THE INFLUENCE OF OPERATIONAL PARAMETERS ON BOILER PERFORMANCE: AN EXERGY ANALYSIS

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ABSTRACT

Mostly the performance of pulverised fuel fired boiler depends on the combustion process and the emission level in the boiler. Combustion improvement offers the greatest potential for economic savings regarding the operation of industrial boilers and furnaces. In practice, combustion processes are never ideal, and additional or excess air must be supplied to completely burn the fuel. Thus the combustion process is affected by the amount of excess air required for complete combustion. Inadequate amount of excess air results in unburned combustibles, soot deposition and higher emission level, while too much result in heat lost due to the increased flue gas flow and thus reduces the overall boiler fuel to steam efficiency. This paper deals with the application of energy and exergy to evaluate the performance of a 500 MW pulverized coal fired boiler with varying excess air and unburnt carbon (UBC) percentage. The results of energy and exergy efficiencies of boiler at operating condition are found to be 85.77 % and 41.27 %, whereas in combustion chamber energy and exergy efficiency are found to be 99.4% and 63.57 % respectively. With 0.5 % increase in excess O2 % caused 0.65 % decrease in combustion exergy efficiency and 0.47 % boiler exergy efficiency furthermore with increase in UBC percentage both the energy and exergy efficiency reduces.

KEYWORDS: *Excess air, Energy, Exergy, Combustion, Unburnt Carbon*

I. INTRODUCTION

The efficiency of coal fired power plant boiler is affected by both the operational mode and the operating parameters that influence boiler performance. Operating the boiler with an optimum amount of excess air will minimize heat loss up the stack and improve combustion efficiency. Combustion efficiency is a measure of how effectively the heat content of a fuel is transferred into usable heat. The stack temperature and flue gas oxygen (or carbon dioxide) concentrations are primary indicators of combustion efficiency. Given complete mixing, a precise or stoichiometric amount of air is required to completely react with a given quantity of fuel. In practice, combustion conditions are never ideal, and additional or "excess" air must be supplied to completely burn the fuel. The correct amount of excess air is determined from analyzing flue gas oxygen or carbon dioxide concentrations. Inadequate excess air results in unburned combustibles while too much result in heat lost due to the increased flue gas flow thus lowering the overall boiler fuel-to-steam efficiency. Mostly the thermal efficiency of boiler is evaluated based on first law (energy) analysis but it unable to produce the details of quality aspect of energy where as from exergy analysis it is known that energy losses of boilers and furnaces are much higher than the thermal efficiencies. 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. This method of analysis can able to determine magnitudes, location and cause of irreversibility in the boiler. Hence, a combination of exergetic and energetic analysis can give complete depiction of system characteristics [1-3].

Rosen [2] has compared the performance of operating coal fired and nuclear steam power plant located in Canada of unit size approximately 500MWe using a process simulator. Hasanuzzaman et al. [4] presented the energy, exergy analysis and energy savings of a fire tube boiler. In an another study Hasanuzzaman et al. [5] presented the energy, exergy and economic analysis of an annealing furnace. The result revels that the exergy efficiency of the combustor is 47.1 % and the overall energy and exergy efficiencies of furnace are found to be 16.7 % and 7.3 % respectively. Pattanayak and Ayyagari [6] determine the energy and exergy analysis in a 500 MW coal fired boiler in design and off design condition. The results of energy and exergy efficiencies of boiler at design condition are found to be 85.54 % and 41.81 %, whereas at 80 % and 60% off design case energy efficiency increases to 85.77% and 85.71% respectively. The exergy efficiency at off design condition is 41.64% and 41.59% respectively. In an another paper Pattanayak [7] discussed the energy and exergy analysis of a pulverized coal fired boiler in steady state and the energy and exergy efficiencies of boiler are found to be 84.39 % and 42.09 %. Baojun et al. [8] investigate the combustion characteristics of pulverized coal in air and O_2/CO_2. In another study Baojun et al. [9] analyzed the effects of coal particle size on combustion characteristics under O_2/N_2 and O_2/CO_2 atmospheres were compared using thermo-gravimetric analysis method. Saidur et al. [10] performed economic analysis of industrial boiler based on energy and exergy analysis and the energy and exergy efficiencies are found to be 72.46% and 24.89%, respectively. Hasan [11] discussed the thermodynamic inefficiencies of coal fired thermal power plant in Turkey by compairing each plant to other. Aljundi [12] presented the energy and exergy analysis of a steam power plant in Jordan. Rashad and Maihy [13] presented energy and exergy analysis of Shobra El-Khima power plant in Cairo, Egypt at different load condition of the plant. Kwak et al. [14] presented exergetic and thermo-economic analyses for the 500 MW combined cycle plant by applying mass and energy conservation laws to each components of the power plant. Sciubba et al. [15] presented a brief critical and analytical account of the development of the concept of exergy analysis in the fields of energy conversion, process optimization, diagnostics and management, analysis of Very Large Complex Systems (VLCS), information technology and sustainability analysis. Maghsoudi et al. [16] determines the energy and exergy analysis of 250 MW Shahid Rajaee steam power plant and the result revels that the exergy destruction in boiler is 309.1 MW with exergy efficiency of 46.24 %. Sengupta et al. [17] presented the exergy analysis using the design data from a 210 MW coal fired thermal power plant. Vosough [18] presented the useful concept of energy and exergy utilization in a boiler system and the result revels that the energy and exergy efficiencies of boiler system are 89.21% and 45.48%. 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 [19]. Jamil [20] studied thermodynamics performance of Ghazlan power plant in Saudi Arabia where mixture of methane, ethane and propane were used as fuels. The result shows that exergy efficiency in the boiler furnace was about 18.88% and losses in the boiler heat exchanger found to be 43.4%. Gonzalez [21] studied the improvement of boiler performance by using economizer model. The study describes the uses of hot gas recovery system to improve the boiler performance. Murehwa et al. [22] identify major energy loss areas in Zimbabwe's thermal power stations and develop a plan to reduce them using energy and exergy analysis as the tools. Ehsan and Yilmazoglu [23] presented to design a 240 MWel thermal power plant (TPP) to be operated with ten different types of Turkish lignite and fulfil an exergy analysis including the determination and comparison of the performance for each type of lignite. Jianqiang et al. [24] presented an exergy efficiency analysis in a 300 MW pulverized coal fired boiler at different O_2 and CO_2. The result revels that boiler efficiency can be improved by applying O_2/CO_2 combustion technology. Som and Datta [25] investigate the thermodynamic irreversibility and exergy analysis in combustion process using gaseous, liquid and solid fuels. The study reveals that the major source of irreversibility is the internal thermal energy exchange associated with high temperature gradients caused by heat release in combustion reactions.

This study deals with the application of energy and exergy to analyze an industrial utility boiler system of coal fired thermal power plant. The energy and exergy efficiency of the boiler have been determined by combustion analysis. The analyses have been performed by varying the excess air percentage and unburnt percentage in flue gas to evaluate the energy and exergy efficiency of combustion system and overall boiler. The paper is organized as follows: Section II describes the boiler system used for this study and its main parameters; Section III will address the formulation for energy and exergy analysis in boiler system; Section IV presents result and discussion on the influence of operation parameters on boiler performance. Section V summarizes the current work and section VI points out future work.

II. BOILER DESCRIPTION

The boiler system in consideration is a 500MW pulverized coal fired utility boiler. Schematic diagram of the boiler is shown in Figure 1. The boiler is of drum type with steam reheating. It has subcritical pressure of 170 kg/cm^2 and forced circulation. It is fired with bituminous coal with tangentially corner fired combustion. There are total 8 numbers of Horizontal double ended ball mills having top 6 mills in operation during design condition (E-K). Mill outlet temperature varies in a range of 66-90 ºC. Capacity of each mill is 78 t/h for coal with HGI 50, 70% through 200 mesh. At design condition boiler produces 1507.425 t/h steam with temperature of 540 º C and pressure of 170 kg/cm^2. 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 gross calorific value (GCV) of the coal varies from 16747.2 to 10467 kJ/kg. In the period used for analysis in this study, the GCV of the coal is approximately constant, i.e. 11706.3 kJ/kg. Operating parameters used for this study of the boiler is depicted in Table 1.

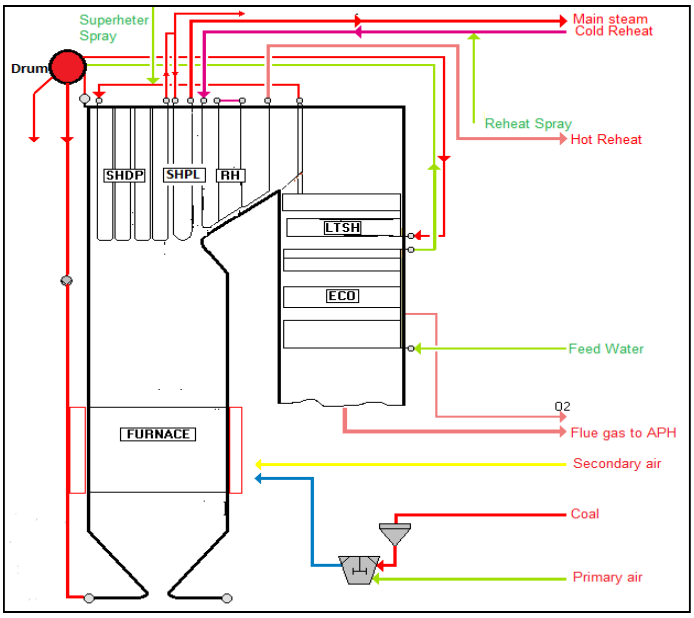


Figure 1. Schematic diagram of boiler

Table 1. Main operating parameters

Description	Unit	Operating Parameters
Gross load	MW	507
Main steam pressure / temperature	kg/cm^2 / °C	170/542
Main steam flow	t/h	1550
Reheat steam pressure/ temperature	kg/cm^2 / °C	40/533
Super heater / Reheater spray flow	t/h	9/17
Feed water temperature economizer inlet	°C	215
Flue gas temperature economizer outlet	°C	355
Flue gas temperature air-heater outlet	°C	150
Coal flow	t/h	453.418
Oxygen air heater Inlet	%	3.0
Unburnt carbon in fly ash	%	0.23
Unburnt carbon in bottom ash	%	1.09
GCV	kJ/kg	11706.3

III. ENERGY AND EXERGY ANALYSIS

The combustion chamber in a boiler is usually well insulated that causes heat dissipation to the surrounding almost zero. It also as no involvement to do any kind of work. Also, the kinetic and potential energies of the fluid streams are usually negligible. The three essential components of combustion are fuel, oxygen, and heat. A combustion calculation is done for determining the flue gas composition and the adiabatic combustion temperature. The flue gas temperatures across each heating surfaces are calculated by the thermodynamic model based on the measured flue gas temperature at economizer outlet and considering measured temperatures of water steam side across all heating surfaces. Mass and energy balance for flow process in a controlled volume system with negligible of potential and kinetic energy changes are as shown in Eqs. (1) & (2) [26, 27].

$$\sum \dot{m}_i = \sum \dot{m}_e \tag{1}$$

$$\sum E_i = \sum E_e \tag{2}$$

Where $\dot{m}$ is the mass flow rate, E is the rate of energy transfer to the system as heat and the subscripts i and e denote inlets and outlets, respectively.

Taking mass flow rate for fuel as $\dot{m}_f$, mass flow rate for air as $\dot{m}_a$, and mass flow rate for products as $\dot{m}_p$, energy balance can be calculated using Eq. (3):

$$\dot{m}_f h_f + \dot{m}_a h_a - \dot{m}_p h_p = 0 \tag{3}$$

where, h_f=specific enthalpy of fuel in kJ/kg, h_a=specific enthalpy of air in kJ/kg, h_p=specific enthalpy of hot products of combustion in kJ/kg.

The energy efficiency of system and component is defined as the ratio of energy in products to total energy input to system or component. Mathematically it can be represented as shown in Eq. (4),

$$\eta = \frac{\text{Energy in product outputs}}{\text{Total energy input}} \tag{4}$$

Exergy is always evaluated with respect to a reference environment. The reference environment is in stable equilibrium, acts as an infinite system, and is a sink or source for heat and materials, and experience only internal reversible processes in which its intensive properties (i.e. temperature T_0, pressure P_0 remains constant). The kinetic and the potential exergy are neglected. The exergy balance calculations have been established using methodology developed by Aljundi, Dincer and Rosen [12, 27, 28] as shown in Eqs. (5) and (6).

$$\dot{X}_{in} - \dot{X}_{out} - \dot{X}_{destroyed} = 0 \tag{5}$$

$$(\dot{m}_f e_f + \dot{m}_a e_a) - \dot{m}_p e_p - I_c = 0 \tag{6}$$

where, I_c is exergy destruction, e_a, e_f and e_p are specific exergy of air, fuel and products respectively.

Total exergy $\dot{X}$ can be determined using Eq. (7) as,

$$\dot{X} = \dot{m}\ e = \dot{m}\ [h - h_0 - T_0(s - s_0)] \tag{7}$$

where h and s denote the specific enthalpy and specific entropy respectively. e is specific exergy in kJ/kg . The subscript 0 denotes the restricted dead state.

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 [28-30] is represented in Eq. (8).

$$\Psi = \frac{\text{Exergy in product outputs}}{\text{Total exergy input}} \tag{8}$$

IV. RESULTS AND DISCUSSION

Figure 2 displays the schematic diagram of boiler divided into heat exchanger and combustor. By employing mass and energy balances a first law analysis was performed across the boiler based on the parameters stated in Table 1 at operating conditions. Total air required for combustion is controlled to maintain the O_2 % (oxygen, 3.62%) at air heater inlet. 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. Boiler energy loss was evaluated based on indirect method (loss method). It was found that the maximum energy loss occurs due to hydrogen in fuel followed by loss due to dry flue gas. The elemental composition and the HHV of fuel have been kept constant. The radiation loss is derived based on ABMA radiation loss chart. For exergy calculation dead state condition is considered as To= 33 ºC and P_o= 1.013 bar.

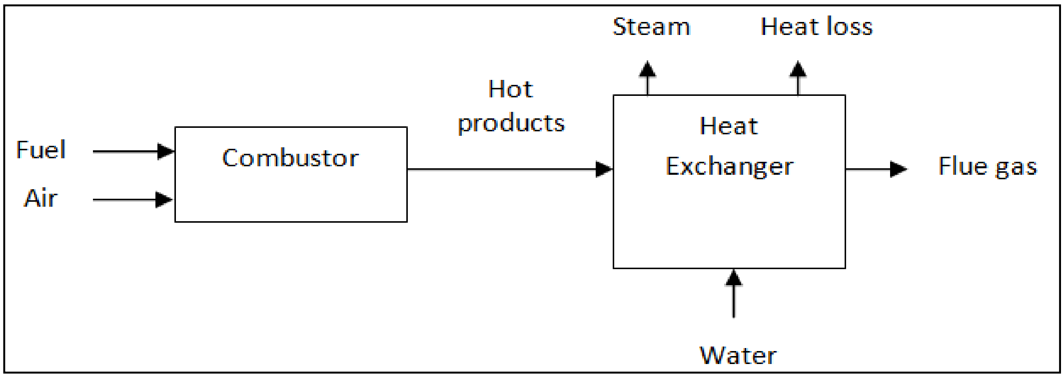


Figure 2. Schematic diagram of combustor and heat exchanger in a boiler [31]

Measuring oxygen alone is insufficient for combustion efficiency purposes because of ever-changing boiler conditions that affect the amount of combustibles in the flue gas. Similarly, measuring combustibles alone doesn't provide sufficient detail to make continuous adjustments to the process. To maintain the highest combustion efficiency level on a continuous basis, both oxygen and combustibles in the flue gas need to be measured. In the furnace combustion chamber, only fuel is used as an energy supply. According to the thermodynamic analysis in this study, air is also included in the energy balancing. Input energy in the combustion system is about 1640449.52 kJ/s. The combustion energy efficiency is found to be 99.4 % and exergetic efficiency is 63.57% respectively. Whereas the overall boiler section efficiency is evaluated as 85.77% and exergy efficiency of boiler is found as 41.27 % with excess O_2 as 3% and unburnt carbon (UBC) in fly ash (FA) and bottom ash (BA) is measured as 0.23% and 1.09% respectively. In the study by Baojun et al. [9] the result revels that a noticeable difference between O_2/N_2 and O_2/CO_2 atmospheres, at a low O_2 concentration and high O_2 concentration. Also at different O_2 concentrations fluctuation effect in combustion chamber is different. Under the O_2/CO_2 atmosphere, the influence of the particle size on coal combustion is different from that under O_2/N_2 condition. Saidur [32] found that flue gas energy savings for oxygen trim system is 549,310,130 GJ for 16.9% of excess air reduction with payback period less than a day.

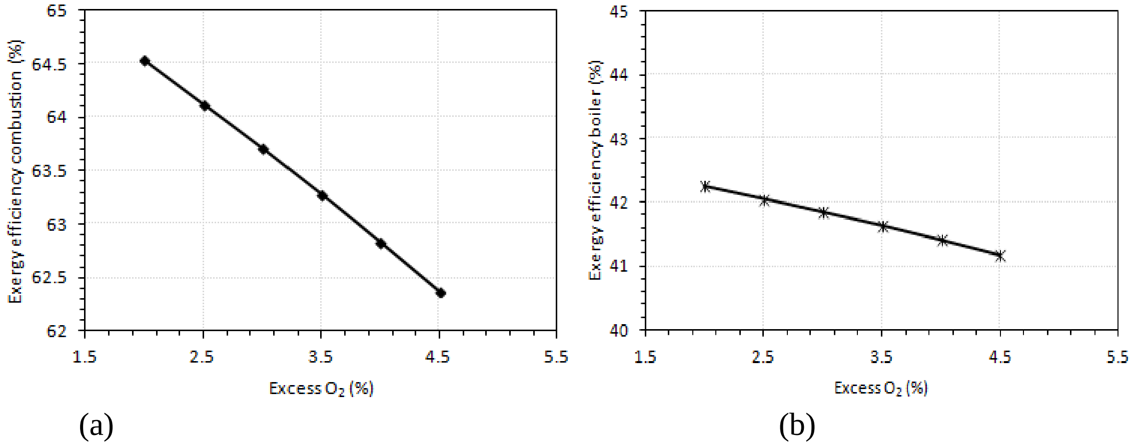
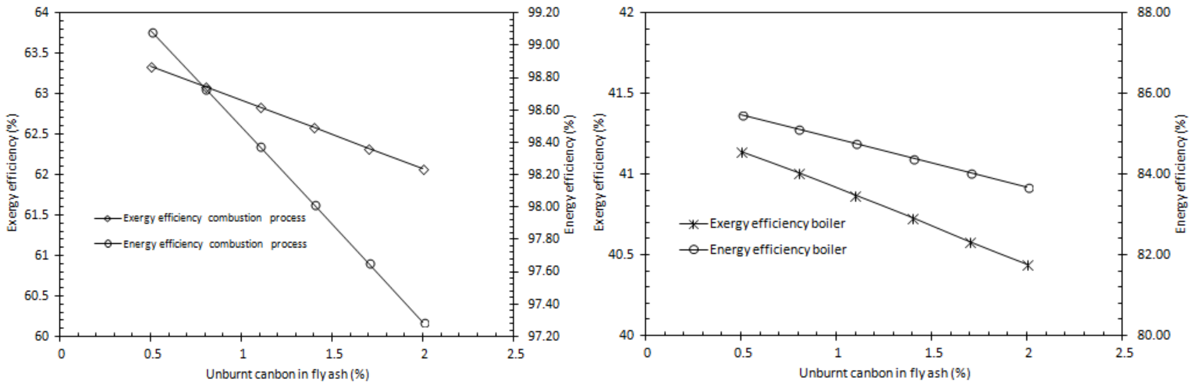


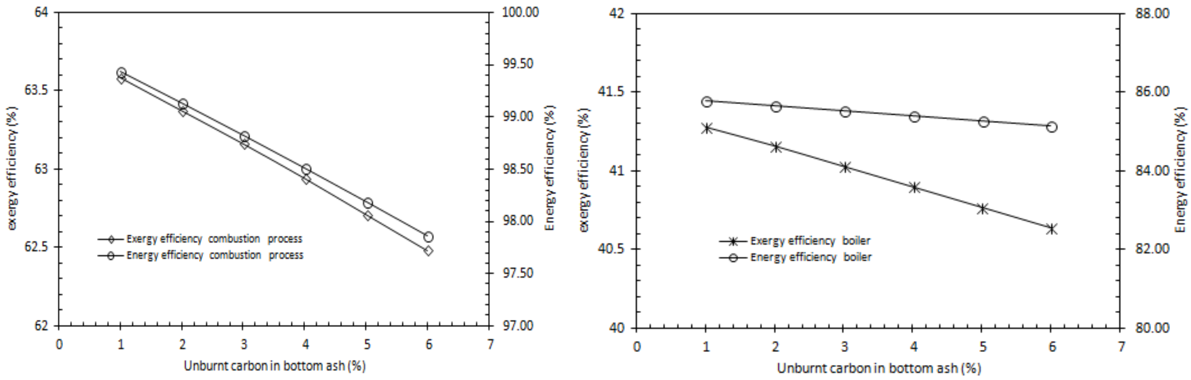
Figure 3. Variation of exergy efficiency with excess O_2 (a) combustion process, (b) overall boiler

With boiler combustion, if some excess air is not added to the combustion process, unburned fuel, soot, smoke, and carbon monoxide exhaust will create additional emissions and surface fouling. From a safety standpoint, properly controlling excess air reduces flame instability and other boiler hazards. Even though excess air is needed from a practical standpoint, too much excess air can lower boiler efficiency. Figure 3 shows the impact of excess O_2 on exergetic efficiency of combustion process and overall boiler performance. The more excess air is used, the greater will be the weight of flue gas per unit weight of fuel burnt. This increases the heat loss because air enters the burners at ambient temperature and leaves the boiler high temperature taking a considerable amount of useful heat with it. As excess O_2 increases from 2 % to 4.5 % boiler exergetic efficiency reduced from 42.27 % to 41.18 %. Whereas exergy efficiency of combustion is reduced from 64.54 to 62.38 %. With 0.5 % increase in O_2 % caused 0.65 % decrease in combustion exergy efficiency and 0.47 % boiler exergy efficiency. Figure 4 and Figure 5 represent the variation of energy and exergy efficiency of combustion chamber and overall boiler with varying UBC in BA and FA. UBC in BA and FA can formed because of many reasons such as if boiler is fired with higher excess air and mill fineness is not proper. When the particle size will more than the desired size this leads to high UBC in BA and incomplete combustion will leads to UBC in FA. With increase in UBC percentage both the energy and exergy efficiency reduces. With 0.3 % increase in UBC in FA the boiler efficiency reduced to 0.4% and the exergetic efficiency of boiler reduced to 0.3%, where as in combustion chamber the energy as well as exergy efficiency reduced approximately 0.35 % for same steam output from the boiler. Combustion efficiency is maximized when the correct amount of excess air is supplied so that the sum of energy losses from both unburned fuel loss and flue gas heat loss is minimized. By measuring the concentrations of oxygen and combustibles, both unburned fuel loss and flue gas heat loss can be minimized. Yuan et al. [33] found out that combustion in an O_2/CO_2 atmosphere produces more fine ash particles than O_2/N_2 atmosphere at the same oxygen level. Increasing the O_2 concentration decreases the amount of the fine ash particles in both atmospheres.



(a) (b)

Figure 4. Variation of energy and exergy efficiency with UBC in FA (a) combustion process, (b) overall boiler



(a) (b)

Figure 5. Variation of energy and exergy efficiency with UBC in BA (a) combustion process, (b) overall boiler

V. CONCLUSION

In this study energy and exergy analysis of operating condition of a 500MW pulverized coal fired boiler has been carried out based on mass, energy and exergy balance equations. Main focus in this study was to evaluate performance of combustion chamber and overall boiler with variation of percentage of excess O_2 and unburnt carbon in fly ash and bottom ash. It has been found that maximum exergy destruction occurs due to combustion process. It has also been found that both energy and exergy efficiency decreases significantly with increase in excess O_2. Also presence of unburnt further deteriorates the boiler performance for the same output of boiler. The energy and exergy efficiencies of boiler at operating condition are found to be 85.77 % and 41.27 %, whereas in combustion chamber energy and exergy efficiency is found to be 99.4% and 63.57 % respectively. With 0.5 % increase in O2 % caused 0.65 % decrease in combustion exergy efficiency and 0.47 % boiler exergy efficiency furthermore with increase in UBC percentage both the energy and exergy efficiency reduces. With 0.3 % increase in UBC in FA the boiler efficiency reduced to 0.4% and the exergetic efficiency of boiler reduced to 0.3%, where as in combustion chamber the energy as well as exergy efficiency reduced approximately 0.35 % for same steam output from the boiler.

VI. FUTURE WORK

This study deals with the application of energy and exergy to evaluate the performance of a 500 MW pulverized coal fired boiler with varying excess air and unburnt carbon (UBC) percentage. Main focus in this study was to evaluate performance of combustion chamber and overall boiler with variation of excess O_2 and unburnt carbon in fly ash and bottom ash. For future studies a detailed parametric study of boiler can be performed in conjunction with optimization function in order to optimize the heat rate and reduce the emission level from the boiler. The study should determine the set points for the operating variables based on the exergetic cost optimization function.

REFERENCES

[1] G. Naterer, P. Regulagadda and I. Dincer, "Exergy analysis of a thermal power plant with measured boiler and turbine losses," *Applied Thermal Engineering,* vol. 30, pp. 970-6, 2010.

[2] M. Rosen, "Energy and exergy based comparision of coal fired and nuclear steam power plants," *International Journal of Exergy,* vol. 3, pp. 180-92, 2001.

[3] T. Ganapathy, N. Alagumurthi, R. Gakkhar and K. Murugesan, "Exergy Analysis of operating lignite fired thermal power plant," *Journal of Engineering Science and Technology Review,* vol. 2, pp. 123-130, 2009.

[4] M. Hasanuzzaman, N. Rahim and R. Saidur, "Analysis of energy, exergy and energy savings of a fire tube boiler," in *IEEE First conference on Clean energy and Technology CET*, 2011.

[5] M. Hasanuzzaman, R. Saidur and N. A. Rahim, "Energy, exergy and economic analysis of an annealing Furnace," *International Journal of the Physical Sciences,* vol. 6, no. 6, pp. 1257-1266, 2011.

[6] L. Pattanayak and S. K. Ayyagari, "Use of Energy and Exergy Analysis in Coal Fired Boiler," *International Journal of Multidisciplinary Sciences and Engineering,* vol. 5, no. 3, pp. 17-23, 2014.

[7] L. Pattanayak, "Steady State Energy and Exergy Analysis of Pulverized Coal Fired Boiler," *International Journal of Engineering Research & Technology (IJERT),* vol. 3, no. 2, pp. 679-683, 2014.

[8] B. Yi, L. Zhang, F. Huang, Z. Luo and C. Zheng, "Combustion Characteristics of Pulverized Coal with Different Particle Sizes in O2/CO2 Atmosphere," *Journal of Combustion Science and Technology,* no. 3, pp. 248-253, 2013.

[9] B. Yi, L. Zhang, Z. Mao, F. Huang and C. Zheng, "Effect of the particle size on combustion characteristics of pulverized coal in an O2/CO2 atmosphere," *Fuel Processing Technology,* vol. 128, p. 17–27, 2014.

[10] R. Saidur, J. Ahamed and H. Masjuki, "Energy, exergy and economic analysis of industrial boilers," *Energy Policy,* vol. 38, pp. 2188-2197, 2010.

[11] H. Hasan, V. Ali, Burhanettin, D. Ahmet, H. Suleyman, S. Bahri, T. Ismail, G. Cengiz and A. Selcuk, "Comparative Energetic and exergetic performance analysis for coal fired thermal power plants in Turkay," *International Journal of Thermal Sciences,* pp. 48:2179-86, 2009.

[12] I. H. Aljundi, "Energy and Exergy Analysis of a steam power plant in Jordan," *Applied Thermal Engineering,* pp. 29:324-8, 2009.

[13] A. Rashad, Maihy and A. El, "Energy and Exergy Analysis of a Steam Power Plant in Egypt," in *13th International Conference on Aerospace Sciences & Aviation Technology, ASAT- 13,*, 2009.

[14] H. Kwak, D. Kim and J. S. Jeon, "Exergetic and thermo-economic analyses of power plants," *Energy,* vol. 28, p. 343–360, 2003.

[15] E. Sciubba and G. Wall, "A brief Commented History of Exergy From the Beginnings to 2004," *Int. J. of Thermodynamics,* vol. 10, no. 1, pp. 1-26, 2007.

[16] K. Maghsoudi, A. Mehrpanahi and M. Tabaraki, "Energy and Exergy Analysis of 250MW Steam Power Plant," *Switzerland Research Park Journal,* vol. 102, no. 11, pp. 1469-1476, January 2013.

[17] S. Sengupta, S. D. Gupta and A. Datta, "Exergy analysis of a 210 MW thermal power plant cycle at different operating conditions," in *Proceedings of the 18th National and 7th ISHMT-ASME Heat and Mass Transfer Conference*, 2006.

[18] V. Amir, "Improving Steam Power PLant Efficiency Through Exergy Analysis: Ambient Temperature," in *2nd International Conference on Mechanical, Production and Automobile Engineering (ICMPAE'2012)*, Singapore, 2012.

[19] M. Kanoglu, I. Dincer and M. Rosen, "Understanding energy and exergy efficiencies for improved energy management in power plants," *EnergyPolicy*, vol. 35, p. 3967–3978, 2007.

[20] J. Jamil, "Energy and Exergy Analysis of Ghazlan Power Plant.," in *A Masters Thesis*, Saudi Arabia, Faculty o fCollege of Graduate Studies, King Fahad University of Petrolium and Minerals., 1994.

[21] M. Gonzalez, "Improved Boiler performance through thermodynamic modeling," in *A MaserThesis*, USA, Texas A and M University,Kingsville, 1998.

[22] G. Murehwa, D. Zimwara, W. Tumbudzuku and S. Mhlanga, "Energy Efficiency Improvement in Thermal Power Plants," *International Journal of Innovative Technology and Exploring Engineering (IJITEE),* vol. 2, no. 1, pp. 20-25, December 2012.

[23] A. Ehsana and M. Z. Yilmazoglub, "Design and Exergy Analysis of a Thermal Power Plant Using Different Types of Turkish Lignite," *International Journal of Thermodynamics (IJoT),* vol. 14, no. 3, pp. 125-133, 2011.

[24] G. Jianqiang, H. Zhifu and Y. Xianglei, "Exergy Efficiency Analysis of a Pulverized Coal-fired Boiler under Different O2/CO2 Atmospheres," *Power Engineering,* no. 12, pp. 899-903, 2011 .

[25] S. Som and A. Datta, "Thermodynamic irreversibilities and exergy balance in combustion processes," *Progress in Energy and Combustion Science,* vol. 34, no. 3, p. 351–376, 2008.

[26] A. Hepbasli and O. Akdemir, "Energy and exergy analysis of a ground source (geothermal) heat pump system," *Energy Convers. Manag.,* vol. 45, no. 5, pp. 737-753., 2004.

[27] I. Dincer and M. Rosen, "Exergy,Energy,Environment and Sustainable Development," *Elsevier*, 2007.

[28] A. Bejan and E. Mamut, "Thermodynamic Optimization of Complex Energy Systems," in *Proceedings of the NATO Advanced Study Institute*, 1998.

[29] G. Tsatsaronis and M. Winhold, "Exergoeconomic Analysis and Optimization of Energy Conversion Plants. Part I: A New General Methodology; Part II: Analysis of a Coal – Fired Steam Power Plant," *Energy,* vol. 10, no. 1, pp. 69-94, 1985.

[30] A. Bejan, G. Tsatsaronis and M. Moran, Thermal Design and Optimization, By Jhon Wiley & Sons, Inc, 1996.

[31] Y. Changel and M. Boles, Thermodynamics:AnEngineeringApproach, Fifth ed., McGrawHill,NewYork, 2006.

[32] R. Saidur, "Energy Savings and Emission Reductions In Industrial Boilers," *THERMAL SCIENCE,* vol. 15, no. 3, pp. 705-719 , 2011.

[33] Y. Chen, G. Wang and C. Sheng, "Comparison of Particle Size Evolution during Pulverized Coal Combustion in O2/CO2 and O2/N2 Atmospheres," *Energy Fuels,* vol. 28, no. 1, p. 136–145, 2014 .

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