Improvement in Energy Efficiency & Heat Loss Minimization during Boiler Operation: A Case Study

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Abstract. A case-study has been done to analyze the 500 MW boiler performance located in middle part of India, manufactured by M/s BHEL (C.E. design). At the power plant consideration, it was observed that they were operating the boiler with high excess air and the soot blowers were being operated once in 10 days. In this paper, an attempt has been made to increase the efficiency of the boiler by making certain changes such as reduction in excess air and increasing the frequency of using soot blowers. It was concluded that the efficiency of the boiler can be improved by at least 1.41% over the existing efficiency. For the evaluation of boiler efficiency the “heat losses method” was applied. With an increase of efficiency by 1.41%, 30,000 MT of fuel can be saved as compared to annual consumption of 2.38 million tonnes of coal for 500 MW boilers. By this we can secure access to all sources of energy including coal, oil and gas supplies worldwide for boilers, till the end of the fossil fuel era, which is fast approaching and it will ensure us that our country will be able to supply energy to all its citizens at affordable costs at all times.

Keywords: Energy Efficiency, Heat Loss, Boiler, Fossil Fuel, Flue gas

1. Introduction

The world today is facing serious problems of depletion of fossil fuels, increasing demand for such fuels which has begun to outstrip the availability and the environmental pollution caused by the use of such fuels [1-7]. The scarcity of petroleum product has resulted in a tremendous rise in the prise of various fuels in the last few years. It has therefore, become imperative to find new ways and means so as to conserve fuel. One such sector in which fuel conservation could be aimed is power sector. In our country about 70 % of the power generated is obtained from thermal power plants [8-13]. It is thus expected that even a slight improvement in the efficiency of a boiler in a thermal power plant would have a significant impact on nation-wide fuel conservation as well as on reducing the fuel cost in industries. Ever since the power generation devices have been put to use, continuous efforts are being made to improve their efficiency. The major contributions to the improvement of efficiency have been achieved by increasing the efficiency using highest steam temperatures, reducing the exhaust gas temperatures to the lowest practical values, regenerative feed water heating, heat loss minimisation, improvement in combustion efficiency [14-19].

2. Heat Loss Minimization
The operation of industrial boiler with high excess air and high stack gas temperature results into large amount of dry flue gas losses. Traditionally, the industrial boiler did not have sophisticated combustion control and therefore the furnace was operated at high excess air level to insure complete combustion which resulted into large amount of dry flue gas losses. For minimising flue gas losses, stack gas temperature should be reduced, which could be limited by corrosion consideration and sulphuric acid condensation in the cold region of the boiler. According to literature survey it was seen that coal fired boilers were designed for burning coal with an excess air of around 25% to achieve complete combustion of coal with optimum flue gas losses. With an increase in excess air of 10% above rated value results in decrease of 0.5% boiler efficiency.

3. Case Study

The present Thermal Power Station is located at Ramagundam in Andhra Pradesh having a generating capacity of 2600MW. It is having 4 boilers of 500MW each and three boilers of 200MW each.

3.1. Boiler Specification for 500 MW Plant

The boiler is a radiant furnace, single drum dry bottom, controlled water circulation type unit. The boiler corner is fitted with tilting tangential burner boxes comprising four high energy arc igniters, four light-p heavy oil fired burners and eight pulverised coal burners. The 500MW unit boiler (MCR) designed for the following terminal conditions at maximum continuous rating

- Evaporation rate
  - a) Super heater outlet : 1,725 T/hr
  - b) Reheater outlet : 1,530 T/hr
- Working pressure after stop valve : 178 Kg/cm²
- Steam temperature at super heater outlet : 540°C
- Steam temperature at Reheater inlet : 344.1°C
- Steam temperature at Reheater outlet : 540°C
- Steam pressure at Reheater inlet : 45.85 Kg/cm²
- Steam pressure at Reheater outlet : 43.46 Kg/cm²

3.2. Boiler General Specification

Manufacturer : BHEL (C.E.design)
Type : Balanced Draught, Dry bottom, Single Drum and controlled circulation
Type of Firing : Tilting Tangential

3.3. Furnace Specification

Type : Control Circulation
Wall : Water steam cooled
Bottom : Dry
Draught : Balanced
Tube arrangement : Membrane
Residence time of fuel particles in the furnace : 3sec
Depth (m) : 15.829
Width (m) : 18.034
Furnace projected area (m²) : 7.620
Furnace volume (m³) : 14.820

3.4. Drum Specification

Design pressure Kg/cm² : 204
Design metal temperature : 366°C
Maximum operating pressure Kg/cm² : 192.2

4. Test Procedure I

• Boiler load was stabilised at the test load for a period of more than three hours.
• Temperature and pressure were recorded at the main steam outlet, feed water inlet, reheater outlet with calibrated thermocouples and calibrated pressure gauge.
• Main steam flow, feed water flow, air flow, mill parameter were recorded from control room.
• Raw coal samples were collected just above the feeders in sealed bags.
• Bottom hopper ash, economiser hopper ash, air heater hopper ash and fly ash samples were collected at the end of the test.

Efficiency calculation at full load for the existing system
Date: 12/9/19 Load: 100% Time: 1PM

Test 1 Value

| Table 1: Steam |
|----------------|
| Pressure (Kg/cm²) | Temperature (°C) |
| Super heater outlet | 180 | 540 |
| Drum | 194.4 | 367 |
| Low temperature super heater outlet | 187.0 | 407 |
| Reheater inlet | 47.7 | 348 |
| Reheater outlet | 45.4 | 540 |

| Table 2: Flow T/hr |
|-------------------|
| Super heater outlet | 180 |
| Feed water inlet | 1448.53 |
| Air flow | 1700.00 |
| Economiser inlet temperature | 244°C |
| Economiser outlet temperature | 288°C |
| Flue gas temperature super heater panel inlet | 1375°C |
| Coal flow | 276 |
| Steam flow | 1502 |
| Air flow | 1700 |
Feed water inlet temperature | 244°C  
Dry bulb temperature      | 30°C   
Wet bulb temperature     | 27°C   
Relative humidity         | 80%    
Absolute humidity kg H₂O/dry air | 0.0215  
Ambient air temperature  | 39°C   
Air heater inlet gas inlet temperature | 374°C  
Air heater outlet gas outlet temperature | 160.78  
Weight of mill rejects (kg/hr) | 1300   
Gross calorific value of mill rejects (kcal/kg) | 1610  

Table 3: Air Heater Flue Gas Analysis

| % Volume | Inlet | Outlet |
|----------|-------|--------|
| CO₂      | 15.76 | 13.58  |
| O₂       | 3.47  | 5.42   |
| N₂       | 81.27 | 81.00  |

Table 4: Proximate Analysis

| Constituents               | Weight % |
|----------------------------|----------|
| Moisture                   | 12.86    |
| Ash                        | 37.22    |
| Volatile matter            | 23.30    |
| Fixed carbon               | 26.62    |
| Gross calorific value (kcal/kg) | 3484    |

Table 5: Unburnt Carbon

| Unburnt carbon | kg/kg of fuel |
|----------------|---------------|
| In bottom ash  | 0.0010        |
In economiser ash \(0.0002\) 
In fly ash \(0.0005\) 
Total \(0.0017\)

Table 6: Ultimate Analysis

| Contents     | % Wt |
|--------------|------|
| Carbon       | 40.75|
| Hydrogen     | 2.41 |
| Nitrogen     | 0.76 |
| Moisture     | 12.86|
| Ash          | 37.22|
| Oxygen       | 5.34 |
| Sulphur      | 0.66 |

The efficiency of the boiler is calculated by heat loss method

Table 7: Dry Gas Loss

| Quantity                                      | Unit  | Loss  |
|-----------------------------------------------|-------|-------|
| Ambient air temperature\((T_a)\)            | °C    | 39    |
| Carbon (C)                                   | %     | 40.75 |
| Sulphur (S)                                  | %     | 0.66  |
| Carbon dioxide at heater outlet              |       | 13.58 |
| Total unburnt carbon (U)                    | Kg/kg of fuel | 0.0017|
| Air heater outlet gas temperature           | °C    | 160.78|
| Gross calorific value Kcal/kg               | Kcal/kg | 3484  |
| Weight of dry gas (Wd)                      | Kg/kg of fuel | 0.2490|
| Sensible heat of dry gas (SH)               | KJ/kg of fuel | 927.89|
| Dry gas loss \(L_1\)                        | %     | 6.4015|

\[*Wd=(C+(S/2.67)-100\times U)/12\times CO_2\]
\[*SH=Wd \times C_p \times (T_g-T_a)\]
\[*L_1= SH \times 100/GCV \times 4.186\]

Table 8: Loss due to Moisture in Fuel

| Quantity     | Unit  | Loss  |
|--------------|-------|-------|
| Total moisture| %     | 12.86 |
| Constituents                  | Unit                      | Loss    |
|-----------------------------|---------------------------|---------|
| Absolute humidity (Ah)      | Kg (H₂O/dry air)          | 0.0215  |
| Carbon (C)                  | %                         | 40.75   |
| Hydrogen (H)                | %                         | 2.41    |
| Sulphur (S)                 | %                         | 0.66    |
| Oxygen (O₂)                 | %                         | 5.42    |
| Carbon dioxide (CO₂)        | %                         | 13.58   |
| Nitrogen (N₂)               | %                         | 81.0    |
| Excess air (EA)             | %                         | 33.24   |
| Stoichiometric air quantity (SA) | Kg/kg of fuel | 5.24    |
| Air quantity (AQ)           | Kg/kg of fuel             | 6.9841  |
| Air moisture loss (L₄)      | %                         | 0.2357  |

L₃ = SW×H×9/4.186×GCV

4.1. Mill Reject Loss

Mill Reject Rate (MRR) = 1300 kg/hr
Gross calorific value of mill rejects (GMR) = 1610 Kcal/kg
Coal flow (F) = 276 T/Hr
Mill reject loss (L₅) = 0.2176
L₅ = MRR×GMR×100/F×GCV×1000

4.2. Unburnt Carbon Loss

Total unburnt carbon (U) = 0.0017 Kg/kg of fuel
Calorific value of carbon (CVC) = 8077.80 kcal/kg
Unburnt carbon loss (L₆) = 0.3940%
L₆ = U×CVC×100/GCV

4.3. Other Calculations
Radiation loss as per agreement ($L_7$) = 0.200%
Sensible heat ash and bottom hopper radiation ($L_8$) = 0.6%
Heat credits as per agreement ($L_9$) = -0.17%

4.4. Observations from Test 1

- Boiler efficiency = 100 – total heat loss(%)= 85.99
- Flux gas temperature is very high
- Excess air is very high
- Mill rejects rate is very high
- Dry flue gas losses increases because of excess air and flue gas temperature. Mill reject loss is more because poor quality of coal that creates problems for mill roller (i.e. jamming).

Based on the above remarks the procedure 2 is to be conducted to improve the efficiency.

Table 11: Total Heat Losses

| Losses                                           | Notation | %    |
|--------------------------------------------------|----------|------|
| Dry flue gas loss                                | L1       | 6.4015 |
| Loss due to moisture in fuel                     | L2       | 2.3085 |
| Loss due to hydrogen                             | L3       | 3.8942 |
| Loss due to air moisture                         | L4       | 0.2357 |
| Mill reject loss                                 | L5       | 0.2176 |
| Unburnt carbon loss                              | L6       | 0.3940 |
| Radiation loss                                   | L7       | 0.20  |
| Sensible heat ash and bottom hopper radiation    | L8       | 0.60  |
| Heat credits                                     | L9       | -0.17 |
| Total heat losses                                | Lt       | 14.01 |

5. Test Procedure II

- Prior to starting of the test pulverised coal fuel fineness in all mills were checked.
- Soot blowing was done prior to the start of the test.
- The wind box dampers and wind box to furnace pressure differential were adjusted to obtain the best combustion conditions.
- Temperature and pressure were maintained closed to the design value at the feed water inlet, super heater outlet, reheater outlet.
- It was ensured that no steam tap off was taken for blow down purposes.

Efficiency calculation at full load with improved condition
Date: 15/9/19 Load: 100% Time: 2PM

Table 12: Water/Steam

|                     | Pressure (Kg/cm²) | Temperature (°C) |
|---------------------|-------------------|------------------|
| Super heater outlet | 178               | 540              |
|                        | Value 1 | Value 2 |
|------------------------|---------|---------|
| Drum                   | 192.4   | 362     |
| Low temperature super heater outlet | 187     | 409     |
| Reheater inlet         | 46.7    | 347     |
| Reheater outlet        | 44.2    | 540     |

Table 13: Flow T/hr

|                                   | Value 1 |
|-----------------------------------|---------|
| Super heater outlet               | 1670    |
| Feed water inlet                  | 1549.41 |
| Air flow                           | 1900.00 |
| Coal flow                          | 290     |
| Steam flow                         | 1670    |
| Air flow                           | 1900    |
| Feed water inlet temperature      | 252°C   |
| Relative humidity                  | 70%     |
| Absolute humidity kg H₂O/dry air   | 0.0192  |
| Ambient air temperature            | 36.5°C  |
| Air heater inlet gas inlet temperature | 368°C  |
| Air heater outlet gas outlet temperature | 154    |
| Weight of mill rejects             | 900kg/hr|
| Gross calorific value of mill rejects | 1300 kcal/kg |

Table 14: Air Heater Flue Gas Analysis

| % volume | Inlet  | Outlet |
|----------|--------|--------|
| CO₂      | 15.45  | 14.32  |
| O₂       | 3.55   | 4.64   |
| N₂       | 81.00  | 81.00  |

Table 15: Proximate Analysis
### Table 16: Unburnt Carbon

| Unburnt Carbon          | kg/kg of fuel |
|-------------------------|---------------|
| In bottom ash           | 0.0010        |
| In economiser ash       | 0.0002        |
| In fly ash              | 0.0005        |
| Total                   | 0.0017        |

### Table 17: Ultimate Analysis

| Constituents     | % Wt |
|------------------|------|
| Carbon           | 43.97|
| Hydrogen         | 2.67 |
| Nitrogen         | 0.81 |
| Moisture         | 12.00|
| Ash              | 35.35|
| Oxygen           | 4.54 |
| Sulphur          | 0.66 |

The efficiency of boiler is calculated on heat losses method:

### Table 18: Dry Gas Loss

| Quantity                  | Unit | Loss  |
|---------------------------|------|-------|
| Ambient air temperature(Ta)| °C   | 36.5  |
| Carbon (C)                | %    | 43.97 |
| Sulphur (S)               | %    | 0.66  |
| Quantity                             | Unit          | Loss  |
|-------------------------------------|---------------|-------|
| Carbon dioxide at heater outlet     |               | 14.32 |
| Total unburnt carbon (U)            | Kg/kg of fuel | 0.0017|
| Air heater outlet gas temperature   | °C            | 154.00|
| Gross calorific value Kcal/kg       | Kcal/kg       | 3926  |
| Weight of dry gas (Wd)              | Kg/kg of fuel | 0.2560|
| Sensible heat of dry gas (SH)       | KJ/kg of fuel | 920.44|
| Dry gas loss (L₁)                   | %             | 5.6010|

Table 19: Loss due to Moisture in Fuel

| Quantity                             | Unit          | Loss  |
|-------------------------------------|---------------|-------|
| Total moisture                      | %             | 12.00 |
| Flue gas temperature leaving air heater common outlet | °C | 154.00 |
| Ambient air temperature             | °C            | 36.5  |
| Gross calorific value               | Kcal/kg       | 3926  |
| Sensible heat of water (SW)         | kJ/kg         | 2616.22|
| Loss due to moisture (L₂)           | %             | 1.910 |

\[*Wd= (C+(S/2.67)-100×U)/12×CO₂\]
\[*SH=Wd × Cp× (Tg-Ta)\]
\[*L₁= SH × 100/GCV × 4.186\]

Table 20: Loss due to Hydrogen

| Quantity                           | Unit | Loss |
|------------------------------------|------|------|
| Hydrogen                           | %    | 2.67 |
| Loss due to hydrogen (L₃)          | %    | 3.826|

\[L₃=SW×H×9/4.186×GCV\]

Table 21: Loss due to Moisture in Air

| Quantity                          | Unit                  | Loss  |
|-----------------------------------|-----------------------|-------|
| Absolute humidity (Ah)            | Kg (H₂O/dry air)      | ------|
| Carbon (C)                        | %                     | 43.97 |
| Hydrogen (H)                      | %                     | 2.55  |
| Sulphur (S)                       | %                     | 0.66  |
| Oxygen (O)                        | %                     | 4.64  |
| Carbon dioxide (CO₂)              | %                     | 14.32 |
| Nitrogen (N₂)                     | %                     | 81.00 |
| Excess air (EA)                   | %                     | 27.14 |
| Stoichiometric air quantity(SA)   | Kg/kg of fuel         | 5.73  |
| Air quantity (AQ)                 | Kg/kg of fuel         | 7.28  |
| Air moisture loss (L₄)            | %                     | 0.1878|

\[*EA= (O₂) × 100/ (0.2682 N₂- O₂)\]
\[*SA= (2.664 ×C +7.937 H -0.996 S – O) / 23.2\]
\[*AQ = SA× (1+EA/100)\]
\[*L₄= AQ×1.88(Tg-Ta) ×Ah×100/GCV×4.186\]
5.1. Mill Reject Loss

Mill Reject Rate (MRR) = 900 kg/hr
Gross calorific value of mill rejects (GMR) = 1300 Kcal/kg
Coal flow (F) = 290 T/Hr
Mill reject loss (L5) = 0.102
\[ L_5 = \frac{MRR \times GMR \times 100}{F \times GCV \times 1000} \]

5.2. Unburnt Carbon Loss

Total unburnt carbon (U) = 0.0017 Kg/kg of fuel
Calorific value of carbon (CVC) = 8077.80 kcal/kg
Unburnt carbon loss (L6) = 0.3497%
\[ L_6 = \frac{U \times CVC \times 100}{GCV} \]

5.3. Other Losses

Radiation loss as per agreement (L7) = 0.200%
Sensible heat ash and bottom hopper radiation (L8) = 0.6%
Heat credits as per agreement (L9) = -0.17%

Table 22: Heat Loss Comparison between Test 1 & Test 2 Values

| Losses                                      | Notation | Test 1 (%) | Test 2 (%) |
|---------------------------------------------|----------|------------|------------|
| Dry flue gas loss                           | L1       | 6.4015     | 5.601      |
| Loss due to moisture in fuel                | L2       | 2.3085     | 1.910      |
| Loss due to hydrogen                        | L3       | 3.8942     | 3.826      |
| Loss due to air moisture                    | L4       | 0.2357     | 0.1878     |
| Mill reject loss                            | L5       | 0.2176     | 0.102      |
| Unburnt carbon loss                         | L6       | 0.3940     | 0.3497     |
| Radiation loss                              | L7       | 0.20       | 0.20       |
| Sensible heat ash and bottom hopper radiation | L8   | 0.60       | 0.60       |
| Heat credits                                | L9       | -0.17      | -0.17      |
| Total heat losses                           | Lt       | 14.01      | 12.60      |
| Boiler efficiency                           |          | 85.99      | 87.40      |

6. Results and Discussion

The basic intention of the study is to know the effect of boiler performance with some parameter such as excess air, flue gas temperature, moisture content and ash content. Results obtained from various collected data are as follows

6.1. Effect of Excess Air and Flue Gas Temperature on Boiler Efficiency Improvement

The maximum efficiency is obtained at 27% of excess air. The efficiency decreases on either side of this excess air value because of unnecessary heating of excess air which is exhausted out of the chimney or results in unburnt carbon loss. It is also observed that decreasing the excess air by 6% the dry gas losses comes down to 0.8%.

6.2. Effect of Moisture Control on Boiler Efficiency

It is found that as the moisture content increases, efficiency decreases. This is because of high moisture content reduces the calorific value of fuel. The moisture absorbs the heat required to turn it
into steam at flue gas temperature. It is also observed that for every 1% decrease in moisture content the efficiency increases by 0.4%.

6.3. Effect of Ash on Boiler Efficiency

It is found that the efficiency decreases with increase in ash content because of unburnt fuel loss. When high ash is present it is necessary to run it with excess air and thus reduces the efficiency. It is also observed that, for every 1% reduction in ash content the efficiency increases to 0.05%.

7. Conclusion

From the results obtained it is concluded that the efficiency of boiler can be improved by controlling the variable factors such as excess air, moisture content, ash content. Reducing the excess air from 33% to 27% the dry gas losses come down to 0.8%. So the efficiency is increased to 0.8%. By reducing the moisture content from 13% to 12 the efficiency is increased to 0.4%. By reducing the ash content from 37% to 36% the efficiency is improved by 1%. Improving the boiler efficiency by 1.41% leads to a fuel saving of 30,000MT as compared to annual consumption of 2.38 million tonnes of coal for 500 MW boilers.

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