Steady State Energy and Exergy Analysis of Pulverized Coal Fired Boiler

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***Abstract* -Both energy and exergy analysis gives an idea about the real useful energy loss in terms of quality and quantity. Exergy analysis provides a method to evaluate the degradation of energy during a process and offers a measure for improvement of power plant performance. Typical steady state plant operation conditions were determined based on available trending data and the resulting condition of the operating hours. The present study deals with the energy and exergy analysis of a 500 MW pulverized coal fired boiler in steady state condition. Locations and magnitude of exergy destruction is evaluated in the boiler and found that the major exergy destruction occurs at combustor followed by heat exchanger. The Ebsilon®Professional software was used for component wise modelling and simulation of the boiler and its heating surfaces. The results of energy and exergy efficiencies of boiler are found to be 84.39 % and 42.09 %.**

Key Words: Boiler Losses, Heating surfaces, Energy, Exergy, Ebsilon® Professional

1. INTRODUCTION

Energy is one of the major inputs for economic development of any country. In the case of the developing countries, the energy sector assumes a critical importance in view of the ever increasing energy needs requiring huge investments to meet them. The Indian Power sector is a giant 232.16 GW power generator, diversified to coal, gas, oil, nuclear, hydro, and other renewable sources as operating source. In India, Non Renewable Power Plants constitute 87.3% of the installed capacity, and Renewable Power Plants constitute the remaining 12.7% of total installed Capacity. Additionally, captive power plants add another 34.44GW to the generation [1]. Since these energy sources generally use boiler- steam turbine system to convert its chemical potential energy to electricity generation, one can only imagine the possible way of savings derivable from improving the efficiency of a steam boiler by just a small fraction. 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 loss in the boiler. Normally heat loss from the steam boiler occurs because of radiation loss, blow down loss, hot flue gas loss, high spray (Reference ERC 2004) etc. In order to optimize the boiler operation it is necessary to identify the areas to achieve the saving potential by minimizing the losses [2].

To meet the increase in demand and effective utilization of the available energy and minimizing the losses it is essential to evaluate the performance of thermal power plants. Normally the performance of thermal power plants is evaluated through energetic criteria, based on first law of thermodynamics. This method unable to justify the real useful energy loss since it cannot distinguish between quality and quantity of energy. Growing concerns about energy savings have led to the development of analysis techniques based on second law of thermodynamics. Exergy is the consequent of second law of thermodynamics. Exergy is a combination property of a system and its environment because unlike energy it depends on the state of both the system and environment. The exergy of a system in equilibrium with the environment is zero. The exergetic performance analysis has found as useful method in the design, evaluation and optimization of thermal power plants. This method can able to determine magnitudes, location and cause of irreversibility in the plant along with individual component efficiency. These points are the basic differences from energetic performance analysis. Therefore, it can be said that a combination of exergetic and energetic analysis can give complete depiction of system characteristics. Such type of comprehensive analysis will be a more convenient approach for the performance evaluation and determination of the steps towards improvement [3], [4], [5].

Recently large number of studies has been carried out based on energetic and exergetic analysis in thermal power plants. Thermodynamic inefficiencies as well as reasonable comparison of each plant to others are identified and discussed for coal fired thermal power plants in Turkey by Hasan [6]. Energy and exergy analysis of a steam power plant in Jordan has been carried out by Aljundi [7]. The performance of the plant was estimated by component wise modelling and a detailed break-up of energy and exergy losses of the plant. An exergy analysis of coal base thermal power plant was presented by Sengupta, using the design data from a 210 MW thermal power plant [8]. Exergy analysis of coal fired power generating unit of 110 MW at

Panki Thermal Power station has been done by Asthana [9]. Naterer analysed the coal fired thermal power plant with measured boiler and turbine losses [3]. Energy and exergy losses of the individual component have been found out in a lignite fired thermal power plant at Neyveli by Ganapathy et al. [5]. The result revealed that maximum energy loss of 39% occurs in condenser, where as the maximum exergy loss of 42.73% occurs in combustor. Amount and source of irreversibilities generated in a boiler of 30MW thermal power plant was discussed by Pradeep and Ibrahim based on first and second law analysis [10]. Exergy analysis of 4.5 MW biomass based steam power plant in Karempudi was done by R.Jyothu Naik .The result of the analysis indicate that the boiler produces the highest destruction [11]. The relation between the irreversibility in combustion and the loss of exergy due to mixing in the exhaust was also considered in the analysis [12]. Vosough describes the useful concept of energy and exergy utilization in a boiler system and the energy and exergy efficiencies are found to be 89.21% and 45.48% [13]. An understanding of both energy and exergy efficiencies is essential for designing, analyzing, optimizing and improving energy systems through appropriate energy policies and strategies. If such policies and strategies are in place, numerous measures can be applied to improve the efficiency of industrial boilers [14]. Jamil [15] studied thermodynamics performance of Ghazlan power plant in Saudi Arabia where mixture of methane, ethane and propane were used as fuels. Author found that exergy efficiency in the boiler furnace was about18.88 %. Author also found the total losses are high in the boiler especially in the heat exchanger (43.4%) compared to other devices. Author also studied Qurayyah power plant where exergy efficiency in the furnace was about 16.88 % and in the heat exchanger 25.19 %. Gonzalez [16] studied the improvement of boiler performance by using economizer model. Author used hot gases recovery system to improve the performance of the boiler. Author reported that upto 57% of cost can be saved with the heat recovery system.

The present study deals with the energy and exergy analysis of a 500 MW pulverised coal fired boiler in steady state condition. Locations and magnitude of exergy destruction is also evaluated in the utility boiler at operating condition. The Ebsilon® *Professional* software was used for component wise modelling and simulation of the boiler and its heating surfaces. Simulation is carried out with measured operating data collected from the plant Distributed Control System (DCS) at 500 MW, to evaluate the energy and exergy efficiencies of boiler and heating surfaces. Exergy destruction of each component is derived to identify the exact location of component degradation.

2. DESCRIPTION OF BOILER

The schematic diagram of boiler is shown in Figure 1. Feed water from economizer enters the boiler at 330.56 oC and 187.42 bar. Saturated steam produced leave drum and goes to three stages super heating, low temperature (LTSH), division panel (SHDP) and platen super hater (SHPL) respectively. Reheating of steam is done in one stage of reheater. Desuperheating is done two stages, first in super heating stage and second in reheating stage. The operating data of the boiler at 500 MW load is shown in Table 1.

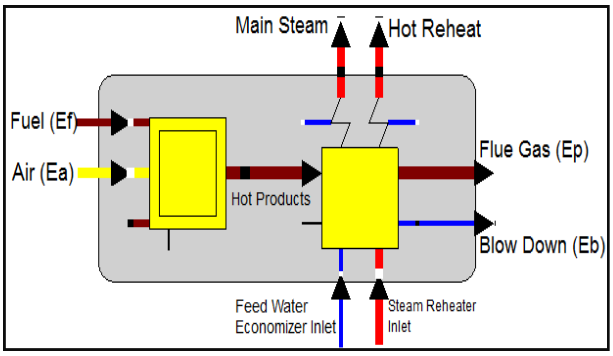

Figure 1. Schematic diagram of boiler.

Table 1. Operating parameters of boiler

Description	Unit	Operating data
Gross load	MW	500
Main steam pressure	bar	173.284
Main steam temperature	°C	540
Main steam flow	Kg/s	415.333
Reheat steam pressure	bar	40.109
Reheat steam temperature	°C	540
Super heater spray flow	kg/s	2.5
Reheater spray flow	kg/s	0
Feed water temperature economizer inlet	°C	254
Feed water temperature economizer outlet	°C	359.47
Flue gas temperature economizer outlet	°C	325
Flue gas temperature airheater outlet	°C	125
Oxygen air heater Inlet	%	3.62
Unburnt carbon in fly ash	%	0.3
Unburnt carbon in bottom ash	%	0.7
Coal Parameter (Ultimate Analysis)		
Carbon	%	29.76
Hydrogen	%	3.70
Nitrogen	%	2.38
Oxygen	%	8.66
Sulphur	%	0.5
Ash	%	40
Moisture	%	15
HHV (higher heating Value)	kcal/kg	3300

3. SYSTEM ANALYSIS

Detailed process model with various significant component of the boiler considered in this study is shown in Figure 2. The operating parameter of boiler used for thermodynamic simulation is presented in Table 1. The boiler system is divided in to 3 sub-regions. Sub region-I corresponds to the combustion zone, sub-resgion –II corresponds to the heat transfer zone, include SHDP,SHPL,RH and LTSH and sub-region –III corresponds to the heat recovery zone consists of economizer and air heater (region of dissipating). Heat loss in the steam generator is calculated using indirect method for evaluating energy efficiency of the boiler section. The flue gas temperatures across each heating surfaces is back calculated by the model based on the measured flue gas temperature at economizer outlet and considering measured temperatures of water steam side across all heating surfaces. A combustion calculation is done for determining the flue gas composition and the adiabatic combustion temperature. Combustion efficiency is calculated by the model taking into account the fluegas analysis reports of unburnt carbon percentage in fly ash and bottom ash . Input data for boiler model is like steam temperature & pressure, flue gas and air temperatures & pressure, ambient parameters etc as shown in Table 1 and Figure 3.

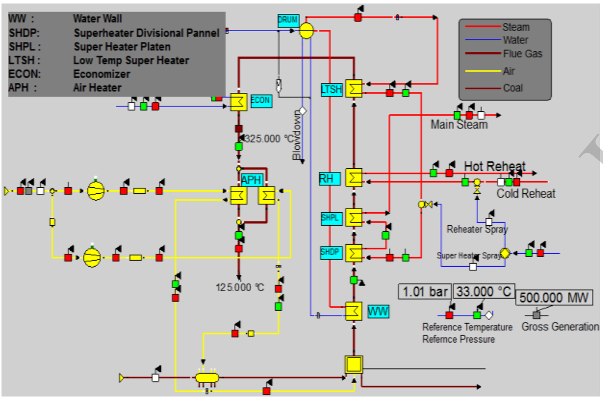

Figure 2: Boiler model with arrangement of components

3.1. Energy and Exergy Analysis in Boiler

The first law of thermodynamics or energy balance for steady state flow process in a controlled volume system with negligible of potential and kinetic energy change is,

$$\dot{Q} - \dot{W} = \sum \dot{m}_e \; h_e - \sum \dot{m}_i \; h_i \quad (1)$$

Where $\dot{Q}$ is the rate of energy transfer to the system as heat, $\dot{W}$ is the rate of work done by the system and the subscripts i and e denote inlets and outlets, respectively.

The energy or first law efficiency of system and component is defined as the ratio of energy output to energy input to system or component. Mathematically,

$$\eta_I = 1 - \frac{\text{Energy loss}}{\text{Energy input}} = \frac{\text{Energy output}}{\text{Energy input}} \quad (2)$$

The exergy analysis is the combination of the first and second laws of thermodynamics. In this analysis the heat does not have the same value as the work, and the exergy losses represent the real losses of work. Exergy analysis provides a quantitative measure of the quality of the energy in terms of its ability to perform work and leads to a more rational use of energy.In this study for steady state flow processes the kinetic and the potential exergy are neglected. Also for the exergy calculation the reference pressure and temperature are taken respectively as 1.013 bar and 33 ^{o}C. For steady state flow of stream the exergy balance is as follows [17],

$$\sum(1 - \frac{T_0}{T})\dot{Q} + \sum_{in} \dot{m}_i \, e_i = \dot{W} + \sum_{out} \dot{m}_e \, e_e + \dot{E}_D \quad (3)$$

Where $\sum(1 - \frac{T_0}{T})\dot{Q}$ is the exergy transfer at temperature T, and the subscripts i and e denote inlets and outlets, respectively. $\dot{W}$ is the work rate excluding the flow work. The exergy transfer rates at inlets and outlets are denoted respectively as, $\dot{E}_i = \dot{m}_i e_i$ and $\dot{E}_e = \dot{m}_e e_e$.

$\dot{E}_D$ is the time rate of exergy destruction due to irreversibilities within the control volume. The exergy destruction rate is related to the entropy generation rate by [17],

$$\dot{E}_D = T_0 \dot{S}_{gen} \quad (4)$$

$$e = h - h_0 - T_0(s - s_0) \quad (5)$$

Where e is specific exergy in kJ/kg

$$\text{Total exergy}, E = \dot{m}\, e = \dot{m}\,[h - h_0 - T_0(s - s_0)] \quad (6)$$

Where h and s denote the specific enthalpy and specific entropy respectively. The subscript 0 denotes the restricted dead state.

In steady state, exergy balance for control volume is shown as [17],

$$\dot{E}_F = \dot{E}_P + \dot{E}_D + \dot{E}_L \quad (7)$$

Where $\dot{E}_F$ is the rate at which fuel is supplied and $\dot{E}_P$ is the product generated. $\dot{E}_D$ and $\dot{E}_L$ denotes the rate of exergy destruction and exergy loss respectively.

To define the exergetic efficiency both a product and a fuel for the system are identified. The product exergy represents the desired result produced by the system and the fuel exergy represents the resources expended to generate the product. The exergetic efficiency is the ratio between product exergy and fuel exergy [17], [18].

$$\varepsilon = \frac{\dot{E}_P}{\dot{E}_F} \quad (8)$$

4. RESULTS AND DISCUSSION

The boiler was analyzed with reference temperature and pressure of 33 °C and 1.013 bar. By employing mass and energy balances a first law analysis was performed across the boiler based on the measured operating parameters. Figure 3 displays the relevant thermodynamic state for various components of boiler model based on the first law energy balance. The total combustion air requirement is controlled to maintain the O_2 % (Oxygen) at economizer outlet. Energy balance equation is solved taking fuel flow rate as m_f, air flow m_{sa} (secondary air), m_{pa} (primary air) and hot product mass flow as m_p.

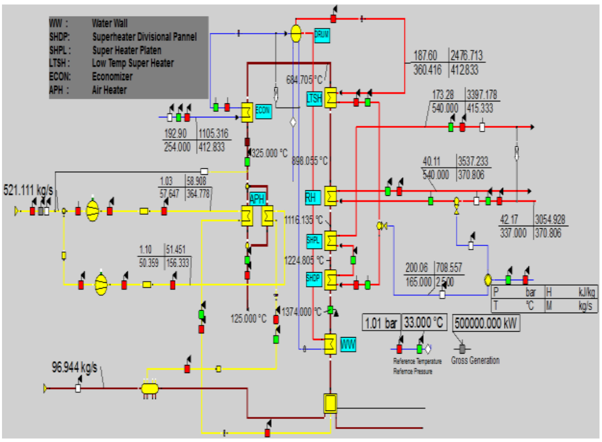

Figure 3: Energy analysis of boiler model

Boiler energy loss was evaluated based on indirect method (loss method), the loss percentage is shown in Figure 4. It was found that the maximum energy loss occurs due to hydrogen in fuel flowed by loss due to dry flue gas.

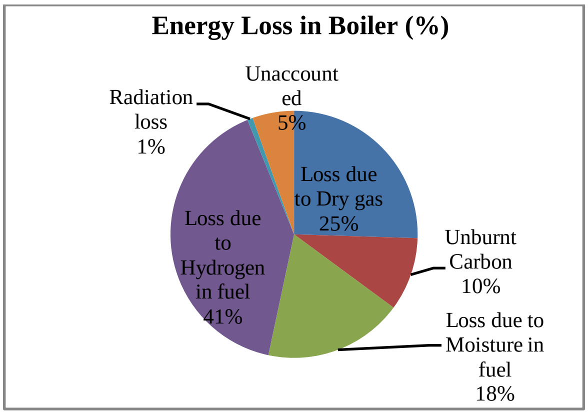

Figure 4: Energy loss in boiler

Exergy analysis at different streams is shown in Figure 5. Exergy efficiency and percentage of exergy destruction are summarized in Table 2 for all components of boiler. It is assumed that the combustor operates in steady flow process since there is no change of process with time at any point. It is also assumed that the kinetic and potential energies are negligible. The exergy destruction of combustor is found to be 35.90 % with efficiency of 65.54 %. It may be stated that the combustion is not fully adiabatic and the combustion may not be completed. Energy and exergy efficiency at different stages is depicted in Figure 6.

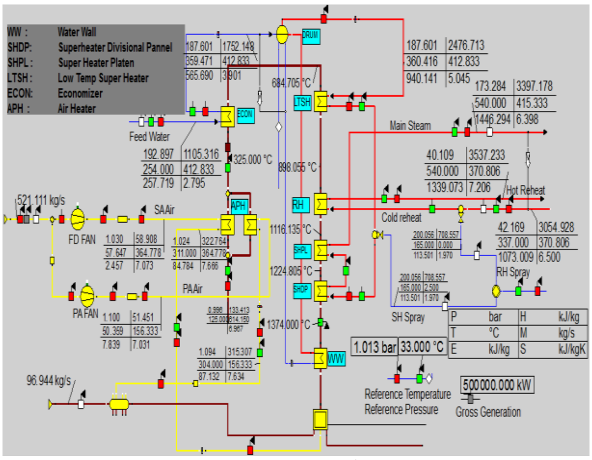

Figure 5: Exergy analysis of boiler model

Table 2: Energy, exergy efficiency and exergy destruction of boiler

	Exergy Destruction (%)	Energy Efficiency (%)	Exergy Efficiency (%)
Combustion Chamber	35.90	99.65	65.54
Heat Exchanger	8.92	100	91.49
Heat Recovery	0.62	100	97.19
Overall Boiler	54.55	84.39	42.09

Calculated exergy and energy efficiency of overall boiler for different load condition is depicted in Figure 7. Results shows that the energy efficiency of boiler decreases with increase in load may be because of operational constraints. This indicates that tremendous opportunities are available for improvement. However part of the irreversibility cannot be avoided due to physical, technological and economic constraints.

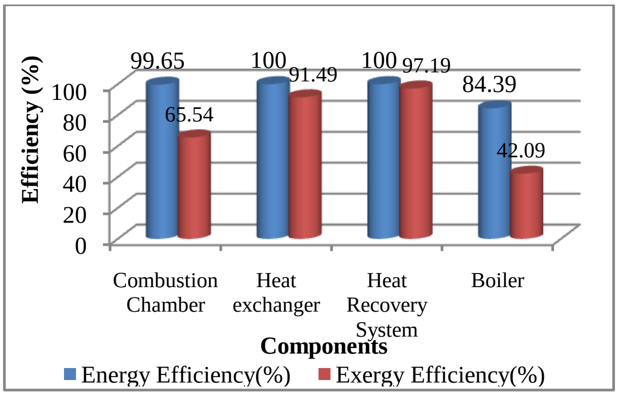

Figure 6: Energy and exergy efficiency at different stages

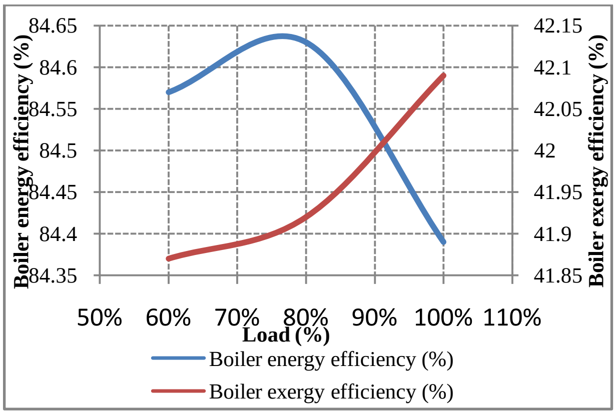

Figure 7: Boiler energy and exergy efficiency

5. CONCLUSION

In the present work a energy and exergy analysis of operating condition of a coal fired thermal power plant has been carried out based on mass, energy and exergy balance using Ebsilon® Professional. The power plant boiler was simulated based on the measured operating data and the thermodynamic states of the plant components are shown in Figure 3 and Figure 5. The energy input with the fuel is calculated based on the higher heating value (HHV) of the fuel. Exergy destruction, exergy and energy efficiency of the boiler components are presented in Table 2 and corresponding comparison diagram is shown in Figure 6. The overall energy efficiency of boiler is 84.39 % according to the first law analysis, the main losses occurs due to hydrogen in fuel followed by dry flue gas. Overall exergy efficiency of boiler is 42.09 % according to second law analysis. It has been found that exergy efficiency is lower than the energy efficiency. Combustor is the major contributor for exergy destruction in boiler.

6. REFERENCES

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Nomenclature

$\dot{W}$	Work done (kW)
$\dot{Q}$	Heat transfer (kW)
$\dot{m}$	Mass flow (kg/s)
s	Specific entropy (kJ/kgK)
h	Specific enthalpy (kJ/kg)
e	Specific exergy (kJ/kg)
I	Irreversibility (kJ/s)
E	Exergy (kW)
η_I	First law efficiency (%)
ε	Exergetic efficiency (%)
T	temperature (^{o}C)
P	pressure (bar)