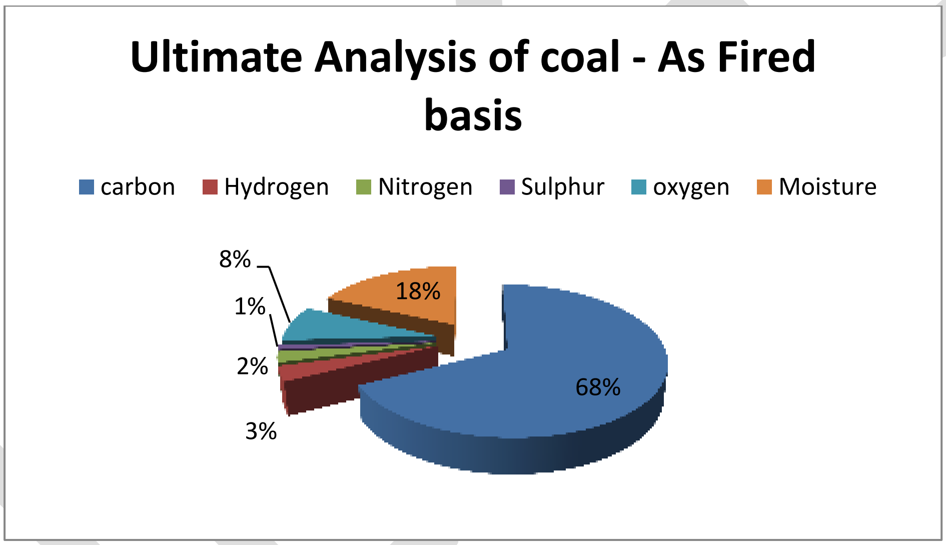

Fig.3 Pie Chart of Ultimate Analysis of coal - As fired basis

4.1 The efficiency of boiler calculated by using the following Equation

Correction factor $X = \frac{100-TM}{100-IM}$

Conversion formula for proximate analysis to ultimate analysis:

%C = 0.97 x FC + 0.7(VM + 0.1 x A) - M (0.6-0.01 x M).

%N = 2.10 – 0.020 x VM.

%H = 0.036 x FC + 0.086(VM- 0.1 x A) –0.0035 x M2 (1-0.02 x M)

%O = 100 – (%C+%H+%N)

Where,

C- Carbon content. **A**- Ash. **H**- Hydrogen. **O**- Oxygen. **VM**-Volatile Matter. **TM**- Total moisture. **FC**- Fixed carbon.

4.1.1 Unburnt carbon loss calculation (Z_1)

Some amounts of unburnt carbon will be left in the ash and this constitutes a loss of potential heat in the fuel. To assess these heat losses, samples of ash must be analyzed for carbon content.

Unburnt Fly Ash $UF= \frac{CF}{100-CF}\times\frac{DF}{100}\times\frac{A}{100}$

Unburnt Bottom Ash $UB= \frac{CB}{100-CB}\times\frac{DB}{100}\times\frac{A}{100}$

Total Unburnt Combustibles Ash $U=UF + UB$

Unburnt Carbon Loss $Z_1=U \times CVc$

4.1.2 Dry gas loss calculation (Z_2)

This is the greatest boiler loss and can be calculated with the following formula

Carbon burnt per KG of Fuel $C_b= \frac{C}{100-U}$

Weight of dry gas

$W_g = (44.01\times CO_2+32\times O_2+28.02\times N_2+28.01\times CO) \times (C_b+\frac{12.01}{32.07}\times\frac{S}{100})/(12.01\times(CO_2+CO))$

Reference air temperature $T_r=(Ts\times Qs+Tp\times Qp)/(Qs+Qp)$

Heat loss due to dry flue gas $Z_2=Wg\times Cpg\times (Tg-Tr)$

4.1.3 Loss due to moisture in fuel calculation (Z_3)

Moisture entering the boiler with the fuel leaves as a superheated vapor. This moisture loss is made up of the sensible heat to bring the moisture to boiling point, the latent heat of evaporation of the moisture, and the superheat required bringing this steam to the temperature of the exhaust gas. This loss can be calculated with the following formula

Loss due to moisture in fuel $Z_3=M/100\times (H_{tg}-H_{ta})$

4.1.4 Loss due to hydrogen in fuel calculation (Z_4)

Loss due to hydrogen in fuel $Z_4=H/100\times 8.936\times (H_{tg}-H_{ta})$

4.1.5 Loss due to moisture in fuel (Z_5)

Weight of Nitrogen in dry gas

$W_{N2}=28.02\times N_2\times (C_b+12.01\times S/(100\times 32.07)/(12.01\times (CO_2+CO))$

Weight of dry air $Wa=(W_{N2}-N/100)/.7685$

Loss due to moisture in air $Z_5=Wwv\times Wa\times (Htg-Hsv)$

4.1.6 H eat loss due to carbon monoxide (Z_6)

Loss due to carbon monoxide $Z_6=CO\times CV\times (C/100-U)/(CO2+CO)$

4.1.7 Sensible heat loss in fly ash (Z_7)

Sensible heat loss in fly ash $Z_7=A/100\times DF/100\times Cp_f\times (T_{fa}-T_r)$

4.1.8 Sensible heat loss in bottom ash (Z_8)

Sensible heat loss in bottom ash $Z_8=A/100\times DB/100\times Cp_b\times (T_{fa}-T_r)$

4.1.9 Radiation loss (Z_9)

The other heat losses from a boiler consist of the loss of heat by radiation and convection calculated by following formula.

Radiation loss Z_9=%loss/100×GCV×4.186

Loss Calculation (In Amount)

Total losses $Z=Z_1+Z_2+Z_3+Z_4+Z_5+Z_6+Z_7+Z_8+Z_9$

Loss Calculation (In Percentages)

$$\text{Loss in \%} = \frac{\text{Loss in KJ/Kg}}{\text{GCV in KJ/Kg}} \times 100$$

Total losses $Z=Z_1+Z_2+Z_3+Z_4+Z_5+Z_6+Z_7+Z_8+Z_9$

Boiler Efficiency = 100 - Total losses (Z)

BOILER RESULTS

4.2 Loss tabulation of boiler

Table 3 various losses in boiler (In Amount)

Parameter	Symbol	Unit	Values
Unburnt Carbon Loss	Z_1	KJ/kg	1096.922
Dry flue gas loss	Z_2	KJ/kg	821.103
Loss due to Moisture in Fuel	Z_3	KJ/kg	319.887
Loss due to Hydrogen in Fuel	Z_4	KJ/kg	513.342
Loss due to Moisture in Air	Z_5	KJ/kg	20.660
Loss due to Carbon monoxide	Z_6	KJ/kg	48.334
Sensible heat loss in fly ash	Z_7	KJ/kg	24.976
Sensible heat loss in bottom ash	Z_8	KJ/kg	58.797
Radiation loss	Z_9	KJ/kg	178.786
Total losses $Z= Z_1+Z_2+Z_3+Z_4+Z_5+Z_6+Z_7+Z_8+Z_9$	Z	KJ/kg	**3082.807**

Table 4 various losses in boiler (In percentage)

Parameter	Symbol	Unit	Values
Unburnt Carbon Loss	Z_1	%	6.1442
Dry gas loss	Z_2	%	4.5993
Loss due to Moisture in Fuel	Z_3	%	1.7918
Loss due to Hydrogen in Fuel	Z_4	%	2.8754
Loss due to Moisture in Air	Z_5	%	0.1157
Loss due to Carbon monoxide	Z_6	%	0.2707
Sensible heat loss in fly ash	Z_7	%	0.1399
Sensible heat loss in bottom ash	Z_8	%	0.3293
Radiation loss	Z_9	%	1.0014
Total losses $Z=Z_1+Z_2+Z_3+Z_4+Z_5+Z_6+Z_7+Z_8+Z_9$	Z	%	17.268
Boiler Efficiency		**%**	**82.73**

Design efficiency		%	**85.94**

Pie chart of boiler losses distribution of BTPS, Unit-1.

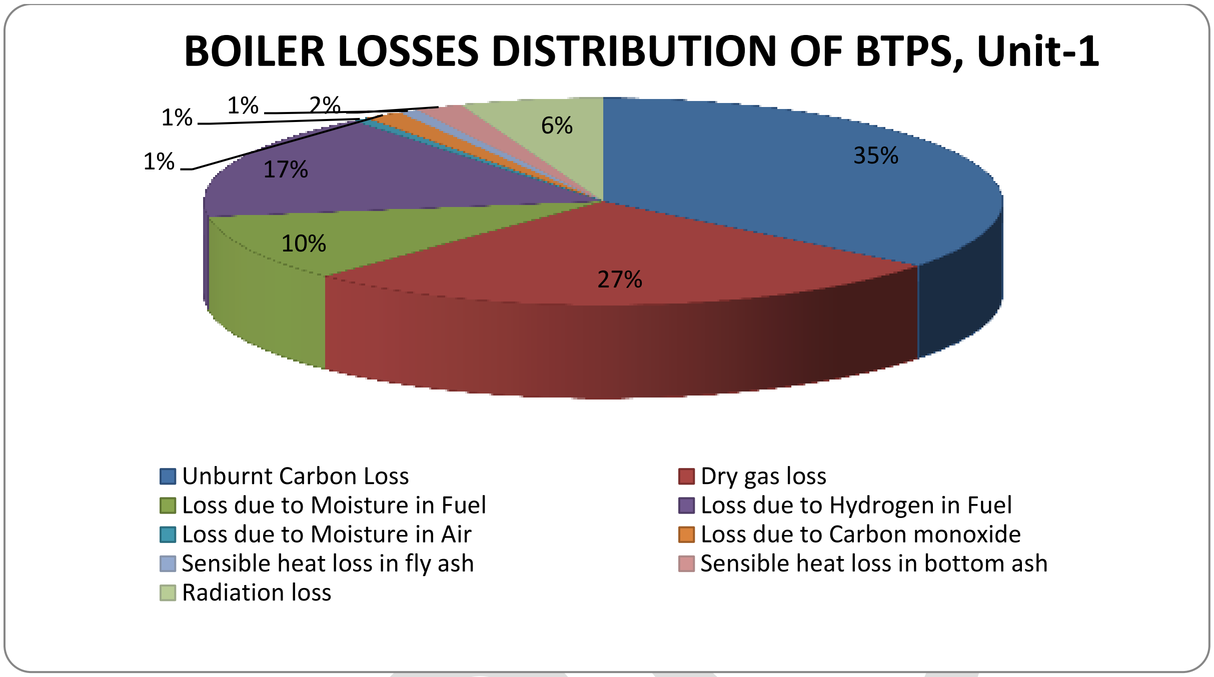

Figure 4 Pie charts of Boiler losses distribution of BTPS, Unit-1

AIR PREHEATER (APH)

5. APH performance

Regenerative type APH performance data is collected and calculated it.

Table 5 APH data

Sl. No.	Particulars	Units	Unit-I
1	O2 at APH inlet(A)	%	5.49
2	O2 at APH outlet(A)	%	10
3	O2 at APH inlet(B)	%	4.67
4	O2 at APH outlet(B)	%	9.1
5	O2 at ID Outlet	%	11.5
6	Flue gas inlet temp. at APH	°C	293.00
7	Flue gas exit temp (A) at APH (Test Value)	°C	132.00
8	Flue gas exit temp (B) at APH (Test Value)	°C	129.00
9	Air exit temp (A)	°C	262.7
10	Air exit temp (B)	°C	255.21
11	Reference Air in temp.	°C	30.24
12	O2 at APH inlet (Design value)	%	3.9
13	Flue gas exit temp (A) at APH (Design Value)	°C	142

5.1 The performance of air APH can be calculated by using the following equation

Air Pre-Heater Leakage: - The leakage of the high pressure air to the low pressure flue gas side due to the differential pressure , increased seal clearances in hot condition , seal erosion, improper seal settings.

Air Pre-Heater Leakage Determination

$$\text{APH Leakage in \%} = \frac{(\text{AH O2 out \%}) - (\text{AH O2 in \%})}{(21) - (\text{AH O2 out \%})}$$

Or

$$\text{APH Leakage in \%} = \frac{(\text{AH CO2 out \%}) - (\text{AH CO2 in \%})}{(\text{AH CO2 out \%})}$$

Air Pre-Heater X-Ratio Determination

X-Ratio: -The ratio of heat capacity of flue gas passing through the air heater to the heat Capacity of air is passing through the air heater.

$$\text{APH X-Ratio} = \frac{(\text{Flue gas inlet Temp.0C}) - (\text{ flue gas out Temp.0C})}{(\text{Air out Temp.0C}) - (\text{Refrence air inTemp.0C})} \text{ No unit}$$

X-Ratio depends:

- Moisture in coal, air infiltration, air and gas mass flow rates.
- Leakage from the setting.
- Specific heats of air and flue gas.

Gas side efficiency:

The ratio of gas temperature drop across the air heater, to the air temperature head.

$$\text{APH Gas Side effectiveness} = \frac{(\text{Flue gas inlet Temp.0C}) - (\text{ flue gas out Temp.0C})}{(\text{Flue gas inlet Temp.0C}) - (\text{Refrence air inTemp.0C})}$$

APH RESULTS

Table 6 APH Results

Sl. No.	Particulars	Units	Unit-I
1	APH Leakage (A)	%	41.01
2	APH Leakage (B)	%	37.25
3	Gas side effectiveness (A)	%	57.4
4	Gas side effectiveness (B)	%	62.1
5	X-Ratio (A)	%	64.93
6	X-Ratio (B)	%	69.34

CONCLUSION

The conclusions drawn from the energy audit of a boiler and waste heat recovery system of Bokaro Thermal Power Plant Unit-1 of 210MW capacity are listed below:

- Total un-burnt carbon loss due to bottom and fly ash is 6.1442%. These losses can be reduced by crushing of coal to maintain the average particle size in the range of 70 to 74 micron. The classifier in mills should be cleaned and checked on monthly basis.
- Dry gas loss is found as 4.5993% is more than the design value of 3.52%. It can be reduced by controlling excess air supply. To reduce losses due to excess air, it is required to continuously monitor excess air and this is done by either portable equipment like an Orsat flue gas analyzer or a Permanent Probe Type Sensor.
- Heat loss due to moisture present in fuel is found 1.7918%. So, moisture of coal should be reduced before use. The moisture can be removed by primary air coming from Air Pre Heater .The dry coal increases boiler efficiency.
- Heat loss due to radiation cannot be completely eliminated. Due to age factor of Rock wool insulation it can be reduced by replaced by new Rock wool insulation surfaces.

- Air leakage (or air-ingress) in Air-pre heater (A) and (B) is 41.01% and 37.23% respectively. Air leakage cannot be completely eliminated but it can be controlled or minimized by replacing new seals, gaskets and joints of Air Pre- heater assembly to reduce air ingression. So, boiler efficiency and overall power plant efficiency will be improved.
- The flue gas exit temperature from APH (A) and (B) is 132°C and 129°C respectively against the design value of 142°C. Flue gas exit temperature of Air Pre-heater should be in range of 140 to 160°C, so that it will not corrode the chimney walls or metal components in its path.
- Oxygen content in flue gases at inlet of APH (A) and (B) is 5.49% and 4.67% respectively, about 1% higher than the design value of 3.9%. It indicates that the insufficient quantity of air causing incomplete combustion of coal in furnace. So, these excess oxygen contents can be reduces by improving radial and axial seals of APH by overhaul or replace the same if found damaged for reducing air-ingress percentage, which in turn reduces auxiliary power consumption in Induced Draught fan and Forced Draught fan. Every 4°C reduction in flue gas temperature increases efficiency of boiler by 1%.
- Cleaning of heat transfer element of APH and boiler water tube (Risers), whenever the unit is shut down, to increase rate of heat transfer.

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