Abstract: The energy and exergy analyses especially of boiler of 50 MW unit of Lakhra power is demonstrated through EES software in this research paper because of its consistent, persistence and recurring failure even its minor failure renders whole power plant to remain shut down for indefinite period of time till its rectification, repairing, maintenance and replacing. However, the chief parts of boiler in the plant are fluidized bed combustion chamber, super heater, economizer and air preheater which are aimed at increasing overall efficiency and optimizing performance by proper utilizing supposed-to-be wastage like flue gas and its high temperature heat and energy potential. Through energy analysis the energy loss along with the first law efficiency of the parts have been computed and calculated which shows quantitative loss while for qualitative loss the exergy method has been employed to figure out second law efficiency of components, generation of entropy, irreversibility and destruction. Through the investigation it was witnessed that the most destructive parts of boiler is the combustor where uncontrolled chemical reactions and maximum loss and destruction, due to heat loss and radiation losses, take place where energy loss is 90% and exergy destruction is 55% succeeded by super heater where 5% energy loss occurs and 36% exergy destruction happens. The highest optimized part of the boiler is air preheater that has 78% and 79% energy and exergy efficiency respectively.

Keywords: Energy, Exergy, Boiler, Combustor, Energy Loss, Exergy Destruction.

1. Introduction

Generally, the world’s electricity demands are met by fossil fuels. Although much progress has been done on inexhaustible sources of energy like power of wind and solar power to name a few, still the dominance of fossil fuels is anticipated to prolong for many decades to come [1]. In Pakistan, by source electricity generation comes as Oil 35.2%, Gas 29.0%, Hydel 29.9% and Nuclear and imported 5.8% [2]. Power production Industry of Pakistan chiefly comprises of thermal and hydropower plants with fixed capacity of 12442 and 6481 MW respectively [2]. Moreover, these thermal power plants are operated with very low efficiencies due to many technical and management inefficiencies. For such reasons, the electricity supply and demand gap is get widening, which is leading the country’s social and economic growth near to standstill. Recently, Pakistan is experiencing worst energy crisis in history. The gap between electricity demand and supply keeps widening; a maximum shortfall of higher than 6000 MW was recorded in year 2010 [3]. The scenario has yet to be better as country witnesses currently massive protests. Many businesses have to be shut off owing to severe power crisis. Many factors contribute to the acute shortage of dwindling of energy in Pakistan involving absence of Integrated Energy Planning and Demand Forecasting and nonappearance of central and concentrated entity answerable for the sector of energy, unevenness energy mix with greater interdependence on gas and oil and their exorbitant import. Nonutilization of enormous local coal of Thar and hydro proficiency, dearth of efficacious project structuring, planning and implementation of known and feasible projects are leading causes of crisis of power. Country has tremendous hydro & coal energy potential (185 billion tones) [3] that could be put into action in order to overcome the electricity crises. Global generation of electricity is offered 40% through coal. On the other hand, regardless of having massive stockpile of lignite, Pakistan brings about only 0.1% electricity from Lakhra FBC power plant. The performance assessment of power plants is
mostly performed on the basis of energy concepts, whereas exergy concepts are being widely used nowadays for more elaborate investigation as exergy is outlined as the useful work performed by the system when it comes in touch with a state of equilibrium and moreover unlike energy, exergy is not conserved but is destructed in the system that renders the reduction in the performance therefore exergy analysis assists in identifying the magnitude, location and the source of inefficiencies in a thermal system. Furthermore, the exergetic performance assessment is more beneficial in designing, evaluation, and optimization of various energy conversion processes than using energy principles alone [4]. The great constraint of energy and pollution of environment demand the efficient utilization of already scant resources and getting optimized performance. So the sophistication and complexities has increased to a great extent of power generating plants as with low input and low wastage high performance is required so this in turn needs high accuracy with respect to thermodynamic point of view and this is resulted in high expenditure in designing and optimization stages [5]. A thermal power plant is the best depiction in terms of the utilization of thermodynamic analysis by employing both technics energy and exergy to know the quantitative and qualitative areas of measurement of energy and moreover the considerable real amount of loss and destruction happens in the boiler and its components where tremendous amount of entropy is produced so this area has to be focused and bring into study in order to evaluate its complex working and functioning [6]. The efficiency of boiler has direct effect in terms of energy savings relative to heating so it is of utmost importance to decrease losses of heat by transferring that to the water as much as possible however there are various sources of heat losses in boiler like the carrying away most of the heat by hot flue gases and losses connected with radiation. So in order to get the optimized performance the areas have to be seen where the losses likely occur and it is a proven fact the much amount of the exergy is lost because of the flue gases as the heat generated by burning is not transferred effectively to water in the generating tubes surrounding the boiler shell [7]. Amir, et al. [8] analyzed power plant constituents and identified and quantified areas of greatest energy and exergy destructions and found boiler as a site which generates maximum irreversibilities with nearly 86% exergy destruction of total followed by stack with 13% Dai, et al. [9] applied the exergy concepts to analyze a cogeneration system and concluded that turbine, condenser and heat recovery steam generator (HRSG) are the major contributors towards exergy destruction. Kotas [10] illustrated the importance of exergy methods for performance evaluation of the thermal plants. Ganapathy, et al. [11] performed exergy analysis on 50MW lignite coal plan in India that maximum losses of 42.73% accrue in combustor. Senugpata, et al. [12] and Regulagadda, et al. [1] investigated actual steam power plants by exergy methods under designed and off-designed conditions. They reported that plant performance is highly affected by the load variations and highest exergy destruction occurs in boilers. It is therefore essential that exergy methods should be widely employed to evaluate the performance of power plants for effective and efficient utilization of energy resources [13].

Keeping in view the current energy scenario of Pakistan and importance of exergy methods for power plant evaluation, this paper demonstrates energy and exergy based analysis of boiler and its chief components Lakhra Coal Power Plant situated in Lakhra 187 km from major city Karachi. A 50 MW capacity unit of the power plant is selected for the study which is first thermodynamically modelled in Engineering Equation Solver (EES) software and simulated under various operating conditions.

1.2. Process Description and Assumptions Made

The schematic diagram of the unit under study is shown in Fig.1. The plant has three identical and same capacity units each comprises of 50 MW unit with total capacity of 150 MW however, first and third units are dysfunctional and dormant due to various technical reasons so in this study Unit#2 has been analyzed which is active, operative and functional. The water at 200 ton/hr is superheated in the FBC boiler to the temperature of 540°C and pressure of 9 MPa. The superheated steam is directed to the turbine through main pipe and main stop valve achieves its regulation. Here two cycles perform their respective work simultaneously; one is flue gases cycle which has high potential of heat and thus energy and second one steam or saturated water cycle which when in made indirect contact with super heater and economizer extracts heat potential from flue gases so thus high level saving of supposed-to-be waste energy occurs. The atmospheric air at temperature of 25 °C is sucked by forced draught fan at pressure of 1.587 kPa and then this air is passed through air preheater, from which flue gases at temperature of 343°C and pressure of 0.1 kPa pass to atmosphere by the induced draught fan from stack, by gaining temperature 298 °C reaches combuster bottom for the ignition. In combuster hot air enters from bottom while coal lignite with flow rate of 14 kg/s is pulverized and then sprayed in furnace from the top as here the furnace utilizes fluidized bed combustion technology due to which through cyclone attached at the bottom of the furnace
helps in mixing properly the air and fuel ratio 12:1, that behaves like gas, properly and then this mixture stays in the combustion chamber for a while in order to let the proper and effective ignition takes place because lignite with very low calorific value coal is of very low quality so it takes time to it in complete burning and with the burning the ash is emitted because of chemical reaction which is then betterly absorbed by limestone bed this process is known as desulphurization and moreover in the inside of the combustion chamber the temperature reaches in between 750 °C to 840 °C which converts the saturated water with flow of 55.55 kg/s at temperature of 318°C pressure of 11 Mpa into saturated steam with same flow rate and pressure at temperature of 480°C in generating tubes surrounding the furnace. The next stage after combustor is super heaters final and primary which achieve purpose of transmitting immense heat potential from flue gases 754 °C to saturated steam 480°C thus raising the steam temperature to 540 °C by making it superheated steam with very negligible moisture content to strike the blades of turbine with no fear of damage and erosion to them. After this the economizer achieves its purpose by extracting heat from flue gases 514 °C and transferring it to feedwater by rising its temperature from 218°C at 11.5 Mpa to 318 °C at 11 Mpa in order to give it better advantage in furnace. The last stage of boiler is air preheater where flue gases at temperature of 343°C pressure of 0.1 kPa enters to transfer its heat potential to atmospheric air by raising its temperature from 25 °C to 298 °C for the better ignition and burning in combustion chamber.

The main assumptions made for analysis are given as

- Steady state flow conditions prevails for all fluid streams with negligible changes in kinetic and potential energies.
- The dead-state condition is at 101.32 kPa and 25°C.
- Lignite coal is taken as fuel.
- The air and fuel ratio is assumed as 12:1
- Mass flow rate of saturated feedwater or saturated steam or superheated steam is presupposed to remain same throughout the analysis
- Mass flow rate of inlet air or exhaust flue gases is assumed to remain same throughout the analysis
- Exhaust of the first with respect to mass flow rate is assumed to be the initial of the second components and so on so forth.

1.3. Thermodynamics Model Equations and Schematic Diagrams

The thermodynamic equations of boiler and its parts are demonstrated in terms of energy and exergy analysis along with the relevant diagram.

1.3.1. Energy Analysis for Boiler Combustion Chamber

\[ E_{in} = m_f \times h_f + m_a \times h_a + m_{fwi} \times h_{fwi} \]  \hspace{1cm} (1)

\[ E_{out} = m_g \times h_g + m_{fwo} \times h_{fwo} \]  \hspace{1cm} (2)

\[ E_{loss} = E_{in} - E_{out} \]  \hspace{1cm} (3)

\[ n_{comb} = E_{out}/E_{in} \]  \hspace{1cm} (4)

1.3.2. Energy Analysis for Boiler Combustion Chamber

\[ Exergy_{in} = \varepsilon_f + \varepsilon_a + \varepsilon_{fwi} \]  \hspace{1cm} (5)

\[ Exergy_{out} = \varepsilon_g + \varepsilon_{fwo} \]  \hspace{1cm} (6)

\[ Exergy_{destruction} = Exergy_{in} - Exergy_{out} \]  \hspace{1cm} (7)
### Exergy Analysis

\[
\text{Exergy}_{\text{efficiency}} = \frac{\text{Exergy}_{\text{out}}}{\text{Exergy}_{\text{in}}} \quad (8)
\]

\[
\varepsilon_f = m_f (h_f - T_o S_f) \quad (9)
\]

\[
\varepsilon_a = m_a (h_a - T_o S_a) \quad (10)
\]

\[
\varepsilon_{fwi} = m_{fwi} (h_{fwi} - T_o S_{fwi}) \quad (11)
\]

\[
\varepsilon_g = m_g (h_g - T_o S_g) \quad (12)
\]

\[
\varepsilon_{fwo} = m_{fwo} (h_{fwo} - T_o S_{fwo}) \quad (13)
\]

**Figure 1. Schematic Diagram of Combustor**

#### 1.3.3. Energy Analysis for Super Heater

\[
E_{\text{in}} = m_g (h_{gi} - h_{gout}) \quad (14)
\]

\[
E_{\text{out}} = m_{\text{steam}(i)} (h_{\text{steam}(0)} - h_{\text{steam}(i)}) \quad (15)
\]

\[
E_{\text{loss}} = E_{\text{in}} - E_{\text{out}} \quad (16)
\]

\[
n_{\text{isup}} = \frac{E_{\text{out}}}{E_{\text{in}}} \quad (17)
\]

#### 1.3.4. Exergy Analysis for Super Heater

\[
\text{Exergy}_{\text{in}} = m_g (h_{gi} - T_o S_{gi}) - m_g (h_{g0} - T_o S_{g0}) \quad (18)
\]

\[
\text{Exergy}_{\text{out}} = m_{\text{steam}(i)} (h_{\text{steam}(0)} - T_o S_{\text{steam}(0)}) \quad (19)
\]

\[
\text{Exergy}_{\text{destruction}} = \text{Exergy}_{\text{in}} - \text{Exergy}_{\text{out}} \quad (20)
\]

\[
\text{Exergy}_{\text{efficiency}} = \frac{\text{Exergy}_{\text{out}}}{\text{Exergy}_{\text{in}}} \quad (21)
\]
1.3.5. Energy Analysis for Economizer

\[ E_{\text{in}} = m_g (\Delta h_{gi} - \Delta h_{gout}) \]  \hspace{1cm} (22)

\[ E_{\text{out}} = m_{fwi} (\Delta h_{eco} - \Delta h_{ecol}) \]  \hspace{1cm} (23)

\[ E_{\text{loss}} = E_{\text{in}} - E_{\text{out}} \]  \hspace{1cm} (24)

\[ n_{\text{eco}} = E_{\text{out}}/E_{\text{in}} \]  \hspace{1cm} (25)

1.3.6. Exergy Analysis for Economizer

\[ Exergy_{\text{in}} = m_g (\Delta h_{gi} - T_0 \Delta S_{gi}) - m_g (\Delta h_{g0} - T_0 \Delta S_{g0}) \]  \hspace{1cm} (26)

\[ Exergy_{\text{out}} = m_{fwi} (h_{fwo} - T_0 S_{fwo}) - m_{fwi} (h_{fwi} - T_0 S_{fwi}) \]  \hspace{1cm} (27)

\[ Exergy_{\text{destruction}} = Exergy_{\text{in}} - Exergy_{\text{out}} \]  \hspace{1cm} (28)

\[ Exergy_{\text{efficiency}} = Exergy_{\text{out}} / Exergy_{\text{in}} \]  \hspace{1cm} (29)

1.3.7. Energy Analysis for Air Preheater

\[ E_{\text{in}} = m_g (\Delta h_{gi} - \Delta h_{gout}) \]  \hspace{1cm} (30)

\[ E_{\text{out}} = m_a (\Delta h_{a0} - \Delta h_{ai}) \]  \hspace{1cm} (31)

\[ E_{\text{loss}} = E_{\text{in}} - E_{\text{out}} \]  \hspace{1cm} (32)
\[ n_{\text{airp}} = \frac{E_{\text{out}}}{E_{\text{in}}} \quad (33) \]

### 1.3.8. Exergy Analysis for Air Preheater

\[ Exergy_{\text{in}} = m_d (\Delta h_{g1} - T_g \Delta S_{g1}) - m_d (\Delta h_{g0} - T_g S_{g0}) \quad (34) \]

\[ Exergy_{\text{out}} = m_a (h_{ai} - T_o S_{ai}) - m_a (h_{ao} - T_o S_{ao}) \quad (35) \]

\[ Exergy_{\text{destruction}} = Exergy_{\text{in}} - Exergy_{\text{out}} \quad (36) \]

\[ Exergy_{\text{efficiency}} = \frac{Exergy_{\text{out}}}{Exergy_{\text{in}}} \quad (37) \]

#### Figure 4. Schematic Diagram of Airpreheater

All enthalpies and exergies are calculated under dead state conditions.

#### Table 1. Baseline data

<table>
<thead>
<tr>
<th>Name</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main Steam pressure</td>
<td>9 Mpa</td>
</tr>
<tr>
<td>Main Steam temperature</td>
<td>540°C</td>
</tr>
<tr>
<td>Fuel supply (coal)</td>
<td>14 Kg/s</td>
</tr>
</tbody>
</table>

#### 2. Results and Discussion

Now with the help of the energy and exergy analysis as per shown in above equations the result is computed at the load of 100 % at designed conditions and satisfactory outcomes have been gotten by comparing with other studies from literature review.

#### Table 2. Energy Loss and Exergy Destruction of the Components of Boiler

<table>
<thead>
<tr>
<th>Component</th>
<th>Energy Loss in KJ/S</th>
<th>Exergy Destruction in MW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Combustor</td>
<td>700751</td>
<td>148.425</td>
</tr>
<tr>
<td>Superheater</td>
<td>42392</td>
<td>96.818</td>
</tr>
<tr>
<td>Economiser</td>
<td>22457</td>
<td>18.789</td>
</tr>
<tr>
<td>Airpreheater</td>
<td>10330</td>
<td>4.319</td>
</tr>
</tbody>
</table>
3. Conclusion

It is concluded through investigation that combustor is the main component which yields high loss and destruction and it completely wastages the useful energy and work potential of energy despite utilizing the fluidized bed combustion technology to conserve energy and is supposed to give way to effective and proper burning and mixture of fuel and air however the very low performance in terms of energy and exergy suggest that combustor is not functioning adiabatically and the combustion is not taking place in the complete sense thus leaving the most part of the precious fuel to wastage and in combustor huge irreversibility around 55% can be witnessed in process of combustion thus it is the need of an hour that there should be modification aimed at reduction of destruction in perspective of designing to heighten performance. After furnace is succeeded by super heater which is the second major components where losses and destruction accrue as the transfer of heat between flue gases and saturated steam doesn’t take place effectively and efficiently. The air preheater and economizer are the most efficient components where in tremendous amount the transfer of heat takes place between air to flue gases and flue gases to feedwater.

Acknowledgment

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Nomenclature

\begin{align*}
E & \quad \text{Energy flow (kJ/s)} \\
h & \quad \text{Specific enthalpy (kJ/kg)} \\
i & \quad \text{In} \\
o & \quad \text{Out}
\end{align*}
Abbreviations
FBC Fluidized Bed Combustion
I.D FAN Induced Draught Fan
F.D FAN Forced Draught Fan

References