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Exergy Analysis of a Coal Based 63 MWe Circulating Fluidized Bed Boiler- A Case Study

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Abstract: The boiler taken up for analysis has a steam generating capacity of 250 tph, 11 MPa with 540°C of steam temperature. This study focuses on identifying the energy and exergy flow of each component of the system in order to identify the areas of major exergy loss. The plant components are grouped under three subsystems. The analysis was first made in the subsystems individually and as a whole. The coefficient of influence of important components was also studied. From the energy analysis, it has been found that the boiler system utilizes 88.41% of the total energy supplied to the plant and nearly 6.7% of heat supplied is carried away by the exhaust gas. The overall energy efficiency of the plant is found to be 31.15%. It has been noticed that the maximum exergy loss occurs in the furnace combustion chamber, i.e., 54.1% of the exergy supplied to Circulating Fluidized Bed (CFB). The exergy loss in the turbine is estimated to be around 8.3%. The maximum loss of exergy that occurs in boiler combustion chamber is due to irreversibility of the combustion process. The exergy efficiency of the boiler system is estimated to be 43.09% with respect to total exergy supplied to the plant. The overall exergy efficiency of the plant is evaluated to be 29.29%. Thus the study gives a frame work for the power plants, to conduct exergy efficiency studies in future.

Key words: Exergy, energy, exergy efficiency, fluidized bed boiler, power plant

INTRODUCTION

The world's major power generations rely on the use of fossil fuels. Despite the growth of renewable energy utilization for power generation, the power generation through fossil fuel route has been indispensable and massive. One of the major threats to this source of energy is the depletion of fossil fuel. Hence effective use of energy conversion technologies is warranted. An analysis of energy and exergy helps to develop an improved technology for energy conversion. Exergy analysis is an effective tool for optimization and process analysis. Now a days, greater efforts are to be given for reducing air pollution and global warming. This can be achieved by operating the plant using efficient and improved technologies.

Circulating Fluidized Bed (CFB) technology has been found to be conducive for environmental issues. Gungor (2009) carried out studies on size of heat transfer surfaces to ensure the proper operation and optimization of circulating fluidized beds (CFB's), considering particle based approach for the 2D CFB model. The influence of water flow rate and heat exchanger tube diameters are investigated based on second law of thermodynamics. Auracher (1984) studied the fundamental aspects of energy application for the optimization of energy process. It is concluded that thermodynamic process optimization is for the saving of exergy rather than energy. Further, an energy and exergy balance analyses proves to be an effective tool to quantify the exergy losses for optimizing the plant process parameters. Ganapathy *et al*. (2009) conducted an exergy study for a 50 MW power plant, which uses lignite as fuel. The study finds out about 39% of energy loss in the condenser and 43% of exergy destruction in combustion system. Erdem *et al*. (2009) conducted comparative study of nine different capacities of power plants using low grade fuel. They developed a thermodynamic model using first law and second law as the first stage. The developed model has been compared with design values of those power plants as the second stage. Finally, the design point performance analyses are made for both energy and exergy basis. This proves to be more helpful for the designer. Aljundi (2009) studied the energy and exergy analysis of a power plant of capacity 56 MW using heavy oil as fuel. The energy efficiency of the plant is 26%. Two thirds of energy loss occurs in the condenser and the exergy loss is about 9%. Seventy seven percent of exergy loss occurs in boiler system and

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the exergy efficiency of the cycle is estimated as 25%. Khaliq and Kaushik (2004) studied the second law analysis of high thermal efficiency of re-heat combined Brayton/Rankine power cycle. It has been concluded that overall exergy destruction is about 50% in combustion chamber. Addition of further two re-heater stages enhances the combined cycle efficiency.

Energy and exergy analysis of a low calorific value pulverized coal fired power plant of 150 MW, 13.5 MPa, 535°C has been studied by Kopac and Hilalci (2007). Their study concludes that the loss of energy in boiler had much influence on the loss of total efficiency and the rational efficiency of the plant. The ambient temperature had greater effects on the changes of the irreversibility of boiler. Further it had low effect on outside components of the plant. Nag and De (1997) conducted a thermodynamic study on a Heat Recovery Steam Generator (HRSG) to minimize the entropy generation of saturated steam in combined cycle operation. Their study concludes that operating the HRSG with maximum load could reduce the entropy generation. Further they optimized the saturation pressure corresponding to a suitable number of transfer units of the evaporator thermodynamically. Nikulshin *et al.* (2002) developed a new novel calculation method of exergy efficiency for a 500 MW, K500-240 turbine complex energy system. It has invariant of the technical details and structure, which can be applicable in different industries.

Thermodynamic analysis of a 32 MW low pressure coal fired power plant, operating at various operating conditions were studied by Regulagadda *et al.* (2010). They conclude that power plant's energy and exergy efficiency is about 30.12 and 25.38%, respectively for the gross generator output. They report that the maximum exergy destruction is found in the boiler. studied the exergy analysis on a 210 MW power plant keeping constant pressure mode operation of turbine. Their study concludes that about 60% of exergy destruction is found in the boiler system. Further it also states that the withdrawal of high pressure heaters led to the enhancement of exergy efficiency.

A review of literature reveals that energy and exergy analysis have not been made in practical thermal power plants on Circulating Fluidized Bed (CFB) boilers in operating conditions. Hence, a detailed study on a 63 MW CFB boiler power plant, situated in Tuticorin, India has been considered for the present study.

DESCRIPTION OF THE PLANT

Figure 1 and 2 show the schematic representation of the boiler and cycle of a 63 MWe Circulating Fluidized Bed (CFB) boiler considered for the present study. The present boiler has single coal-fired furnace with full water cooling wall, high temperature steam cooled volute type cyclone separator of natural circulation and balanced

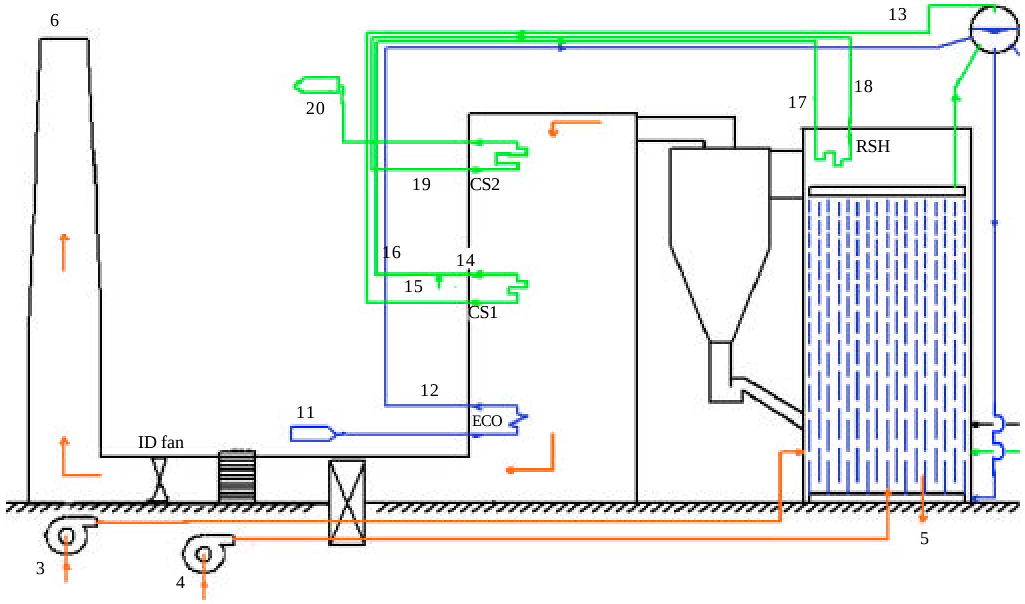

Fig. 1: Schematic representation of 63 MWe circulating fluidized bed boiler, ID: Induced draught, ECO: Economizer, CS: Convective super heater, RSH: Radiant super heater

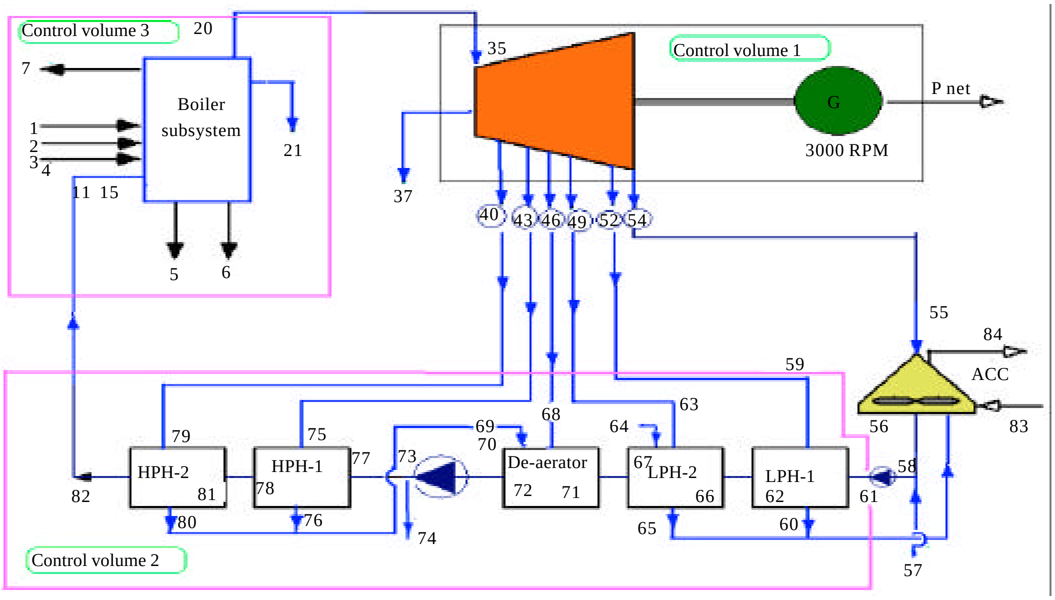

Fig. 2: Energy flow diagram of 63 MWe circulating fluidized bed boiler, HPH: High pressure heater, LPH: Low pressure heater, ACC: Air cooled condenser, G: Generator, P_{net}: Power

ventilation. It has 250 tph, 11 MPa and superheat temperature of 540+5/-0°C steam generating capacity. The steam generator consists of water cooled furnace enclosure with two number of steam cooled cyclones separators and back pass cage.

The middle and upper furnace has two of evaporation wing walls. The boiler consists of two convective super heaters and one radiant super heater with two stage water spray attemperators. The back pass cage is made up of two parts such as steam cooled Convective Heat Recovery Area (CHRA) which contains two stages of super heaters and the second part consists of economizer and air pre-heaters. The generated steam has been admitted to the steam turbine, which consists of five steam extractions for the purpose of feed water heating and de-aeration. The last stage of steam has been admitted to the Air cooled Condenser (ACC). Further this power plant consists of two numbers of Low Pressure Heaters (LPH) and High Pressure Heaters (HPH) with one number of De-Aerator (DA). The drains from each HPH are mixed with DA water, similarly the drains from LPH has been mixed with ACC hot well. The gland leaking steam from the steam turbine is allowed to the LPH2. The water leaving from the HPH2 is sent to the economizer.

MATERIALS AND METHODS

The present study aims to estimate the energy and exergy destruction of the CFB boiler power plant. The plant components are grouped into three subsystems (control volumes), such as turbine, feed water heaters and boiler and their heat transfer components, in order to estimate the individual contribution towards their gross irreversibility and the response of different components towards exergy destruction. The detailed analysis has been carried out by considering the mass, energy and exergy flow across the control surface of individual sub systems and the plant as a whole.

The exergy analysis has been carried out for each component in the sub system and then finally on the overall individual subsystems. The loss of exergy is obtained by balancing the available exergy and used exergy. The energy and exergy losses of the components are calculated by using basic balancing equation of mass, energy and exergy. In the present study the energy and exergy efficiency has been evaluated for all components. The co-efficient of influence (β) (Aljundi, 2009) defined as:

$$\beta = \frac{\text{Exergy flow rate (available)}}{\text{Exergy flow rate (available) for system on the whole}}$$

The exergy loss of each component is evaluated and presented in Table 1.

Table 1: Component wise flow exergy of the power plant

Name of elements	Flow exergy E_{iu} MJ h^{-1}	Flow exergy, E_{ia} MJ h^{-1}	Coefficient of influence β_i	Flow exergy losses MJ h^{-1}	Exergy efficiency η_{iex}
B	322619.162	752882.688	1.0000	430263.526	0.4285
T	226429.200	288716.353	0.3834	62287.153	0.7843
ECO	39522.019	50433.127	0.0669	10911.107	0.7837
CSH1	25163.799	33207.712	0.0441	8043.913	0.7578
CSH2	30046.175	36105.677	0.0479	6059.501	0.8322
DSH	440.641	577.106	0.0007	136.464	0.7635
LPH1	4752.614	7601.072	0.0101	2848.458	0.6253
LPH2	2690.808	13085.515	0.0173	10394.707	0.2056
DA	25984.819	26273.229	0.0349	288.410	0.9890
HPH1	16451.813	17738.027	0.0235	1286.213	0.9275
HPH2	4219.610	5171.646	0.0068	952.035	0.8159

B: Boiler, T: Turbine, DSH: De-Super heater, DA: Deaerator, $_u$: Used$_a$: Available, $_i$: ith component

EXERGY ANALYSES

The engineering applications considered in this work are analyzed on control volume basis. According to the control volume formulations, the mass, energy and entropy balances presented in this study play an important role. Equations of mass, energy and entropy, work, heat interactions, irreversibility, energy efficiency and exergy efficiencies, differential equations and rate equations taken from the available literature (Bejan *et al*., 1996;Kotas, 1985) are used.

The rate of exergy entering the control region is always greater than that of the exergy leaving the region. The rate of loss of exergy is the difference in exergies entering and leaving the control region and is also called the irreversibility rate. This statement is applicable to all real processes:

$$\Sigma\dot{E}x_{in} - \Sigma\dot{E}x_{out} = \Sigma\dot{E}x_{dest} \text{ or } = \Sigma\dot{Q}_k[1-(T_0/T_k)] - \dot{W} + \Sigma\dot{m}_{in\psi in} - \Sigma\dot{m}_{out\psi out} \tag{1}$$

with:

$$\psi = (h-h_0)-T_0(s-s_0) \tag{2}$$

where, ψ is called specific flow exergy, h is specific enthalpy, Q_k is the heat transfer rate through the boundary at temperature T_k at location k, W is the work rate, ψ is the flow exergy, s is the specific entropy and the subscript zero indicates the properties at the dead state and P_0 and T_0 are the pressure and temperature corresponding to the dead state. The exergy destroyed or irreversibility may be expressed as follows:

$$\dot{I} = \Sigma\dot{E}x_{dest} = T_0\dot{S}_{gen} \tag{3}$$

where, S_{gen} is the rate of entropy generation and the subscript zero represents reference environment conditions. The exergy of an incompressible substance may be written as follows:

$$\dot{E}x_{ic} = C((T-T_0)-T_0\ \ln(T/T_0)) \tag{4}$$

where, C is the specific heat.

The exergy efficiency ε is given as:

$$\varepsilon = \left(1-\frac{\text{Exergy destroyed}}{\text{Exergy input}}\right) \tag{5}$$

Exergy destroyed = Exergy input-exergy utilized

$$\varphi = \frac{E_{f^\circ}}{(NCV)^\circ} \tag{6}$$

φ = Ratio of specific exergy of fuel to NCV of fuel
E_f = Specific exergy of fuel
° = Environment state
NCV = Net calorific value:

$$\varphi_{dry} = 1.0437+0.1882\frac{h}{c}+0.0610\frac{o}{c}+0.0404\frac{n}{c} \tag{7}$$

(for the ratio O/C<0.667)

where, c, h, o and n are the mass fractions of C, H, O and N of fuels used (Kotas, 1985) from the plant design data energy gain due to sulfation is taken as h_{sul} = 2345.8 kJ kg^{-1} of lime stone.

In the present study, the exergy efficiency in a control volume is calculated as:

$$\varepsilon = \frac{P_{net}}{\dot{E}_{in}-\dot{E}_{out}} \tag{8}$$

where, $\dot{E}$ is the measure of flow exergy across the control surface. Two types of exergy are taken into account, thermo-mechanical exergy for all the streams and chemical exergy for the fuel stream. The total rate of exergy in a stream is obtained from the specific value:

$$\dot{E}_i = \dot{m}_j e_j \tag{9}$$

The exergy of fuel supplied is calculated by using the following relation. The specific thermo-mechanical exergy (neglecting kinetic and potential energy) is obtained:

$$e_j = (h_j - h_0) - T_o (s_j - s_0) \tag{10}$$

The chemical exergy of other than fuel is neglected as it has very small values.

Analysis of the control volume 1 (Fig. 2): Only the thermo-mechanical exergy is associated with the streams across the control volume 1. The exergy flow rate entering the control volume 1 is shown in Fig. 1:

$$\dot{E}_{in} = \dot{E}_{35} \tag{11}$$

The exergy rate leaving the control volume:

$$\dot{E}_{out} = \dot{E}_{37} + \dot{E}_{40} + \dot{E}_{43} + \dot{E}_{46} + \dot{E}_{49} + \dot{E}_{52} \tag{12}$$

The exergy efficiency of the control volume of turbo generators (ε_{turgen}) is calculated using the equation, where P_{net} corresponds to power output of the turbo-generator.

Analysis of the control volume 2 (Fig. 2): Two low pressure heaters, two high pressure heaters and one de-aerator are used to heat the feed water supplied to the boilers with the use of extracted steam from the turbine in the control volume 2. To increase the pressure of the feed water two feed water pumps are placed before the LPH1 and after deaerator. Considering the thermo-mechanical exergy for stream in this case, the exergy entering and leaving the control volume are:

$$\dot{E}_{ava\text{-}ex} = \dot{E}_{56} + \dot{E}_{57} + \dot{E}_{59} + \dot{E}_{63} + \dot{E}_{64} + \dot{E}_{68} + \dot{E}_{75} + \dot{E}_{79} - (\dot{E}_{60} + \dot{E}_{65}) \tag{13}$$

$$\dot{E}_{used\text{-}ex} = \dot{E}_{74} + \dot{E}_{82} - \dot{E}_{60} - \dot{E}_{65} \tag{14}$$

Analysis of the control volume 3: The boiler subsystem is considered as control volume 3. The energy and exergy enter by the following streams such as fuel, lime stone, primary and secondary combustion air and leaving with unburned carbon, ash and hot gas through chimney. The supplied energy and exergy are gained by the cooling stream of feed water and de-super heater water into the subsystem and leave as a heated steam and blow down water.

The thermo-mechanical exergy and chemical exergy are associated with the streams across the control volume 3 of the boiler sub systems. The available exergy and used exergy of the subsystem are calculated by the following equations:

$$\dot{E}_{ava\text{-}ex} = \dot{E}_1 + \dot{E}_2 + \dot{E}_3 + \dot{E}_4 - (\dot{E}_5 + \dot{E}_6 + \dot{E}_7) \tag{15}$$

$$E_{uesd\text{-}ex} = \dot{E}_{20} + \dot{E}_{21} - (\dot{E}_{11} + \dot{E}_{15}) \tag{16}$$

Exergy efficiency of the boiler subsystem is the ratio of utilized exergy to available exergy. The exergy interaction of the air cooled condenser section is neglected.

The overall exergy efficiency of the whole system is the ratio of the net power output of the plant to the available exergy into the boiler sub system. The net power output of the plant is the difference between the power generated by the alternator and the power consumed by the auxiliary systems.

RESULTS AND DISCUSSION

From the energy analysis made by the study, it has been found that the boiler system utilizes 88.41% of the total energy supplied to the plant and nearly 6.7% of heat is carried by the exhaust gas. The Fig. 3 shows the amount of energy available and the energy utilized by the each power plant component. The heat loss in condenser is estimated to be nearly 51.16% of the energy admitted to the boiler. The overall energy efficiency of the plant is 31.15%. All the components of the plant are found to have the energy efficiency more than 90%.

Hence, the thermodynamic first law analysis need not be used to point the prospective areas for improving the efficiency of the electric power generation. But the thermodynamic second law analysis serves to identify the exact power production inefficiencies which exist all over the power plant components. The comparisons of exergy losses between the components of the plant are shown in Fig. 4.

It has been noticed that the maximum exergy losses occur in the furnace combustion chamber i.e., 54.1% of the exergy supplied to CFB boiler. This loss constitutes 74% of the total loss of exergy of the plant. The next maximum exergy loss occurs in turbine and is around 8.3% of total exergy supplied to the plant and is around 11% of the total loss of exergy of the plant. The maximum loss of

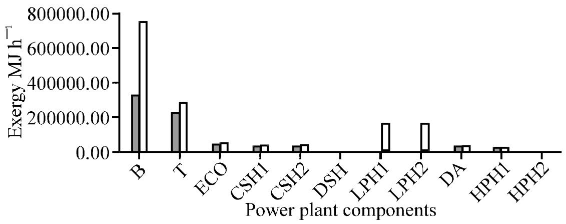

Fig. 3: Exergy values of various components of CFB power plant

exergy that occurs in boiler combustion chamber is due to irreversibility of the combustion process. The plant exergy destruction is estimated at around 69.76% of the total exergy into the plant, it is 3.24% less than the results of (Ganapathy *et al*., 2009) 50 MW using lignite as fuel.

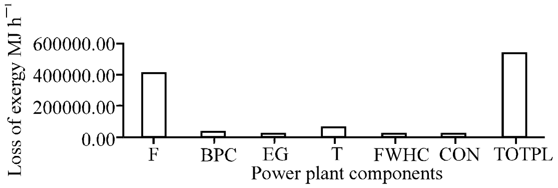

Fig. 4: Exergy loss of various components of the CFB power plant, F: Furnace, BPC: Back pass components, EG: Exhaust gas, FWHC: Feed water heating circuit, CON: Condenser, TOTPL: Total plant

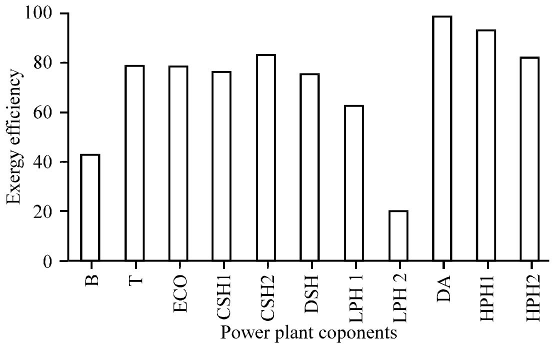

Fig. 5: Second law efficiency of various components of the CFB power plant

The second law efficiency of the plant components are shown in Fig. 5. It is concluded that the second law efficiency of the components of the turbine, economiser, convective super heaters 1 and 2 and high pressure feed water heaters 1 and 2 are around 75%. The loss of exergy of the power plant components are shown in Fig. 6. It is clearthat nearly three fourth of exergy losses occur in furnace of the boiler system. The exergy efficiency of the boiler system is estimated to be 43.09% with respect to total exergy supplied to the plant. The overall exergy efficiency of the plant is evaluated as 29.29%. Ganapathy *et al.* (2009) evaluated the exergy efficiency of their power plant as 27%, but in this present work is higher. Figure 7 and 8 show the exergy flow through the plant components (MJ h^{-1}).

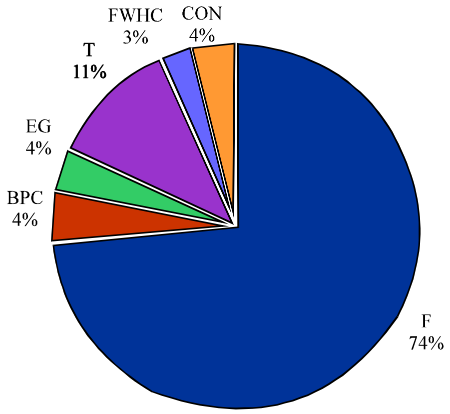

Fig. 6: Exergy loss percentage of various components of CFB boiler

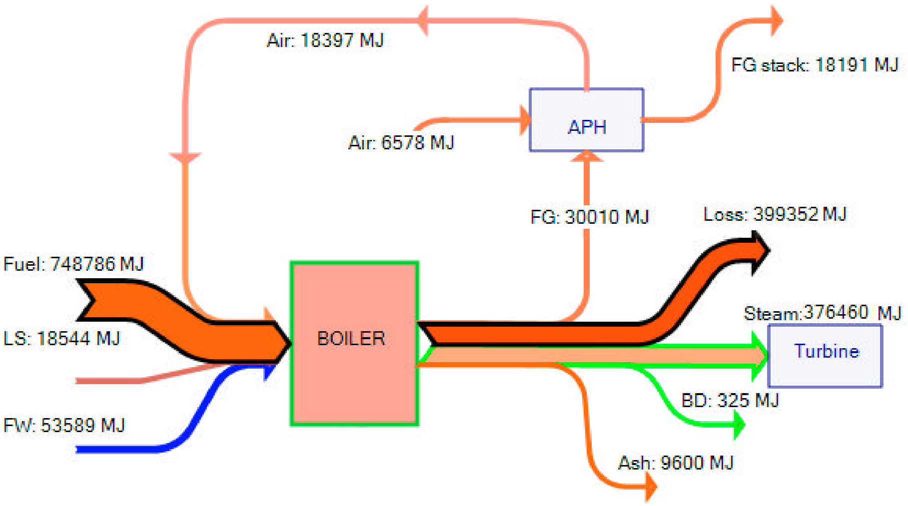

Fig. 7: Shankey diagram of exergy flow across CFB boiler, APH: Air pre heater

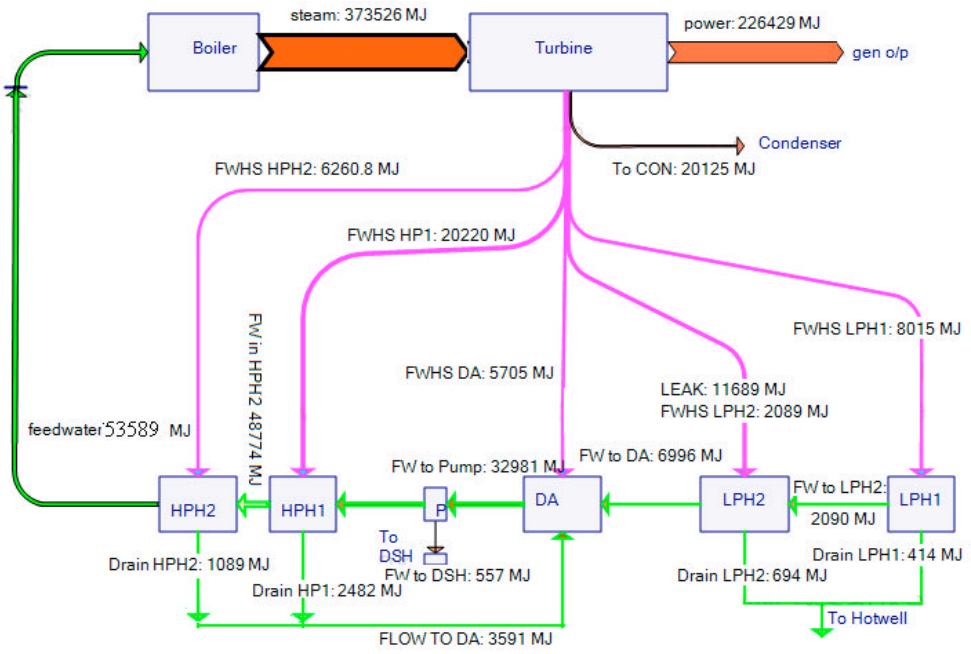

Fig. 8: Shankey diagram of exergy flow in turbine and feed water heaters, P: Pump, FW: Feed water

CONCLUSION

Thermodynamic analysis of a 63 MWe CFB boiler has been performed using first and second laws. The energy input, output and losses at various control volumes of the plant have been estimated. From the exergy analysis, the exergy loss is found to be more than 51% in the furnace. The energy and exergy efficiencies of the overall plant are 31.15 and 29.29%. It can be concluded that the exergy analysis locates the system or components where the necessary attention has to be paid to improve the performance of the plant. It is suggested that more attention is required towards the improvement and utilization of the exergy loss in the combustion system. Exergoeconamics studies can be useful for effective operation of the power plant.

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