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Coal Fired Power Plant with Chemical Looping Combustion

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Abstract

Around 54.7% of the total energy in India is produced from coal-fired power plants. In order to reduce the emission of CO_2 into the atmosphere from these power plants, the effluent CO_2 needs to be captured and sequestered or utilized. Chemical looping combustion (CLC) is an inherent CO_2 capture technique in which coal is reacted with oxygen in the form of metal oxide instead of air and produces concentrated CO_2 as a mixture of CO_2 and steam. CO_2 from this mixture can be easily separated and captured by condensing the steam. In this paper, a CLC integrated coal fired power plant with Fe_2O_3/Al_2O_3 as oxygen carrier was simulated using Aspen Plus ® simulation tool and the energy analysis was presented. High ash Indian coal was used in the present work. Results showed that CLC integrated coal fired power plant (CFPP) is more energy efficient with CO_2 capture.

Keywords: chemical looping combustion, power plant, coal, CO_2 capture

1. Introduction

The carbon dioxide level in the atmosphere is considered as a main environmental problem to be solved immediately. This level of carbon dioxide in the atmosphere has been increased at a tremendous pace for last decades [1]. Since carbon dioxide is the most powerful greenhouse gas [2], it causes global warming and subsequent rise in atmospheric temperature. Average global temperature is raised from14.25°C in 2000 to 14.6°C in 2010 [3].

Power and industrial sectors are the main sources of carbon dioxide [4]. Among the power plants, fossil fuel combustion accounts for about 40% of CO_2 emissions to the atmosphere. At the same time, more than 50% of the energy demand in the world is satisfied by the fossil fuels. Carbon dioxide capture and sequestration is the best method to get concentrated CO_2 stream from power plants to store it safe and permanently. There are three methods of carbon dioxide capture; pre-combustion, post-combustion and oxy-fuel combustion methods [5]. In pre- combustion method, fuel is partially oxidized to CO and H_2 (syngas), CO formed can be converted to CO_2 to capture prior to the combustion step using physical absorption, adsorption etc. Post-combustion method separates the CO_2 from the flue gas of combustion, i.e. after the combustion step. In oxy-fuel combustion method, an additional air separation unit is provided to give pure oxygen as oxidant for combustion. So the combustion products are pure CO_2 and H_2O that eases the separation of carbon dioxide. But both gas separation unit and air separation unit are energy-intensive that reduces the efficiency of the plant.

Chemical looping combustion (CLC) is a novel technology for combustion that enables the CO_2 capture unit integration in an IGCC power plant without compromising the efficiency of it as in conventional CO_2 capture methods.

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In CLC, combustion occurs in two reactors - air reactor and fuel reactor. Solid materials (metal oxides) called oxygen carriers circulate in between these reactors to transfer oxygen required for combustion. Air reactor and fuel reactor are fluidised by air and fuel respectively. Fuel takes the oxygen from metal oxides for combustion and converts the metal oxides to reduced form. Thes e reduced metal oxides are further oxidised in air reactor, as it utilise the oxygen from air to form metal oxides. This loop continues and combustion occurs in fuel reactor without any contact between air and fuel. Also the combustion products are pure CO_2 and H_2O and CO_2 can be separated by a simple condensation of water.

Reaction in air reactor is exothermic and that in fuel reactor is endothermic (most often). So the heat required in fuel reactor can be carried from air reactor by oxygen carriers. Therefore, the total heat evolved from the system remains same as that of normal combustion.

As the coal consumption will be increasing by coming years, the countries like India having a great coal reserves can achieve the future energy demand with cheaper resource. In this work, Indian coal having high ash content has been taken as the fuel and checked the feasibility of integration of CLC. The software used for the simulation studies is ASPEN Plus.

2. Process Model forCLC Integrated Coal Direct Power Plant with Combined Cycle

In this case solid fuel can be directly sent to the fuel reactor of CLC system in gas turbine section. The gasification and reduction of metal oxides take place in a single physical system (fuel reactor). So there is no need of a separate gasification section to produce syngas. Therefore, an air separation unit to provide pure oxygen for gasification and gas treatment processes for separation of CO_2 from the other gases are not required. This reduces the capital cost as well as the size of the plant. Being one of the most energy consuming processes, elimination of ASU enhances the thermal efficiency of the plant. Flow sheet of the plant is given in Fig. 1.

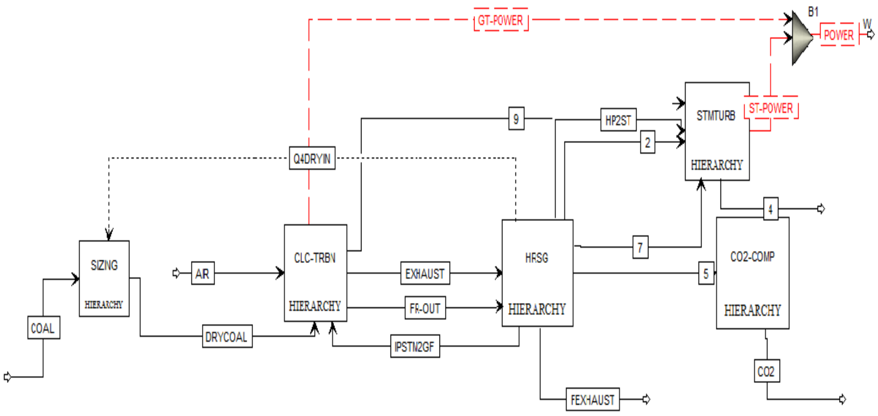

Fig. 1 Aspen flow sheet of iG-CLC with combined cycle

RYield block converts the coal into its constituent elements and they are sent to fuel reactor. The fuel reactor is simulated using two RGibbs reactors allowing for gasification at the bottom section and reduction reaction at the top. Metal oxide particles coming from air reactor enter the fuel reactor from the top and flow down under gravity. Meanwhile coal is introduced at the bottom section along with the gasifying agent - steam. Metal oxides (Fe_2O_3) react with the gasified products in the top section while going down and they are reduced to Fe_3O_4. The gaseous products rise up and come out from the top section. Reduced metal oxides along with char and ash come out from the bottom. Metal oxides are separated from ash and char using a component separator block 'Sep2' and recycled to air reactor for further oxidation. Air reactor is maintained in isothermal condition with 1100°C. Fuel reactor is kept at adiabatic conditions. Sensitivity analysis has been carried out to study the effect of solids on char conversion by varying the steam requirement.

Coal is defined as a NCPSD sub stream as its state is not included in the software database. NCPSD sub streams are solids with a particle size distribution that has to be specified. The heat of combustion is specified in dry basis as 3850 kcal/kg

In these simulations, wet coal mass flow rate of 15.5 kg/sec corresponding to 250 MW of heat input energy has been used. The composition analysis of the coal considered for the present study is given in Table 1.

Table 1 Component attribute analysis of coal

Proximate analysis (weight %)	
Moisture	7.72
Volatile matter	22.35
Ash content	38.39
Fixed carbon	31.54
Ultimate analysis (weight %)	
Carbon	42.39
Hydrogen	3.33
Nitrogen	2.49
Oxygen	5.28
Sulphur	0.4
HHV value (kcal/kg)	3850
Sulfur analysis (weight %)	
Pyritic	0.2
Sulfate	.16
Organic	.04

3. Results and Discussion

A detailed study of in-situ CLC is required to improve its performance. As oxygen carriers have a direct effect on conversion, higher carbon conversion can be achieved in this case. It is found that the steam requirement for this case is high. 0.43 kmo l/s of steam is used, which is relatively high. So the sensible use of oxygen carriers to reduce steam consumption would boost the net power production.

3.1. Effect of oxygen carriers flow rate on overall conversion of fuel

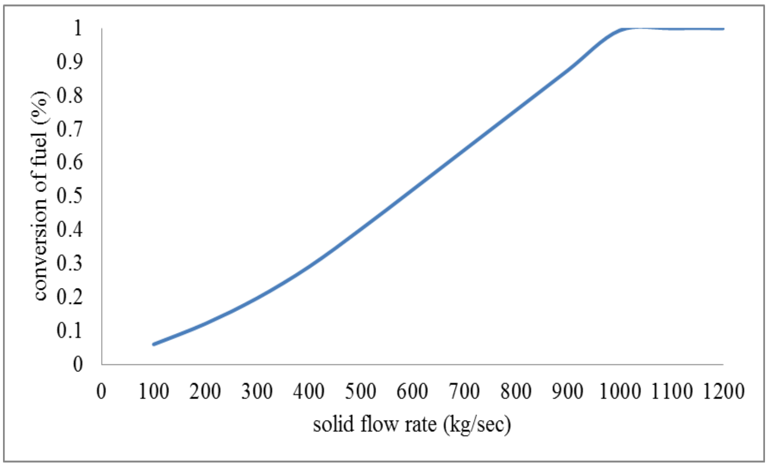

Fig. 2 Effect of Fe_2O_3 flow rate on overall conversion of fuel

Overall Conversion of fuel is calculated on the basis of carbon present in the coal. So the conversion can be defined as;

$$Overall\ Coversion\ (\%) = \frac{CO_2\ out}{Cin} \tag{1}$$

where, $CO_{2\,out}$-Moles of CO_2 present in fuel reactor outlet and C_{in}-Moles of carbon in the coal input

Split fraction of steam from HRSG is kept at 0.5 (0.43 kmol/s). The variation of conversion with flow rate of Fe_2O_3 is given in Fig. 2. It can be observed from the figure that the fuel conversion can be increased by increasing the solids flow rate. Since higher conversion helps in extracting more CO_2 and results in more power production, further simulations are carried out for 97% of carbon conversion.

3.2. Role of oxygen carriers on gasification of coal in fuel reactor

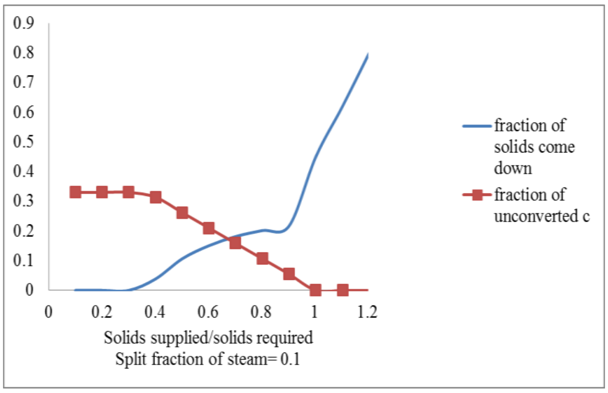

Fig. 3 Effect of solids on char conversion for Fe_2O_3

The oxygen carriers, which are unconverted in the top section of reduction reaction, will be flowing down to the gasification section. Fig. 3 represents the variation in the amount of unconverted carbon with respect to the oxygen carrier flow. Solid flow rate is represented by the ratio of solids supplied to solids required for the complete coal conversion.

With the help of above sensitivity analysis for various parameters on the CLC process, the plant is simulated and the results are summarised in Table 2. It contains total energy production, total energy consumption and CO_2 capture efficiency.

Table 2 Simulation results of the CLC integrated coal direct power plant

ENERGY (MW)	Value
Coal input	250
Gas turbine output	35
Steam turbine output	56.3
Total output	91.3
Total power consumption	
Air separation unit	------
O_2 compression	------
CO_2 capture unit	4.2
Net power production	87.1
Overall efficiency	34.84 %
% CO_2 capture	99.94%

4. Conclusions

A CLC integrated coal fired power plant with Fe_2O_3/Al_2O_3 as oxygen carrier and high ash Indian coal as the fuel was simulated using Aspen Plus ® simulation tool and the energy analysis was presented. Results showed that CLC integrated coal fired power plant (CFPP) has an overall net thermal efficiency of 34.84% with a CO_2 capture efficiency of 99.94%. This level of thermal efficiency is higher than the conventional coal fired power plant with post combustion CO_2 capture.

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