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Comparative 3-E (Energy, Exergy & Environmental) Analysis of Oxy-Coal and Air-Coal Combustion based 500 MWe Supercritical Steam Power Plants with CO_2 Capture

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Abstract
The comparative performance study is carried out for 500 MW Supercritical (SupC) Oxy-Coal Combustion (OCC) and Air-Coal Combustion (ACC) power plants with membrane-based CO_2 capture at the fixed furnace temperature. The proposed configurations are modelled using a computer-based analysis software 'Cycle-Tempo' at different operating conditions, and the detailed thermodynamic study is done by considering Energy, Exergy, and Environmental (3-E) analysis. The result shows that the net energy and exergy efficiencies of ACC power plants with CO_2 capture are about 35.07 % and 30.88 %, respectively, which are about 6.44 % and 5.77 % points, respectively higher than that of OCC power plant. Auxiliary power consumption of OCC based power plant is almost 1.97 times more than that of the ACC based plant due to huge energy utilization in the Air Separation Unit (ASU) of OCC plant which leads to performance reduction in OCC plant. However, environmental benefit of OCC based power plant is more than that of ACC based power plant with respect to CO_2 emission. OCC plant emits about 0.164 kg/kWh of CO_2 which is approximately 16.75 times lower than the CO_2 emission in ACC based power plant. It is also analyzed that the performance of the CO_2 Capture Unit (CCU) for the OCC based plant is about 3.65 times higher than the ACC based power plant due to higher concentration of CO_2 (nearly 80.63%) in the flue gas emitting from OCC plant. The study also reveals that the auxiliary power consumption per kg of CO_2 capture of the OCC based plant is about 0.142 kWh/kg, which is approximately 0.06 times lower than the ACC based plant. The higher performance of the OCC based power plant is found at lower value of flue gas recirculation due to the fact that reduction in exergy destruction at the mixing zone of the combustor is higher than the increase in exergy destruction of the heat exchangers at higher furnace exit temperature. But the metallurgical temperature limit of boiler tube materials restricts the use of the higher value of furnace temperature. OCC based power plant with CO_2 capture can be preferred over ACC based plant with CO_2 capture due to higher environmental benefits towards mitigating CO_2, the key greenhouse gas on earth in spite of exhibiting lesser energy and exergy efficiencies.

Keywords- Air-coal combustion, CO_2 capture, Oxy-coal combustion, Supercritical, Power plant.

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1. Introduction

The growing demand for Power and Electricity reflects the development of any country. About 3,052 KWh/year is the world average per-capita electricity consumption (BP statistical review of world energy, 2017). Although India's per-capita electricity consumption is about 859 kWh/year, still it is placed among the lowest in the world, but it is the third-largest electricity generating country among the world. India has a total power generating capacity of 329 GWe with coal-based thermal power plants have a generating capacity of 59 % of the total (CEA, 2017). The environment gets adversely affected by greenhouse gases (GHG), and one of the main gases is Carbon dioxide (CO_2). India is contributing nearly 5.6 % of the total CO_2 emission in the world (BP statistical review of world energy, 2017). Coal-based power plants are the largest point source of CO_2 emission. Either of the pre-combustion, post-combustion, or oxyfuel combustion technique of capture of CO_2 can be an effective way to mitigate CO_2 (Metz and Coninck, 2005). Compared to the above CO_2 capture methods, the most promising technique seems to be oxy-fuel combustion (Buhre et al., 2005). This paper comprises a comparative performance study of Oxy-Coal Combustion (OCC), and Air-Coal Combustion (ACC) based 500MW_e Supercritical (SupC) power plants with membrane-based CO_2 capture system at the fixed furnace temperature. High Ash (HA) Indian coal is used as a fuel source. The increase in the concentration of CO_2 in the flue gas helps in capturing CO_2 easily without using solvents or membranes. Huge energy consumption of the Air Separation Unit (ASU) reduces plant efficiency (Mansouri and Mousavian, 2012). Coal has continued to be the primary energy source and will remain so for much time in the Indian power sector. Old coal-fired units of large numbers with less efficiency are still in use in India, and currently, larger capacity units (500 MW_e and above) have been developed that can accept plant load factor (PLF) of about 87.5% and plant gross efficiency of about 37.5%. The low capacity old plants (about 150 MW_e and less) was designed based on low ash coal, which operates in a quite low plant efficiency of about 30 % with PLF of about 55% (Jain, 2007). The geological conditions of the Indian mines change over the year, which causes a high ash percentage in coal. The operating parameters and equipment design are getting mismatched due to the above-said reason. The above said reason is the main factor responsible for old coal-fired power plants having lower plant efficiencies in India. Poor operation practices and natural deterioration in original equipment are the main factors for the poor performance of the plants (Asthana et al., 2006). As the existing plants still operate on Subcritical (SubC) steam parameters, their efficiency is limited. The efficiencies of the plants can be improved by switching to Supercritical (SupC) / Ultra Supercritical (USC) steam parameters (Suresh et al., 2010; Khankari and Karmakar, 2018). It is estimated that there will increase in CO_2 emission to about 3.08 BT by 2030, and the emission of CO_2 from coal-based electric plants was about 0.99BT per year (Garg and Shukla, 2009). For meeting the growing challenges of energy requirement for developing countries like India, advanced power production technologies that can give better efficiencies is of high importance. Efficiencies can be reached up to 50% by switching to the use of combined cycles rather than using conventional cycles (Enders et al., 2000). Mansouri and Mousavian (2012) showed that among the additional components of the retrofitted plant, the ASU and CCS have the largest amount of exergy destruction. Kurtulus et al. (2018) carried out the thermo economic study of a regenerative Organic Rankine Cycle (ORC) where waste heat of CO_2 compression system is used as heat source. For fulfilling the growing energy demand and safeguarding the environment, at Indian climatic conditions, the detailed thermodynamic study of the advanced power generation technologies is required. The main aim of the present work is to carry out a 3-E (Energy, Exergy, and Environment) analysis of ACC and OCC based 500 MW_e Supercritical power plants by applying High Ash (HA) Indian coal as a primary fuel source with CO_2 capture systems under Indian climatic conditions.

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2. System Description

The schematic diagram of a membrane-based CO_2 capture system ACC based 500 MW_e SupC power plants is shown in Figure 1. The plant has operating drum pressure 242.2 bar, and the main steam temperature is 537 °C and hot reheat temperature of about 565 °C with reheating of a single stage. The economizer inlet temperature of feed water is about 280 °C. There is one number of High Pressure (HP) turbine, which is of single-flow type, one number of Intermediate Pressure (IP) turbine, which is of dual-flow type, and two numbers of Low Pressure (LP) turbines which is of double-flow type in the SupC power plant. There are three numbers of HP Feed Water Heaters (FWHs) and four numbers of LP Feed Water Heaters (FWHs). To obtain a high mole purity of CO_2 the flue gas is made to pass through a Flue Gas Desulfurization (FGD) unit and Flue Gas Condenser (FGC) for separating the moisture after passing through Electrostatic Precipitator (ESP). Through four-stages of compressors with intercoolers for ease of transportation and storage, the CO_2 is compressed to about 110 bar and 35°C temperature. Figure 2 shows the schematic diagram of an OCC based 500 MW_e SupC power plant with CO_2 capture system. In Figure 2, an Air Supplying Unit (ASU) is integrated with the steam generator, which consists of two-stage air compressors with intercoolers to obtain 95% mole purity of O_2. For controlling the furnace exit temperature, flue gas recirculation technology is used, which is tapped before the membrane-based CO_2 capture system. Indian coal, which is low graded (due to high mineral matter ~ 43%) and high quality due to (low sulfur content < 0.6%), is mainly used in Indian power plants. In typical HA Indian coal, the characteristics [Suresh et al., 2010] is tabulated in Table 1. The used coal in the present work has high ash content, and its Lower Heating Value (LHV) is about 15234 kJ/Kg.

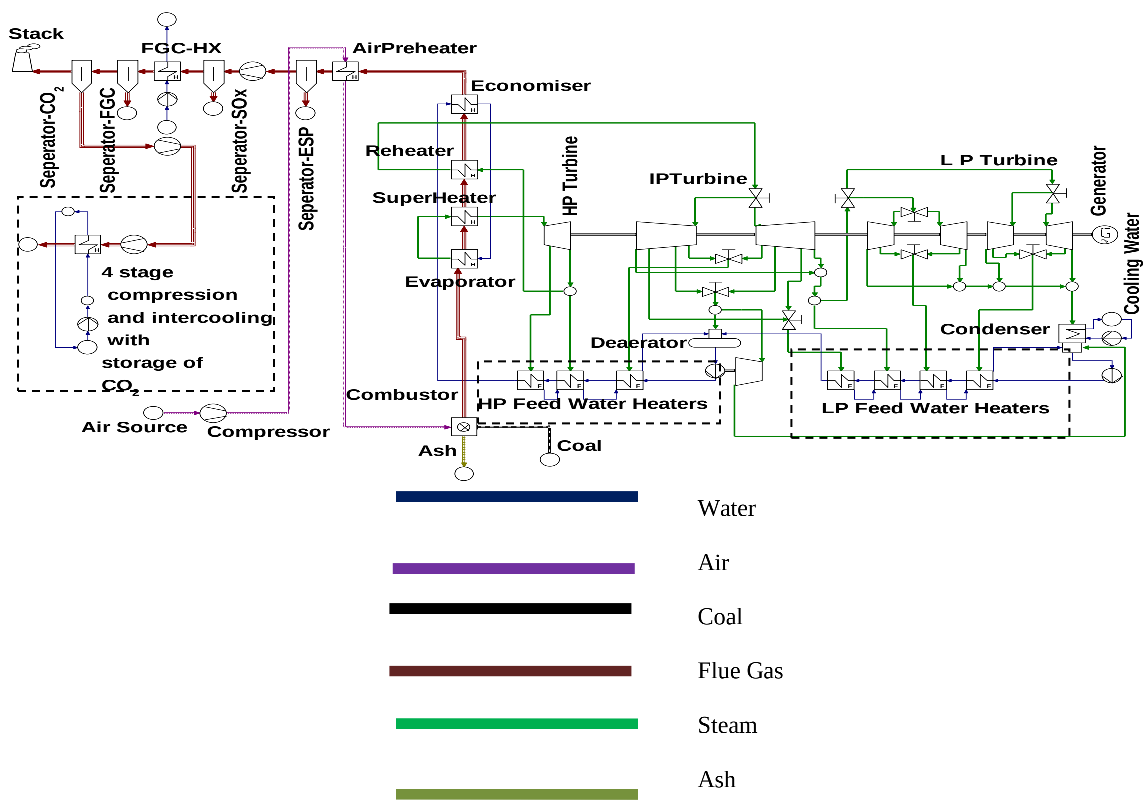

Figure 1. Schematic diagram of an ACC based 500 MW_e SupC power plant with CO_2 capture

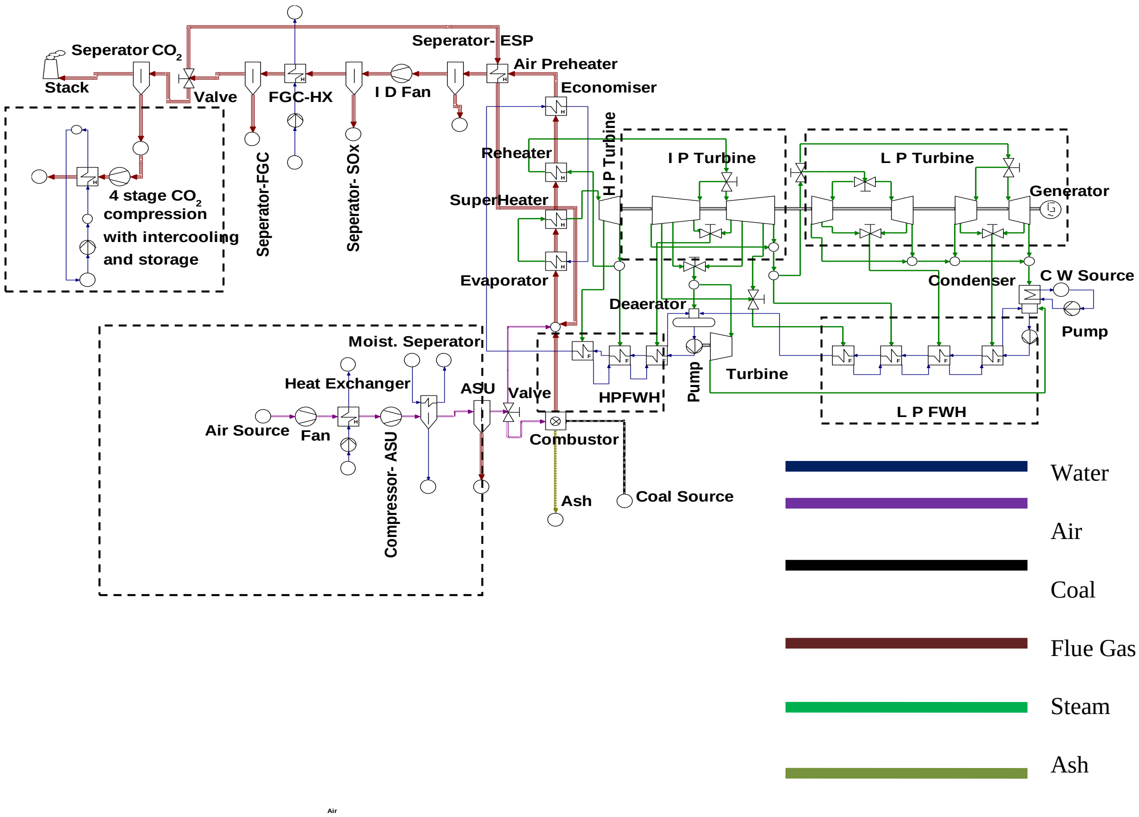

Figure 2. Schematic diagram of an OCC based 500 MW_e SupC power plant with CO_2 capture

3. Methodology

Energetic and exergetic performance analysis is carried out at steady-state conditions for the ACC and OCC based 500MW SupC steam power plants using coal firing. The proposed plants are simulated in the computer flow-sheet program 'Cycle-Tempo' (Cycle-Tempo, 2007) at different plant conditions based on conservation of mass and energy principle. The efficiency of equipment and the condition of process paths like pressure and temperature are specified as an input parameter that is required for the computer program.

Performance Parameters:
Net plant energy efficiency:

$$\eta_{plant} = \frac{\dot{W}_{TG} - \dot{p}_{aux.}}{\text{Total energy of supplied coal}} \quad (1)$$

$\dot{W}_{TG}$: Gross turbo-generator (TG) output of electric plant.

$\dot{p}_{aux.}$: Power consumed by the electrical drives of the plant.

$$\text{Total energy of supplied coal} = \dot{m}_{coal}\ LHV \quad (2)$$

Net plant energy efficiency:

$$\psi_{plant} = \frac{\dot{W}_{TG} - \dot{p}_{aux.}}{\text{Exergy supplied by coal}} \quad (3)$$

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$$\text{Total exergy of supplied coal} = \dot{m}_{coal}\ \mathcal{E}_{coal} \tag{4}$$

Specific exergy of primary fuel ($\mathcal{E}_{coal}$) is given as follows (Suresh et al., 2010):

$$\mathcal{E}_{coal} = (0.9775LHV_{coal} + 2.416) \pm (0.0065LHV_{coal} + 0.054) \tag{5}$$

$$\text{Condenser energy loss} = \dot{m}_{cw}(h_{cw}^{out} - h_{cw}^{in}) \tag{6}$$

$$\text{Condenser exergy loss} = \dot{m}_{cw}(\varepsilon_{cw}^{out} - \varepsilon_{cw}^{in}) \tag{7}$$

where, $\dot{m}_{cw}$ indicates the cooling water flow rate in the condenser.

Component's wise losses of the plant are calculated based on the energy and exergy balance of the equipment (Ray et al., 2007; Sengupta et al., 2007).

Table 1. Coal analysis report

Proximate Analysis	As-Received (wt %)	Dry Basis (wt %)
Fixed Carbon (FC)	24.00	27.27
Volatile Matter (VM)	21.00	23.86
Ash	43.00	48.87
Total Moisture (TM)	12.00	-
Ultimate Analysis		
Carbon	34.46	39.16
Hydrogen	2.43	2.76
Oxygen	6.97	7.92
Nitrogen	0.69	0.78
Sulphur	0.45	0.51
Ash	43.00	48.87
TM	12.00	-
Lower Heating Value (LHV) (MJ/kg)	13.14	15.23
Higher Heating Value (HHV) (MJ/kg)	13.96	15.83
Exergy (MJ/kg)	15.26	17.30

4. Results and Discussion

4.1 Comparative Thermodynamic Analysis of ACC and OCC Plants

The energy and exergy analysis of the ACC and OCC based 500MW SupC coal-based power plants are studied based on simulated operating data and compared with each other. From Table 2, it is found that the gross energy efficiency of the OCC based power plant with the flue gas recirculation system is lower than the ACC based power plant by about 0.747 % point due to an increase in fuel consumption by about 1.85 % point. But it is also analyzed that the gross energy efficiency of OCC based power plant without flue gas recirculation is higher than the ACC based power plant by about 0.415% point. Incorporation of flue gas recirculation for controlling the furnace exit temperature (< about 1800°C) in the OCC based power plant increases the irreversibility in the steam generator, which is observed in Table 3. In Table 2, it is also found that the stack loss of OCC based power plant is drastically reduced to about 0.291 % compared with ACC based plant (Stack loss: 1.325 %) due to the amount of dry flue gas reduction.

Table 2. Comparative energy analysis at full load

Components	ACC based power plant	OCC based power plant
Gross efficiency (%)	41.125	40.378
Condenser loss (%)	48.332	47.454
Stack loss through the chimney (%)	1.325	0.291
Bottom ash loss in the boiler (%)	0.272	0.272
Other losses (by difference) (%)	8.946	11.605

From Table 3, it is observed that the gross exergy efficiency of OCC based power plant with flue gas recirculation is lower than ACC based power plant as additional exergy destruction occurred in the steam generator due to flue gas recirculation by about 5.98 % points. Overall, both net efficiencies (i.e., energy and exergy) of ACC based 500MW SupC steam plant with CO_2 capture are about 35.07 % and 30.88 %, respectively, which is higher than OCC based plant by about 6.44 % and 5.77 %, points respectively. Moreover, the higher auxiliary power consumption of OCC based power plant, which is about 1.97 times more than ACC based power plant, causes less energetic and exergetic plant performances compared to ACC based power plant. For the environment protection, OCC based power plant may be promoted over the ACC based power plant instead of poor plant performance.

Table 3. Comparative exergy analysis at full load

Components	ACC based power plant	OCC based power plant
Gross efficiency	36.211	35.553
Condenser loss	0.605	0.594
Turbine losses	4.021	3.813
Heaters losses	0.762	0.749
Boiler loss (without combustor and flue gas mixing zone)	18.447	18.056
Combustor losses	34.165	33.448
Losses due to flue gas mixing	-	5.979
Others losses (by difference)	5.789	1.810

4.2 Environmental Impact of ACC and OCC Plants

The environmental impact of the ACC and OCC based power plants are studied, and analysis results are given in Figure 3 and Figure 4. From Figure 3, it is found that the environmental benefits of OCC based plant is more than the ACC based plant as the amount of atmospheric emission and the CO_2 captured is drastically reduced to about 0.164 kg/kWh and 0.684 kg/kWh, respectively. The amount of dry flue gas at the inlet of membrane-based CO_2 Capture Unit (CCU) of OCC based power plant is lower than the ACC based power plant. Thereby, the amount of CO_2 capture is reduced by about 0.094 kg/kWh compared to ACC based power plant. It is also analyzed that the performance of CCU for the OCC and ACC based plants is about 0.806 and 0.220 points, respectively, and the same is shown in Figure 3. The performance of CCU for the OCC based power plant is higher than the ACC based power plant, which is about 3.65 times due to the increase in the CO_2 concentration in the flue gas stream. The auxiliary power consumption of a 500MW SupC ACC based power plant with CO_2 capture system is higher than the conventional coal-based steam power plants due to the addition of electric power consumption by the compressors of CCU. From Figure 4, it is found that the auxiliary power consumption of the OCC based power plant is about 29.089 % of the total generation, which is higher than the ACC based plant due to additional power consumed by the Air Separation Unit (ASU). It is also analyzed from Figure 4 that the auxiliary power consumption per kg of CO_2 capture for the OCC based electric plant is about 0.142 kWh/kg which is about 0.06 times lower than the ACC based plant, and this reduction is due to increase the performance of CO_2 Capture Unit (CCU) of OCC based plant.

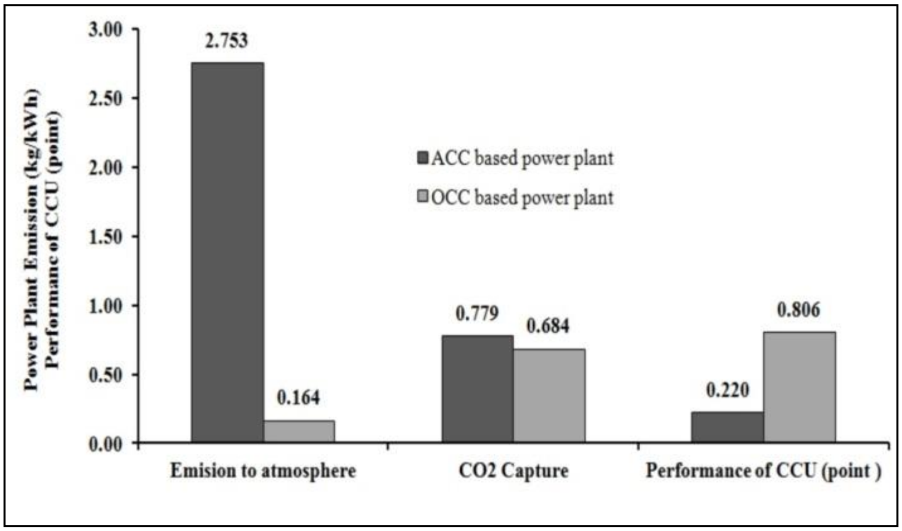

Figure 3. Environmental impact of the plants

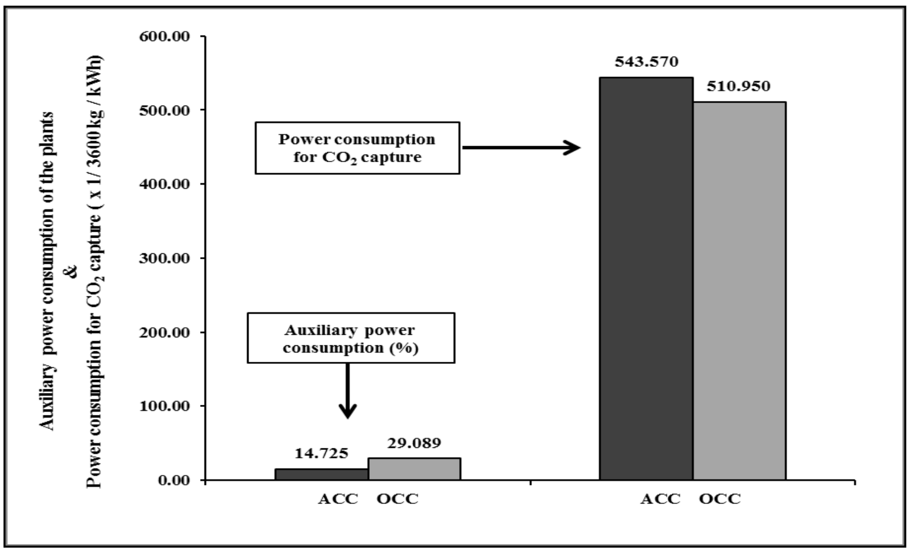

Figure 4. Comparative study on auxiliary power consumption of the plants

4.3 Effect of Flue Gas Recirculation on the Performance of OCC Based Power Plant

Flue gas recirculation is used to control the furnace exit temperature of flue gas for avoiding the NO_x formation in the boiler. As per literature, NO_x is normally formed at the combustion temperature of about 1800 °C and above (Srivastava et al., 2005). Conventional coal-based power plants are running with furnace temperature of about 1200-1400 °C, and moreover, it depends upon the coal quality. Tubes metal temperature of the steam generator can go rise above the limiting value at higher furnace temperature due to the limitation of the use of higher steam parameters and higher mass flow rate of working fluid considering maximum power generating capacity of the unit. However, the over-fired air damper is normally used to control the furnace temperature in the ACC based coal power plants. In the OCC based power plants, the furnace temperature is a too much higher value than the ACC based power plant, which is about 2300 °C.

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For avoiding the NO_x formation, tubes failure, and irreversibility in the heat exchangers, flue gas recirculation or staged combustion is used to control the furnace exit temperature and only flue gas recirculation is used in the present scope of research for the said purpose. The effect of flue gas recirculation on the performance of OCC based power plant is studied by varying the amount of flue gas recirculation, and the analysis results are given in Figures 5-6. It is found that the furnace exit temperature increases with a decrease in the amount of flue gas recirculation. From Figure 5, it is studied that the energetic and exergetic performance of the plant increase with the increase in furnace temperature resulting from less flue gas recirculation. Less amount of recirculation decreases the irreversibility of the combustion chamber during mixing and also increases the irreversibility of the heat exchangers due to higher flue gas temperature, which is shown in Figure 6. From Figure 6, it is also analyzed that the decreasing rate of irreversibility due to mixing in the combustor is higher than the increasing rate of exergy destruction in the heat exchangers and thereby, the boiler performance is improved at higher furnace temperature resulting from less recirculation of flue gas. However, there should be an optimum value of flue gas recirculation, and in the present work, the effect of flue gas recirculation on the plant performance are studied within the furnace temperature range of about 1800 °C by considering the environment protection due to NO_x formation.

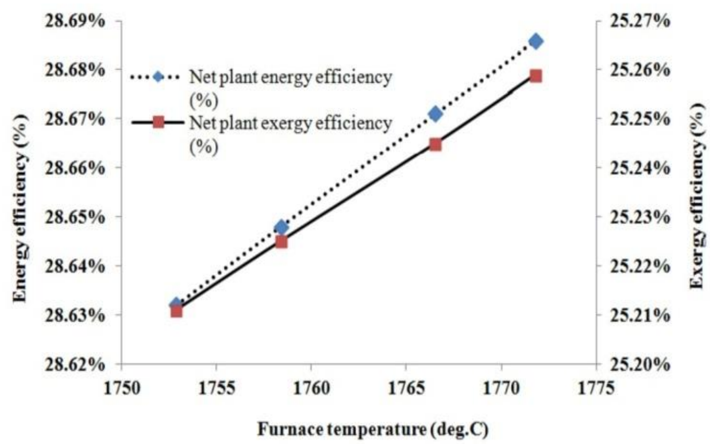

Figure 5. Flue gas recirculation vs. plant performance

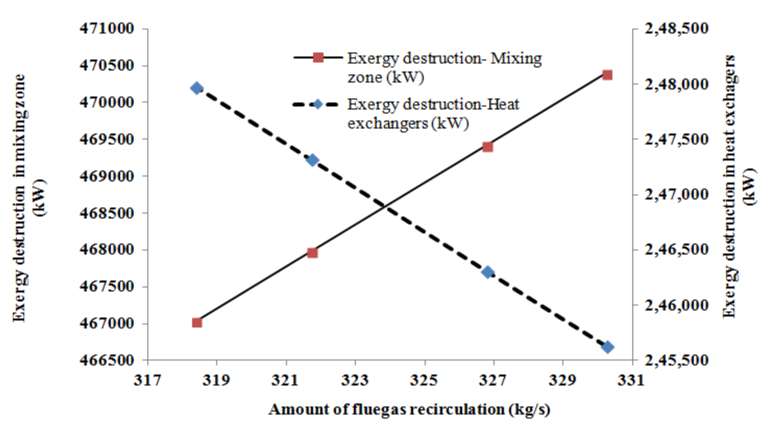

Figure 6. Flue gas recirculation vs. combustor performance

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4.4 Environmental Impact of Flue Gas Recirculation

The environmental impact of flue gas recirculation is studied, and the result is shown in Figure 7. From Figure 7, it is found that the amount of CO_2 capture reduces at higher furnace exit temperature, which is caused due to reduction of flue gas recirculation. The lower amount of flue gas recirculation improves the boiler efficiency by decreasing irreversibility in the flue gas mixing zone, and thereby, it reduces the coal requirements for the plant. As a result, environmental pollutants produced from the combustion reaction are decreased. Moreover, metal temperature limits performance improvement and environmental benefit.

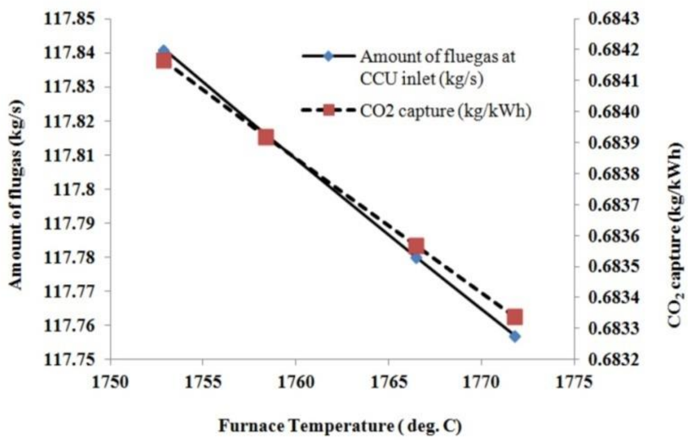

Figure 7. Environmental benefit of flue gas recirculation

5. Conclusions

The overall study concludes the following points:

- Air-Coal Combustion (ACC) based 500MW SupC steam power plant with CO_2 capture is more energy and exergy efficient compared to Oxygen-Coal Combustion (OCC) based plant by about 6.44 % and 5.77 %- points, respectively. Additional power consumption by the Air Separation Unit (ASU) and flue gas recirculation of OCC based power plant cause poor energetic and exergetic performances of the OCC plant.
- Flue gas recirculation system of the OCC based power plant causes more exergy destruction in the steam generator, which is about 5.98% of the total input.
- Less environmental effect is found in the OCC based power plant compared to the ACC based power plant as the amount of emission of CO_2 to the atmosphere of the OCC based power plant is about 0.164 kg/kWh which is about 16.75 times lower than the value observed in ACC based power plant.
- The performance of the CO_2 Capture Unit (CCU) of the OCC based plant is about 80.63%, which is about 3.65 times higher than the ACC based electric plant due to an increase in the CO_2 concentration in the flue gas stream.
- Auxiliary power consumption for the CO_2 capture of the OCC based power plant is about 0.142kWh/kg, which is about 0.06 times lower than the ACC based plant due to the higher performance of CCU.
- The higher performance of the OCC based power plant is found at lower value of flue gas recirculation due to the fact that reduction in exergy destruction at the mixing zone of the

combustor is higher than the increase in exergy destruction of the heat exchangers at higher furnace exit temperature.

Conflict of Interest

The authors declare that there is no conflict of interest.

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