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Energy Analysis of Thermal Power Plant

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Abstract — Energy analysis helps designers to find ways to improve the performance of a system in a many way. Most of the conventional energy losses optimization method are iterative in nature and require the interpretation of the designer at each iteration. Typical steady state plant operation conditions were determined based on available trending data and the resulting condition of the operation hours. The energy losses from individual components in the plant is calculated based on these operating conditions to determine the true system losses. In this, first law of thermodynamics analysis was performed to evaluate efficiencies and various energy losses. In addition, variation in the percentage of carbon in coal content increases the overall efficiency of plant that shows the economic optimization of plant.

Keywords — Energy, efficiency, thermal power plant, first law analysis, energy losses, optimization, coal.

1. Introduction

In boiler, efficiency has a great influence on heating related energy savings. It is therefore important to maximize the heat transfer to the water and minimize the heat losses in the boiler. The thermal power plant is based on a simple Rankine cycle; steam is used as the working fluid, steam generated from saturated liquid water (feed-water). This saturated steam flows through the turbine, where its internal energy is converted into mechanical work to run an electricity generating system. Not all the energy from steam can be utilized for running the generating system because of losses due to friction, viscosity, bend-on-blade, heat losses from boilers i.e. hot flue gas losses, radiation losses and blow-down losses etc [1].

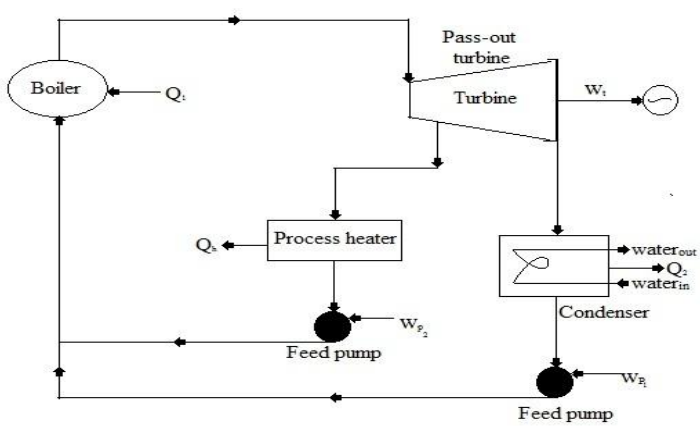

Figure 1 (a) Cogeneration Plant with a Pass – Out Turbine

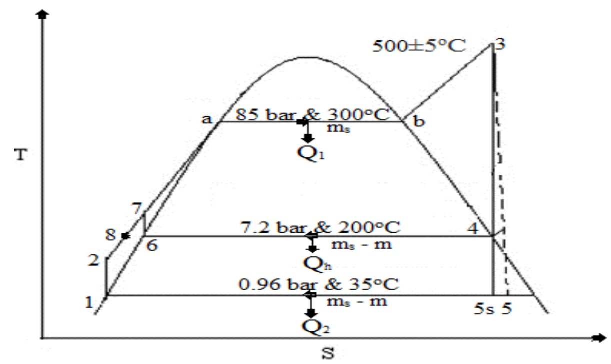

Figure 2 (b) Cogeneration Plant with a Pass – Out Turbine

To optimize the operation of a boiler plant, it is necessary to identify where energy wastage is likely to occur. A significant amount of energy is lost through flue gases as all the heat produced by the burning fuel cannot be transferred to water or steam in the boiler. Since most of the heat losses from the boiler appear as heat in the flue gas, the recovery of this heat can result in substantial energy savings. This indicates that there are huge savings potentials of a boiler energy savings by minimizing its losses.

2. Analytical Approaches

a. Energy analysis of combustion chamber.

Combustion chamber is the most important part of the boiler. The combustor in a boiler is usually well insulated that causes heat dissipation to the surrounding almost zero. It also has no involvement to do any kind of work (w=0). In addition, the kinetic and potential energies of the fluid streams are usually negligible. Then only total energies of the incoming streams and the outgoing mixture remained same for analysis [2]. The conservation of energy principle requires that these two equal each other's that is shown in the figure

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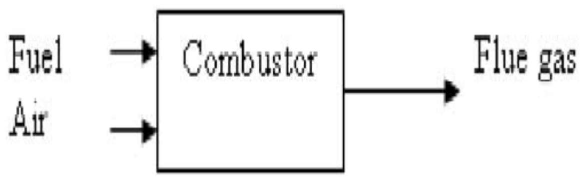

Figure 3 Schematic diagram of Combustion Chamber

Therefore, the total heat released by complete combustion of 1 kg of coal is [1]

$$HHV = 33.91C + 143\left(H - \left(\frac{O}{8}\right)\right) + 9.094S \text{ MJ/kg} \quad (1)$$

In energy efficiency case, we assume that the combustion chamber there is no heat losses [4]. Therefore, $\eta = 100\%$

b. Energy analysis of boiler drum (i.e. heat exchanger)

The boiler is considered as a single cross-flow steam production chamber. The performance of the steam production chamber plays an important role of the boiler efficiency. Heat is transferred from the hot fluid to the cold one through the wall separating them. Heat exchanger is a device where two moving fluid streams exchange heat without mixing. A heat exchanger typically involves no work interactions (w=0) and negligible kinetic and potential energy changes for each fluid streams [3]. The outer shell of the heat exchanger is usually well insulated to prevent any heat loss to the surrounding medium.

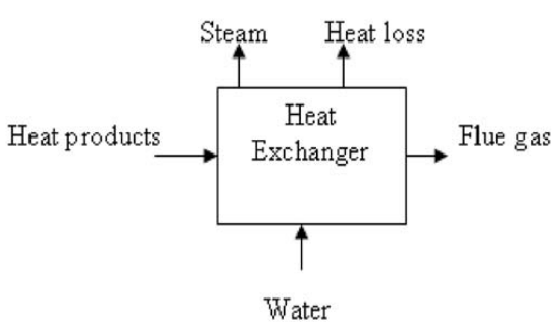

Figure 4 Schematic diagram of Heat Exchanger

Energy balance equation for any system

$$E_{in} - E_{out} = \frac{dE_{sytem}}{dt} = 0 \quad (2)$$

$$m_p \{h_p - h_g\} = m_w \{h_s - h_w\} + Q \quad (3)$$

Heat loss

$$Q = m_p \{h_p - h_g\} - m_w \{h_s - h_w\} \quad (4)$$

Where,

Efficiency of heat exchanger

$$\eta_{HE} = \frac{m_w}{m_p} \times \left\{\frac{h_{sup} - h_{sat}}{h_p - h_g}\right\} \quad (5)$$

c. Energy analysis of turbine.

Energy balance equation for turbine and Work done by turbines actually = 18000 kW

Balancing equation for bleeding mass [5]

$$W_t = m_3 (h_3 - h_4) + (m_3 - m) (h_4 - h_5) \quad (6)$$

Energy loss

$$Q = m_3h_3 - (m_3 - m) (h_3 - h_4) - m (h_4 - h_5) - W \quad (7)$$

Efficiency

$$\eta = 1 - \frac{\text{Energy loss (Q)}}{m_3h_3 - (m_3 - m)(h_3 - h_4) - (m_3 - m)(h_4 - h_5)} \quad (8)$$

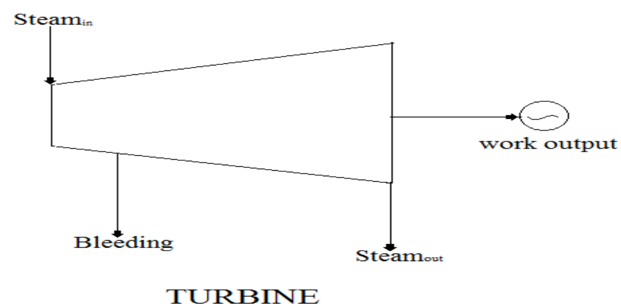

Figure 5 Schematic diagram of Turbine

d. Energy analysis of condenser

Energy balance equation for condenser is-

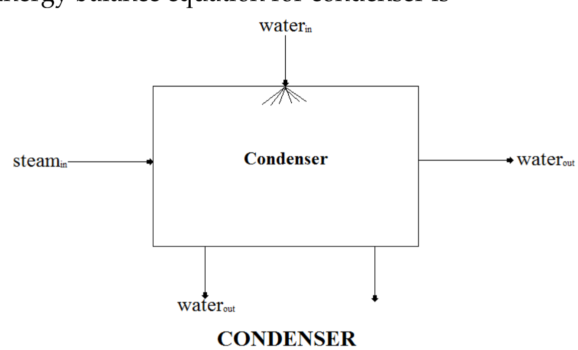

Figure 6 Cooling Tower Type Condenser

Heat given to the system

$$Q_{given} = (m_3 - m) (h_3 - h_2) + m (h_3 - h_7) \quad (9)$$

Heat rejection

$$Q_{rej} = (m_3 - m) (h_5 - h_1) \quad (10)$$

So, from the above equation we get,

$$Q_{rej} = (m_c c_p) (t_5 - t_4) \quad (11)$$

Energy balance

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$$Q_{loss} = m_5(h_5 - h_1) - Q_{rej} \quad (12)$$

Efficiency

$$\eta = 1 - \frac{Q_{loss}}{m_5(h_5 - h_1)} \quad (13)$$

e. Energy analysis of feed pump.

The energy balance equation for feed pump

$$m_2h_2 = m_1h_1 - W_p - Q_{loss} \quad (14)$$

Heat loss in feed pump

$$Q_{loss} = m_1h_1 - W_{p-} - m_2h_2 \quad (15)$$

Efficiency

$$\eta = 1 - \frac{\text{Energy loss}}{W_p} \quad (16)$$

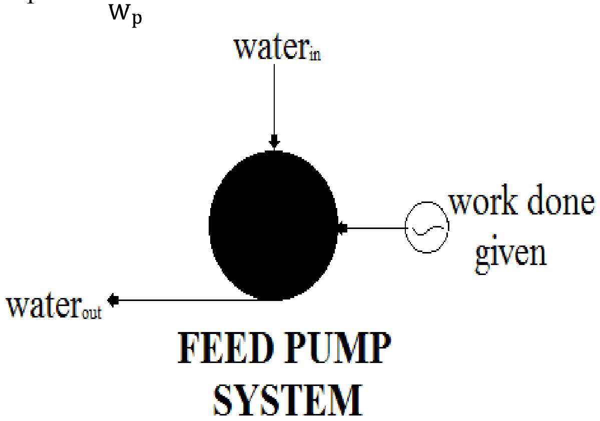

Figure 7 Feed Pump

f. Overall energy analysis of boiler plant.

Basically boiler efficiency can be tested by the following methods:

1) The Direct Method: Where the energy gain of the working fluid (water and steam) is compared with the energy content of the boiler fuel [6, 7].

2) The Indirect Method: Where the efficiency is the difference between the losses and the energy input.

INDIRECT METHOD

There are reference standards for Boiler Testing at Site using indirect method namely British Standard, BS 845: 1987 and USA Standard is 'ASME PTC-4-1 Power Test Code Steam Generating Units'.

Indirect method is also called as heat loss method. A detailed procedure for calculating boiler efficiency by indirect method is given below. However, it may be noted that the practicing energy mangers in industries prefer simpler calculation procedures.

The principle losses that occur in a boiler are:

L_1- Loss of heat due to dry flue gas (Sensible heat)

L_2- Loss due to hydrogen in fuel (H_2)

L_3- Loss of heat due to moisture in fuel (H_2O)

L_4- Loss of heat due to moisture in air (H_2O)

L_5- Loss of heat due to carbon monoxide (CO)

L_6- Loss of heat due to radiation and unaccounted

L_7- Unburnt losses in fly ash (Carbon)

L_8- Unburnt losses in bottom ash (Carbon)

Boiler Efficiency by indirect method

$$= 100 - (L_1 + L_2 + L_3 + L_4 + L_5 + L_6 + L_7 + L_8)$$

In the above, loss due to moisture in fuel and the loss due to combustion of hydrogen are dependent on the fuel, and cannot be controlled by design.

Theoretical (stoichiometric) air fuel ratio and excess air supplied are to be determined first for computing the boiler losses. The equation is given below for the same.

a) Theoretical air required for combustion

$$= [(11.6 \times C) + \{34.8 \times (H_2 - O_2/8)\} + (4.35 \times S)] / 100 \quad (17)$$

b) % Excess air supplied (EA)

$$= \frac{O_2\%}{21 - O_2\%} \times 100 \quad (18)$$

Normally O_2 measurement is recommended. If O_2 measurement is not available, use CO_2 measurement

$$= \frac{7900 \times [(CO_2\%)_t - (CO_2\%)_a]}{(CO_2)_a\% \times [100 - (CO_2\%)_t]} \text{ (from flue gas analysis)} \quad (19)$$

Where, $(CO_2\%)_t = \frac{\text{Moles of C}}{\text{Moles of } N_2 + \text{Moles of C}}$

Moles of $N_2 = \frac{\text{Wt.of } N_2 \text{ in theoritical air}}{\text{Mol.wt 0f } N_2} + \frac{\text{Wt.of } N_2 \text{ in fuel}}{\text{Mol.wt 0f } N_2}$

Moles of C $= \frac{\text{Wt of C in fuel}}{\text{Molecular Wt of C}}$

c) Actual mass of air supplied / kg of fuel (AAS)

$$= \{1 + EA / 100\} \times \text{theoretical air} \quad (20)$$

1. Heat loss due to dry flue gas

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$$L_1 = \frac{m \times c_p \times (T_f - T_a)}{\text{GCV of fuel}} \times 100 \quad (21)$$

2. Heat loss due to evaporation of water formed due to H_2 in fuel (%):- The combustion of hydrogen causes a heat loss because the product of combustion is water. This water is converted to steam and this carries away heat in the form of its latent heat.

$$L_2 = \frac{9 \times H_2 \times \{584 + c_p(T_f - T_a)\}}{\text{GCV of fuel}} \times 100 \quad (22)$$

3. Heat loss due to moisture present in fuel: - 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 to bring this steam to the temperature of the exhaust gas. This loss can be calculated with the following equation

$$L_3 = \frac{M \times \{584 + C_p(T_f - T_a)\}}{\text{GCV of fuel}} \times 100 \quad (23)$$

4. Heat loss due to moisture present in air

$$L_4 = \frac{\text{AAS} \times \text{humidity factor} \times C_p \times (T_f - T_a)}{\text{GCV of fuel}} \times 100 \quad (24)$$

5. Heat loss due to incomplete combustion:- Products formed by incomplete combustion could be mixed with oxygen and burned again with a further release of energy

$$L_5 = \frac{\%\,CO \times C}{\%\,CO + \%CO_2} \times \frac{5744}{\text{GCV of fue}} \times 100 \quad (25)$$

6. Heat loss due to radiation and convection: - The other heat losses from a boiler consist of the loss of heat by radiation and convection from the boiler casting into the surrounding boiler house.

   Normally surface loss and other unaccounted losses is assumed based on the type and size of the boiler as given below.
   For industrial fire tube / packaged boiler = 1.5 to 2.5%
   For industrial water tube boiler = 2 to 3%
   For power station boiler = 0.4 to 1%

$$L_6 = 0.548 \times [(T_s / 55.55)^4 - (T_a / 55.55)^4] + 1.957 \times (T_s - T_a)^{1.25} \times \sqrt{[(196.85\, V_m + 68.9)/68.9]} \quad (26)$$

7. Heat loss due to unburnt in fly ash (%)

$$L_7 = \frac{\text{Total ash collected/kg of fuel burnt} \times \text{GCV of fly ash}}{\text{AGCV of fuel}} \times 100 \quad (27)$$

8. Heat loss due to unburnt in bottom ash (%)

$$L_8 = \frac{\text{Total ash collected/kg of fuel burnt} \times \text{GCV of bottom ash}}{\text{GCV of fuGCV of fuel}} \times 100 \quad (28)$$

3. DATA COLLECTION

The study is based on the energy analysis and energy savings of an industrial boiler. Data has been collected from various thermal power plant. Fuel consumption, excess air, steam production rate, pressure and temperature, air temperature, inlet and outlet temperature of water and steam, inlet and outlet temperature of flue gas of boiler etc. are collected for the analysis.

Parameters used for efficiency calculation

Table 1 Various Data of an Industrial Boiler

Parameters	Unit	Quantity
Steam temperature	^{0}C	525
Steam pressure	kg/cm^2	88
Steam flow	Tph	75
Mass flow rate of fuel	kg/s	4.167
Mass flow rate of water	kg/s	23.88
Turbine power	kW	18000
Ambient temperature	^{0}C	35
Temperature of flue gases	^{0}C	275

The proximate analysis and ultimate analysis of lignite coal are given in Table 2

Table 2 Ultimate and Proximate Analysis of Coal

Description	Unit	Coal sample
Ultimate analysis		
C	%	51.11
H	%	2.76
N	%	1.22
O	%	9.89
S	%	0.41
Ash	%	18.63
Moisture	%	15.98

Proximate analysis

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Description	Unit	Coal sample
Fixed carbon	%	10.29
Volatile mater	%	38.63
Moisture	%	34.69
Ash	%	16.39
Calorific value	Kcal/kg	7600

Some parameters obtain by calculated for losses

Higher heating value = 18.856 MJ/kg
Lower heating value = 7.4949 MJ/kg
Stoichiometric ratio (a/f) = 6.1260
Mass flow rate of water feed in boiler drum = 23.89 kg/s
Mass flow rate of hot product in boiler drum = 41.77 kg
Mass flow rate of steam bleeding = 6.7286 kg/s
Mass of water supply for condensation in condenser = 38.41 kg/s

4. Result and Discussion

By using above values, the various losses are calculated. The calculated values are shown in the following table3.

Table 3 Summary of Boiler Losses

Losses	%
Dry flue gas loss (L_1)	08.86
Heat loss due to formation of water from hydrogen in fuel (L_2)	05.54
Losses due to the moisture in fuel (L_3)	03.91
Losses due to the moisture in air (L_4)	0.341
Losses due to incomplete combustion of fuel (L_5)	02.89
Radiation losses (L_6)	01.37
Losses due to un-burnt in fly ash (L_7)	0.241
Losses due to un-burnt in bottom ash (L_8)	03.42

Total losses = $L_1 + L_2 + L_3 + L_4 + L_5 + L_6 + L_7 + L_8$
= 8.86 + 5.54+3.91+.341+2.89+1.37+.241+3.42
= 26.57%

Boiler Efficiency by indirect method
= $100 - (L_1 + L_2 + L_3 + L_4 + L_5 + L_6 + L_7 + L_8)$
= 100 – 26.57
η = 73.43%

The boiler analysis results of this study are summarized in Tables 4, in which the various main components of Rankine cycle are introduced. The overall boiler energy efficiency is tabulated-

Table 4 Energy Balance Sheet

Section	Efficiency η (%)	Energy loss Q (kW)	Work Output (kW)
Combustion chamber	100		
Heat exchanger	54.22	19707.440	
Turbine	30.187	41620.550	18000
Condenser	89.84	03633.226	
Feed pump	50.47	00191.720	
Overall Boiler	72.0389	65152.936	

In addition, if the variation occurs in coal composition by the increases in carbon percentage of coal and other constitutes being decrease in same ratio.

Table 5 Variations in Coal Composition

Description	Unit	Variations in Coal sample composition
C	%	45.0 – 72.0
H	%	3.00 – .300
N	%	2.75 – .500
O	%	19.0 – 10.0
S	%	2.00 – 0.20
Ash	%	7.25 – 5.25
Moisture	%	21.0 – 12.0

Due to this, the results obtain are show in figure below:-

1. Fig.7 shows. As the carbon percentage, increase the value of efficiency is also increase. This could be attributed in higher heating value. So the increases in carbon percentage is directly proportional to efficiency.

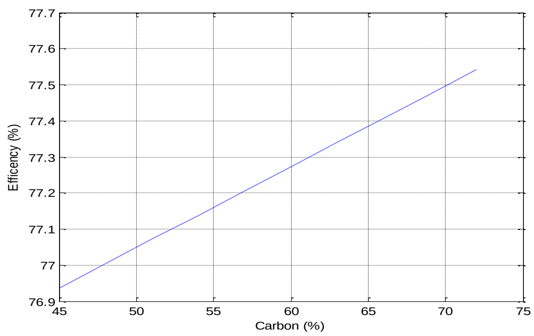

Figure 7 Carbon Percentage Vs. Efficiency

2. This fig.8 shows that the variation in carbon percentage is increase in higher heating value through the consumption of fuel. Therefore, it decreases mass flow rate of fuel. That shows the increase in carbon percentage is inversely proportional to mass flow rate of fuel.

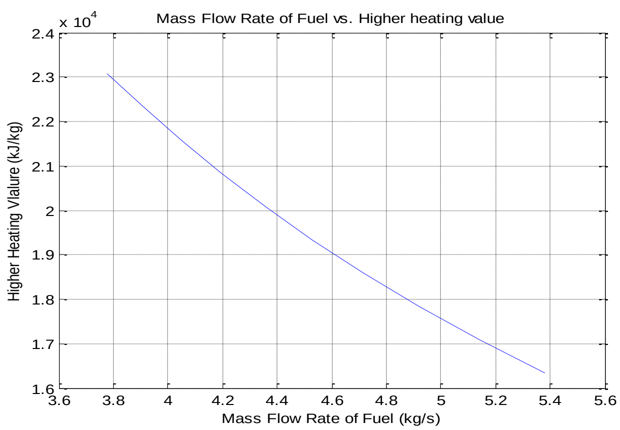

Figure 8 Mass Flow Rate of Fuel Vs. Efficiency

3. Fig.9 shows. Increase in efficiency as the oxygen percentage is decrease.

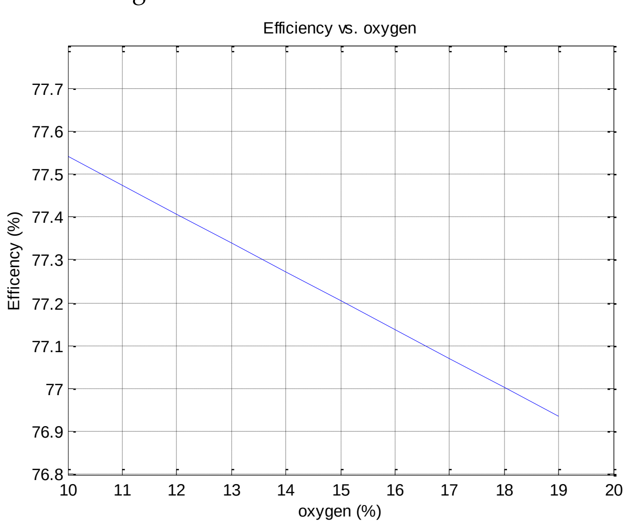

Figure 8 Oxygen Percentage Vs. Efficiency

4. Fig.10 shows. Increase in efficiency as the moisture percentage is decrease.

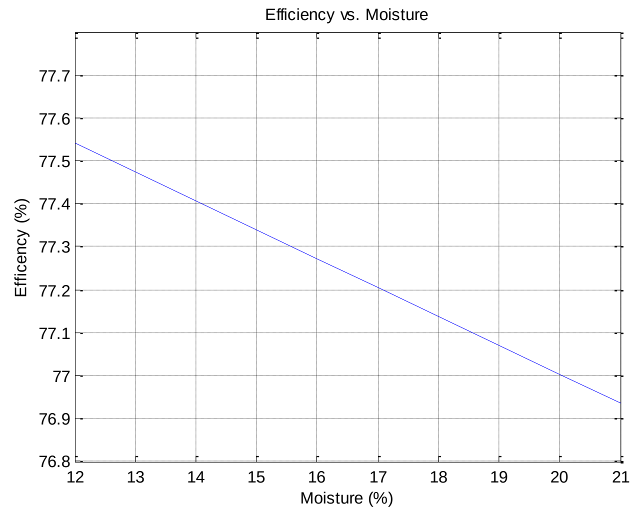

Figure 9 Moisture Percentage Vs. Efficiency

5. Fig.11 shows. Increase in efficiency as the ash percentage decrease.

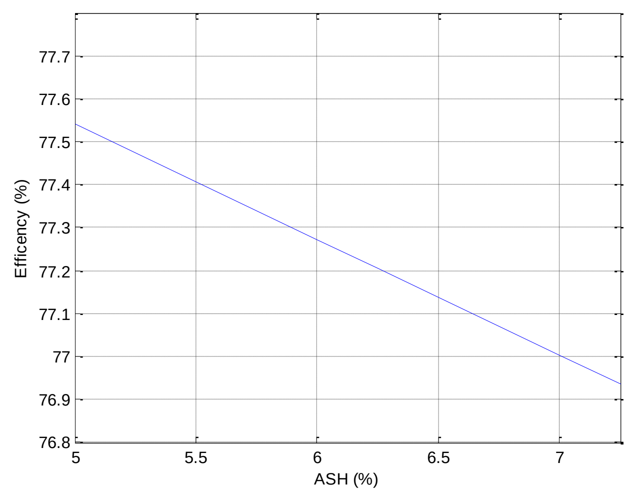

Figure 10 Ash Percentage Vs. Efficiency

Then, we obtain there is increase in the boiler efficiency by 0.61% (approximately) with the help of MATLAB software is given below:-

1. Increment in the carbon percentage increases efficiency.
2. Decrement is ash percentage that observed increases efficiency.
3. In the case of moisture, decrement it has been observed that the rise in efficiency.

5. Conclusion

Energy analysis of a thermal power plant is reported in this paper. It provides the basis to understand the performance of a fluidized bed coal fired boiler, feed pump, turbine and condenser. MATLAB 2008a computer programming is used for the analysis. The energy balance sheet shows that theoretical losses in various component of boiler. It provides information for selection of the components which has maximum losses so, that optimization techniques could be used to make it more efficient. The various energy losses of plant, through different components are calculated which indicates that maximum energy losses occur in turbine.

Following conclusions can be drawn from this study:

- The coal type affects the first law efficiency of the system considerably.
- It has been also analysed that a part of energy loss occurs through flue gases.
- The carbon content in the coal has to be proper.
- The presence of moisture has a detrimental effect on overall efficiency.
- If we use the heat recovery system to recover the heat losses through flue gases then it will be more useful for us.

With the growing need of the coal, which is an non renewable source of energy and depleting with a very fast pace, it is desirable to have such optimal techniques (better quality of coal) which can reduce the energy losses in the coal fired boiler and improves its performance these create impact on production and optimizations uses of energy sources. In addition this study shows the better quality of coal giving the high performance of plant and even though the consumption of coal is been reduced that creates economic condition for overall plant

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NOMENCLATURE

c – Carbon
h – Hydrogen
o – Oxygen
s – Sulphur
E – Rate of energy
dE_{system}/dt – Rate of change
C p = Specific heat capacity, kJ/kg^{0}C
E = Rate of energy
m =Mass flow rate, kg/s
Q = Energy losses
s = Specific entropy, kJ/kg
T = Temperature^{0}C
η = Energy efficiency

Subscripts

in – input
out – Output
p – Product
a – Air
g – Flue gases
s – Steam
w – Water
B – Boiler
f – Fuel