Thermodynamic Analysis of Chemical Looping Combustion Based Power Plants for Gaseous and Solid Fuels

Sivaji Seepana (✉ sivaji@bhel.in)

BHEL: Bharat Heavy Electricals Limited

Aritra Chakraborty

BHEL: Bharat Heavy Electricals Limited

Kannan Kaliyaperumal

BHEL: Bharat Heavy Electricals Limited

Guruchandran Pocha Saminathan

BHEL: Bharat Heavy Electricals Limited

Research Article

Keywords: chemical looping combustion, energy analysis, iG-CLC, net efficiency, solid fuels, power plant

Posted Date: September 3rd, 2021

DOI: <https://doi.org/10.21203/rs.3.rs-645231/v1>

License: This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Thermodynamic Analysis of Chemical Looping Combustion based Power Plants for Gaseous and Solid Fuels

Sivaji Seepana*, Aritra Chakraborty, Kannan Kaliyaperumal, Guruchandran Pocha Saminathan
Bharat Heavy Electricals Limited, Tiruchirappall, Tamil Nadu, India.

*Corresponding author: sivaji@bhel.in

Abstract

The chemical looping combustion (CLC) process is a promising technology for capturing CO₂ at the source due to its inherent separation of flue gas from nitrogen. In this regard, the present study is focused on the development of various Rankine cycle based CLC power plant layouts for gaseous and solid fuels. To evaluate the performance of these CLC based cycles, a detailed thermodynamic analysis has been carried out with natural gas (NG) & synthesis gas as gaseous fuels and lignite as solid fuel. For lignite based power production, in-site gasification CLC (iG-CLC) for syngas generation and CLC based combustion process employed. The Energy analysis showed that NG based power plant has a net efficiency of 40.44% with CO₂ capture and compression which is the highest among all cases while the same for syngas based power plant is 38.06%. The difference in net efficiency between NG and syngas power plants is attributed to the variation in CO₂ compression cost. For lignite based iG-CLC power plant layout, the net efficiency of 39.64% is observed which is higher than syngas fuelled CLC power plant. This shows the potential of CLC technology for power generation applications with or without CO₂ capture.

Keywords: chemical looping combustion, energy analysis, iG-CLC, net efficiency, solid fuels, power plant

1. INTRODUCTION

Recent developments in climate changes such as rise in sea level, forest fires, changes in cold and hot climatic cycles, cyclones, torrential rains, and droughts (El Nino - Quasiperiodical climate pattern) emphasize the importance of the issue of global warming in the day-to-day life of modern man. Climate change is also evident by the fact that the rise in global temperature by approximately 0.8 °C during the last century (Hansen et al. 2006). The observed increase in global average surface temperature from

1951 to 2010 was caused by the anthropogenic increase in GHG concentrations (IPCC 2014). Among the greenhouse gases, CO₂ is largely produced by anthropogenic activities of burning fossil fuels. Statistical analysis showed in the year 2019, 81.3% world's total energy supply was met by burning fossil fuels (IEA 2020). Since thermal power plants are large and stationary and the possibility of introducing additional equipment to capture CO₂ is feasible, there exists an opportunity to cut down CO₂ emissions from fossil fuel fired power generation plants.

In addition to CO₂, coal-fired thermal power plants that provide the largest share of electricity generation in India, are also a source of other pollutants such as SO₂, NO_x, unburnt carbon, particulate matter, mercury, arsenic, and chromium. In order to meet these challenges, many technological advances have been introduced in the combustion process as well as post-combustion process in the past few decades. Notable examples of these technological developments include introducing swirl for enhanced mixing between fuel and air to reduce unburnt carbon, fuel and air staging to reduce NO_x formation, fluidized bed combustion (FBC) & circulating fluidized bed combustion (CFBC) for handling high sulphur, high ash coals, supercritical power plants & advanced ultra-supercritical power plants for improving the efficiency, integrated gasification combined cycle (IGCC) for clean combustion and higher energy efficiency. In order to reduce hazardous pollutant emissions, in addition to the electrostatic precipitator (ESP) for fly ash particle removal, additional measures also have been employed like post combustion treatment methods such as flue gas desulphurization (FGD) for SO₂ removal, selective catalytic or non-catalytic reduction methods for NO_x removal.

While these technological advances have led to improved thermal efficiency and reduced pollutant emissions, none of these directly address the question of reducing CO₂ emissions from concentrated CO₂ generating sources such as power plants, cement industries, metallurgical industries, etc. Some reduction in CO₂ emissions is possible through improved thermal efficiency; however, this gain is insufficient in the context of the continued growth of demand for power in countries such as India and China. In this regard, oxyfuel combustion technology and chemical looping combustion (CLC) technology have been developed in the last couple of decades to capture CO₂ from fossil fuel fired stations. In oxy-fuel combustion, combustion takes place with pure oxygen

instead of air. Hence, the exhaust flue gas consists of only CO₂ and water vapour. Of these, water vapour can be removed directly by cooling the flue gas leaving a highly concentrated CO₂ that can be sent for direct storage/usage. However, the separation of oxygen from the air is a highly energy intensive process that greatly increases the energy penalty in the oxy-fuel combustion process. Whereas, in CLC, the oxidant is in the form of metal oxides and hence the presence of nitrogen during fuel reaction can be avoided. This results in CO₂-rich flue gas at the exhaust which can be directly sent for storage after water vapour condensation. The advantage of this process is that the need for the energy-intensive air separation unit (ASU) can be eliminated, which results in higher energy efficiency with CO₂ capture and sequestration than with oxy-fuel combustion.

CLC process involves interconnected fuel and air reactors between which fuel conversion and metal oxide regeneration take place. The factors such as the design of reactor, selection of oxygen carriers (OC), selection of bed type for the interaction of fuel/air and OC, preparation of metal oxide play a crucial role in the CLC process. The selection of metal oxides decides the heat integration between reactors, the extent of fuel conversion, and solid inventory requirement in the CLC process. In order to increase the reaction rates during fuel and air reactions and to reduce attrition rates, these metal oxides are supported with inert materials (Abad et al. 2007). Commonly used metal oxides for CLC are based on Ni, Fe, Mn, Cu, Co, Ca and their ores and support material are Al₂O₃, NiAl₂O₄, MgO, MgAl₂O₄, ZrO₂, TiO₂, CeO₂, SiO₂, and yttria-stabilized zirconium (YSZ), etc.

Although the CLC process invented decades ago by Lewis and Gilliland (1954), it remained at the conceptual level for a long. The Chalmers University of Technology presented the first demonstration of the CLC technology by showing 100 hours of continuous operation in a 10 kW_{th} CLC plant with NG as fuel and NiO as OC (Lyngfely and Thunman 2005). Since then many experimental studies have been reported in the literature with a thermal capacity ranging from 0.01MW to 3 MW using different metal oxide carriers and fuels. Most of the initial experimental studies were reported with gaseous fuels and later it has been established with solid fuels such as coal, lignite, biomass, petcoke, and sewage sludge. The first solid fuel study was reported in a 10 kW_{th} experimental rig for coal by Berguerand and Lyngfelt (2008), later notable large scale demonstration of CLC were conducted such as 1 MW_{th} CLC plant with ilmenite as OC and

hard coal as fuel at Technische Universität Darmstadt (Strohle et al. 2014) and 3 MW_{th} Limestone Chemical Looping (LCL™) prototype with CaSO₄ as OC and coal as fuel by Alstom Power, USA (Andrus et al. 2013), etc. Promising results from these demonstration plants have provided the much needed assurance on the commercially operable CLC based power plants for future generations. However, the operational experience in in-situ gasification CLC (iG-CLC) has shown that complete combustion of solid fuel is not possible due to slow gasification reaction of char in the operating conditions of the CLC process resulting in high unburnt carbon (Cuadrat et al. 2011; Lyngefelt and Leckner 2015). Therefore, oxy-polishing was proposed recently for combusting the remaining unburnt carbon with pure oxygen after fuel reactor (FR) for 100% fuel conversion (Lyngefelt and Leckner 2015; Adanez et al. 2018).

Since CLC showed assured progress towards commercialization, many studies were carried out theoretically to evaluate CLC based power plant cycle efficiency with or without CO₂ capture to understand the possible energy losses in comparison with other competing methods. Towards this, few studies have been reported in the literature for combined cycle power plants (CCPP) involving power generation by gas turbine and steam turbine combination. Based on a comparative study of exergy analysis of methane and syngas fuelled power generation by using CLC gas turbine (GT) system and conventional IGCC system, it was stated that net power efficiency of CLC-GT for both the fuels with CO₂ sequestration was on par with conventional GT systems (Anheden and Svedberg 1998). An NG-fired CCPP has net thermal efficiency as high as 52–53% in an 800MW_{th} CLC power plant (Wolf et al. 2001) and a similar study with double reheat recycle with CO₂ turbine showed a maximum net plant efficiency of 53.5% by Naqvi (2006). While studying different syngas composition based CCPP using the CLC technique with CO₂ capture, Alvaro et al. (2014) have stated that syngas with higher H₂ content has resulted in higher efficiency (51.57%) than syngas with lower H₂ content (49.99%). Petriz-Prieto et al. (2016) have shown the highest net efficiency with NG based CLC plant of 56.6% was reported when integrating of CLC system into the humid air turbine (HAT) cycle. Exergy analysis of NG fired CCPP showed that the efficiency of the CLC process with CO₂ capture and compression decreases by about 5% points compared to a conventional air-NG fired power plant without CO₂ capture (Petrakopoulou et al. 2011). While applying CLC technique to coal, it showed a net efficiency of 37.7% for CLC-IGCC with CO₂ capture

and compression whereas 34.9% for conventional IGCC with pre-combustion CO₂ capture and compression (Erlach et al. 2011). Similarly, a study of 1126.5 MW_{th} coal based power plant with different combustion technologies showed that CLC - IGCC has a net efficiency of 39.97% and coal direct chemical looping combustion (CDCLC) has the highest net efficiency of 44.42% whereas for conventional IGCC net efficiency with and without CO₂ capture and compression was 37.14 and 44.26% respectively. The oxyfuel combustion based power plant with CO₂ capture and compression has a net efficiency of 35.15% which was the lowest of all due to the higher energy consumption of ASU (Mukherjee et al. 2015). In another study by Fan et al. (2015) using iG-CLC based power plant with anthracite, bituminous, and lignite as fuels reported net efficiencies of 46%, 44%, and 39% respectively. The reason for this efficiency variation was attributed to air compression and pumping costs variation, which are strongly dependent on fuel composition. A similar study conducted by Shijaz et al. (2017) with Indian coal stated that net efficiencies of IGCC with CO₂ capture and compression were 35.8% and 40.2% for conventional power plant and IGCC-CLC based power plants respectively.

For Rankine cycles based power plants using CLC technology, very few papers have been published earlier. The NG fuelled steam cycle of CLC has shown a net plant efficiency of about 44%. The double reheats provided a 1% point higher than a single reheat cycle with CO₂ capture (Naqvi 2006). A similar study reported by Basavaraja and Jayanti (2015) stated that a net efficiency of 43.11% in 761 MW_{th} power plant with NG as fuel.

Based on the recent success in the chemical looping combustion technology with gaseous and solid fuels, many different power plant layout designs have been evolved to analyse the net energy efficiency and most of the studies have carried out with commercially available software packages. Although CLC made more progress towards commercial applications, the interconnected high pressure fuel and air reactors and purity of the gas required for gas turbine applications are still to be proven. Apart from that unburnt carbon while using solid fuels for CLC is considerably high. In this context, the present study focussed on the development of novel Rankine cycle based power generations using CLC technology with gaseous and solid fuels with detailed energy integration (Seepana et al. 2018). For gaseous fuels, NG & coal based syngas are selected and for solid fuel, lignite is selected for thermodynamic calculations of CLC based power plant layouts.

All the steam cycle, flue gas cycle, and energy integration between fuel and air reactors calculations were carried out manually. These studies help in understanding the overall lay-out of CLC based power plants, their energy flows, and energy penalty with or without CO₂ capture to compare with other technologies.

2. Schematic power plant layouts for gaseous and solid fuels using CLC process

In general, combustion of fuel in presence of air (i.e. oxygen) releases energy, whereas, in the CLC process, the combustion energy of the fuel is released in two stages – first when the fuel is reacting with OCs and then when oxygen depleted OCs oxidize in the presence of air. If the first stage is endothermic in nature then total energy releases during the second stage, i.e., metal oxide oxidation. Therefore, energy integration in CLC is critical in achieving better fuel conversion and metal oxide regeneration and efficiency of the overall plant cycle. In this regard, the present study focussed on the development of CLC based power plant scheme integrating heat release/absorption from both fuel and air reactors for NG based (case 1), syngas based (case 2), and lignite based (case 3) steam generation and power production. Depending upon the OCs and fuel combination, FR can act as exothermic or endothermic in nature. Typically fuel reaction with metal oxide occurs at lower temperatures than the air reaction with metal oxides. In order to maintain high conversation rates of fuel and high oxidation rates of metal oxides uniform temperatures are to be maintained within the respective reactors. This study focussed on the development of power plant layout schemes using CLC methodology for three cases. Wherein the symbols in the schemes F, S, A, D, G, and SG represent fuel, steam/water, air, oxygen depleted air, flue gas, and syngas respectively.

2.1. Natural gas based CLC power plant layout

For NG (presumed 100% methane) based steam generation cycle with nickel oxide (NiO) as OC with Al₂O₃ support, the layout of the steam based power plant is shown in Figure 1. The NG from the storage tank is sent through a forced draft (FD) fan to heat with flue gases, this heated NG is admitted to FR for reaction with metal oxides. The flue gas along with oxygen depleted metal oxides are sent to a cyclone separator for the segregation of metal oxides from flue gases. These metal oxides are then admitted to an air reactor (AR).

The fresh air from the FD fan is preheated with oxygen depleted air from AR and then admitted to AR for reaction with oxygen depleted metal oxides. The fuel and air reaction with NiO and Ni respectively and heat of reaction is given below

Since reaction (1) is endothermic in FR, the amount of energy available at AR is more than the thermal energy of admitted fuel and therefore the energy needs to be recovered from AR and supplied to FR. As shown in Figure 1, a dedicated compressed inert fluid is circulated between FR and AR to meet the energy demands of FR. The energy available at AR is extracted using high pressure steam and the superheated steam is admitted to high pressure (HP) turbine for power production after that the exit steam of HP is reheated further with energy available in AR. The reheated steam send to intermediate turbine (IP) and then to low pressure turbine. Low pressure steam from the LP turbine is sent for condensation and then pumped to higher pressure. This water is sent for primary heating using slipstreams from the turbine, flue gases, and oxygen depleted air. The cooled CO₂-rich flue gas after heat extraction is sent for further cooling for water vapour removal, gas cleaning, and then multistage compression. The compressed CO₂-rich flue gases are sent for storage or utilization.

Fig. 1 Schematic drawing of natural gas fuelled CLC based power plant layout for power generation

2.2. Syngas based CLC power plant layout

A schematic layout for generating steam based power using the CLC technique using syngas as fuel and Fe₂O₃ along with alumina support as OC is shown in Figure 2. For syngas reaction, Fe₂O₃/Al₂O₃ is chosen because of the higher reactivity of Fe-based catalyst with H₂ and CO (Adanez et al. 2004). Fe₂O₃ reactions with CO & H₂ are exothermic in nature and Fe₃O₄ reaction with oxygen is also exothermic in nature and therefore energy needs to be extracted from both FR and AR to maintain the constant temperature of these reactors. Here syngas generation was considered not by chemical looping gasification but by conventional oxygen and steam based gasification route (the dotted lined box indicates gasifier where coal to syngas is produced in Figure 2). The syngas at

room temperature is heated with flue gases and then fed to FR through a fan where the syngas reacts with the Fe_2O_3 and release energy and the Fe_3O_4 from FR is send to AR for regeneration of oxygen by reacting with air. The syngas reaction with ferrous oxide (Fe_2O_3) is given by the following chemical reactions. The heat of reaction values for CO and H_2 with Fe_2O_3 are (Adanez et al. 2012)

The fresh air obtained from the FD fan is heated with flue gas and oxygen depleted air and then admitted into AR at 600°C for regeneration of catalyst, the oxygen depleted Fe_3O_4 reacts with oxygen. The reactions details are (taken from Adanez et al. 2012)

The energy generated from FR, AR, flue gas, and oxygen depleted air is recovered using air/water to send to HP, IP, and LP turbines for power generation. The flue gas exchanges heat to steam, syngas fuel, and air and then sent for cooling to remove water vapour and finally for CO_2 compression. The oxygen depleted air from AR also exchanges heat to steam, syngas fuel, and then released to the atmosphere through a chimney.

Fig. 2 Schematic drawing of syngas fuelled CLC based power plant layout for power generation.

2.3. Lignite based CLC power plant layout

In this scheme the solid fuel, lignite is converted to energy in two stage process, in the first stage, lignite is converted to syngas using the iG-CLC technique in a gasification reactor (GR) with steam as a gasifying agent and ilmenite ore as OC. In the second stage, the resultant syngas is admitted to FR where complete combustion of syngas with ilmenite ore takes place, the detailed schematic layout is shown in Figure 3. In the two stage conversion process of lignite to energy, after reaction with lignite and syngas, the oxygen depleted ilmenite ore is admitted to a single AR for regeneration of oxygen in the ilmenite ore. The regeneration ilmenite ore from AR is separated into two streams as per

the requirement of FR and GR and then separated from oxygen depleted air using cyclone separator and then admitted into respective reactors.

In this process, lignite fuel is first crushed and pulverized then admitted to GR for in-situ gasifier along with steam. Here the gasifier operates at atmospheric pressure in presence of steam and metal oxides and the possible reactions considered for volatile combustion with metal oxide and gasification reactions are given below

Water gas shift (WGS) reaction and char gasification reactions were given by Watanabe and Otaka (2006) as follows

The oxygen depleted ilmenite ore from both GR and syngas FR is sent to AR. Where the regeneration of OCs takes place by reacting with air by following reaction along with reaction (5).

The flue gas leaving FR is cooled down by exchanging heat with superheated steam and preheating syngas. The superheated steam is sent to HP, IP, and LP turbines for power generation and then condensed water is pumped and sent for energy recovery. The CO₂ – rich flue gas from FR is sent for energy recovery and condensation to remove water vapour. The dried CO₂ – rich flue gas is sent for multi-stage compression. The compressed flue gas is sent for storage or utilization as per requirement.

Fig. 3 Schematic drawing of lignite fuelled CLC based power plant layout for power generation.

3. Results and Discussions

3.1 Thermodynamic calculations

For the cases discussed above, each stream of the power generation layout has been subjected to the first law of thermodynamics for mass and energy balance evaluations. The calculations for the Rankine cycle are carried out in a similar fashion as mentioned in Seepana and Jayanti (2012) by presuming a steady state operation at a thermal load of 662 MW. The details of the fuel, air, and OCs are given in Table 1 for all cases. During the thermodynamic calculations the following assumptions are made:

- The kinetic and potential energies are negligible.
- The reference state of temperature and pressure are 27 °C and 1.01325 bar.
- FR, AR, and GR are adiabatic in nature and maintained at uniform temperatures throughout the reactor
- The syngas temperature from the gasifier is assumed to be 30 °C for case 2;
- Isentropic efficiency of pumps/fans is 75%.
- Generator efficiency is 100%.
- Compressor efficiency is 85%.
- Complete (100%) combustion of the fuel in FR in all cases.
- 100% oxidation of reduced metal oxide in the AR.
- Air admitted to AR is 20% higher than the stoichiometric requirement of O₂.
- Zero air leakages into FR and AR in all cases.
- Attrition rate for NiO/Al₂O₃ is 0.01%/h (Adanez et al. 2009) and for Fe₂O₃/ Al₂O₃ is 0.09%/h (Gayan et al. 2015). Hence attrition rate is taken as zero for all the cases.

The steam parameters assumed during these calculations were sub-critical in nature for energy balance, pressure, and temperature of steam were 190 bar and 544 °C for HP turbine, 33.6 bar and 540 °C for IP turbine, and for the LP turbine 5.18 bar and 296 °C. The outlet pressure of the LP turbine was 0.06 bar. The flue gas resulting from the FR is cooled by extraction of energy and condensed to remove water vapour and then sent for multi-stage compression of 120 bar. The compressed CO₂-rich flue gas is easier for transportation and storage.

Table 1 Details of the fuel, air, and quantity of oxygen carriers for all cases.

3.2 Natural gas based power plant

In this case, for NG based CLC power plant, the operating temperature of FR and AR are maintained at 900 °C and 1000 °C respectively and the mass ratio of OCs is NiO:Al₂O₃ at 60:40. The amount of NG supplied to FR is 13.24 kg/s for a 662 MW_{th} capacity power plant and 100% conversion of fuel is assumed. The amount of metal oxide supplied for fuel conversion is 20% higher than the stoichiometric requirement. The NG is heated to 800 °C before injecting into FR, higher preheating of NG is preferred to reduce the quantity of energy supply for the endothermic reaction of methane with NiO. Under this scenario, the energy requirement for FR is 62.54 MW_{th} which is proposed to supply from AR using a dedicated compressed fluid. The amount of energy released from AR is 603.8 MW_{th}. The results of thermodynamic analysis such as mass flow, enthalpy, temperature, and pressure for each stream (as shown in Figure 1) are provided in Table 2.

Table 2 Results of thermodynamic analysis of each stream for CLC based natural gas fired power plant.

3.3 Syngas based power plant

In case 2, sub-bituminous coal is considered as fuel with a cold gas efficiency (CGE) of 80.3% and the composition of syngas is given in the second column of Table 3, these values were taken from Yu and Lee (2017). Here the syngas is considered at 27 °C, which is heated with the flue gas and oxygen depleted air before sending to FR at 327°C. The amount of syngas considered in this case is 59.85 kg/s for 662 MW_{th} energy input. The temperatures of FR and AR are maintained at 950 °C and 1000 °C respectively. Here syngas reaction (via reaction (3) & (4)) with Fe₂O₃ in FR is exothermic in nature. The oxygen depleted Fe₃O₄ reaction with oxygen is exothermic (via reaction (5)) in nature in AR. The energy available at FR and AR is 155 MW_{th} and 390.4 MW_{th} respectively, which is to be recovered using superheated steam. The results of thermodynamic analysis such as mass flow, energy, temperature, and pressure for each stream of syngas based CLC combustion as described in Figure 2 are provided in Table 4.

Table 3 Composition and calorific value of syngas for case 2 and case 3.

Table 4 Results of thermodynamic analysis of each stream for CLC based syngas fired power plant.

3.4 Lignite based power plant

In this case, thermodynamic analysis is carried out for gasification of lignite and combustion of syngas generated in gasification. During these studies, ilmenite ore with the composition of 11.7% of Fe_2O_3 , 53.2% Fe_2TiO_5 , 29.5% TiO_2 , and 5.6% inert (Cuadrat et al. 2012) considered as OC. The amount of lignite admitted to GR is 40.74 kg/s and the quantity of ilmenite ore send to GR for the gasification process is 73.68 kg/s, which is equivalent to the stoichiometric requirement of volatile gasification. The composition of lignite and calorific value is shown in Table 5 (Cuadrat et al. 2012), where the fuel composition is close to sub-bituminous Indian coal. The GR temperature is maintained at 870 °C and AR temperature is maintained at 930 °C. Since the gasification reaction of lignite is more effective above 850 °C (Qi et al. 2019) these temperatures are chosen. For modelling of the gasification process, the composition of volatile matter is required which is not known for lignite however, the weight percentage of volatile matter is known. The composition of lignite's volatile matter is modelled by presuming the CO , H_2 , and CH_4 are the only constituents and their individual concentrations were fitted using the trial and error method to match the weight of volatile content. Based on analytical fitting, the molar composition of volatile matter for CO , H_2 , and CH_4 components are 65.72%, 3.13%, and 31.15% respectively. In this study, it is considered that during the gasification process that all the CH_4 from volatile matter reacts with ilmenite ore and generates CO and H_2 via reactions (6) and (7). The CO reacts with steam generates CO_2 and H_2 via WGS reaction (8) thereafter char gasification reactions take place, where carbon reacts with CO_2 and H_2O via reactions (9) and (10) respectively in GR. The number of moles of each constituent of lignite that participated in gasification reaction and energy release is shown in Table 6 and the resultant syngas composition from the iG-CLC process is shown in the third column of Table 3.

Table 5 Proximate, ultimate analysis, and heating value, LHV of lignite considered in the study (Cuadrat et al. 2012).

Table 6 Moles of reactants of lignite fuel participated in the gasification process and energy from each reaction during iG-CLC process (case 3).

Since gasification reactions are endothermic in nature, a large quantity of energy needs to be supplied to GR. In this study, 194.3 MW thermal energy is required to be supplied to GR. This energy has been supplied from AR using a dedicated compressed fluid, which circulates cyclically between AR and GR. For steam based gasification process, the amount of steam admitted to GR is the same as the amount of carbon present in the lignite (S/C = 1) excluding the moisture present in lignite. A quantity of 27.8 kg/s of steam is tapped from the LP turbine at 1.5 bar and 272 °C and supplied to GR. The composition of syngas simulated in this study is closely agreeing ($\pm 6\%$) with syngas composition reported by Shen and Huang (2018), using the same lignite fuel and ilmenite ore as OC. The syngas is separated from metal oxides and ash by sending through series of cyclone separators. It has been assumed that 70% of ash is removed in the cyclone and the rest of the 30% is pneumatically transported with syngas. After exchanging heat to the air, steam, and cleaned syngas, it is sent through ash cleaning and water vapour removal equipment. The cleaned syngas is preheated to 327 °C and then admitted into FR to react further with ilmenite ore. The ilmenite ore after reacting with fuel, the oxygen depleted ilmenite ore is admitted to AR for regeneration by reacting with oxygen. After oxygen reaction with ilmenite ore, the O₂ depleted air leaves the AR at 930 °C which exchanges heat with incoming fresh air (to heat up to 700 °C) and superheat steam. The oxygen depleted air is sent to the atmosphere through the chimney at ~ 100 °C. The results of thermodynamic analysis such as mass flow, energy, temperature, and pressure for each stream (as shown in Figure 3) are provided in Table 7.

Table 7 Results of thermodynamic analysis of each stream in lignite and ilmenite ore based iG-CLC power plant.

4. Comparison of performances of the CLC based power plants

Comparison of results of thermodynamic analysis for case 1, case 2, case 3 using CLC are shown in Table 8. From these results, it is observed that the highest net efficiency of 40.44% with CO₂ capture for case 1 and the lowest net efficiency of 38.05% with CO₂ capture for case 2. The lowest net efficiency is observed for case 2 despite considering the same thermal input and power production as that of case 1. This is primarily due to

high energy consumption by compression of CO₂ in case 2 than in case 1. CO₂ compression energy requirement in case 1 is 12.85 MWe whereas for case 2, it is 29.95 MWe due to the high C/H ratio of syngas (C/H=1.09) than methane (C/H=0.25). The highest gross efficiency of 47.64% is observed for case 3 due to additional energy availability in the form of hot syngas from GR apart from FR and AR. Although case 2 and case 3 are based on syngas, the net efficiency of case 3 is 39.64% which is higher than case 2 of 38.05%, this is due to the higher calorific value of syngas generated in case 3 than in case 2. The higher net efficiency of case 3 is also primarily due to the elimination of the energy penalty of oxygen generation during the gasification process with OC. Among all cases, the auxiliary power consumption including CO₂ compression is of the order case 1 < case 2 < case 3 with values of 31.16, 47.93, and 51.89 MWe respectively. Case 1 has the lowest amount of auxiliary power consumption, the reason for this has been attributed to the lesser CO₂ compression cost.

Table 8 Summary of thermodynamic analysis of all CLC based power plant layouts using Rankine cycle.

While comparing the results of the present study with the results of Basavaraja and Jayanti (2015) for the same fuels, it is observed that net efficiencies of NG and syngas based CLC power plants were 2.67% and 3.03% absolute points higher. However, a net efficiency of 42.9% for NG based CLC power plant with a single reheat steam cycle was shown. The difference in net efficiency is attributed to the super-critical nature of steam parameters used in their studies.

While including the CGE of 80.3% for case 2, the net efficiency of case 2 drops to 30.56%. Similarly, when including the char conversion of 88.9% (equivalent to 92.44% of lignite fuel conversion) during lignite gasification with ilmenite ore as reported by Shen and Huang (2018), the net efficiency of case 3 drops to 36.64%. These numbers indicate that iG-CLC process has better efficiency than the conventional oxygen based gasification and CLC process.

Based on analysis of flue gas composition from FR for all cases, CO₂ capture efficiency is 100% in case 1 because of purity of fuel whereas case 2 has CO₂ capture efficiency of

89.55%, lowest among all cases due to presence of other gases and for case 3, CO₂ capture efficiency is 97.39%. Since in case 3 gasification and combustion carried out using CLC process ingress of other gases are low, this resulted in higher CO₂ capture efficiency than case 2. The composition of flue gas and dry CO₂ concentration is given in Table 9 for all cases.

Table 9 Composition of flue gas at the exit of FR and concentration of CO₂ (dry) for all cases.

5. Comparison of CLC based power plants with other technologies

The thermodynamic analysis of the present iG-CLC based power plant data is compared with the data given by Jayanti et al. (2012) for conventional Indian coal-air and retrofitted oxy-coal based power plant with CO₂ capture. These simulations were also carried out for 662 MW_{th} sub-critical power plant and comparisons are given in Table 10. It can be seen from the comparison that the gross efficiency, net efficiency with or without CO₂ capture is highest for iG-CLC based power plant among all technologies. The net efficiency for the conventional coal-fired power plant is 5.34% and 1.45% absolute points lower than iG-CLC without and with CO₂ capture respectively. Retrofitted oxy-fuel combustion based power plant has the lowest net efficiency with or without CO₂ capture due to high energy penalty by oxygen generation from air using cryogenic technology. When comparing the oxyfuel combustion technology and iG-CLC technology, the iG-CLC plant efficiency with CO₂ capture and compression is 12.68% absolute points higher than retrofitted oxyfuel combustion technology. When considering the carbon conversion of 88.9% in the gasifier for lignite fuel (Shen and Huang 2018), the net efficiency of iG-CLC drops down to ~36.64% which is 9.68% absolute points higher than the retrofitted oxy-fuel combustion case. This value is closely matching with the thermodynamic analysis of a 1126.5MW_{th} combined cycle power plant with CO₂ capture (Mukherjee et al. 2015). Where CDCLC has a net efficiency of 44.42% which is 9.27% absolute points higher than the oxyfuel technology based plant.

Table 10 Comparison of energy analysis of iG-CLC process with conventional PC fired power plant and retrofitted oxy-fuel combustion based PC fired power plant from literature.

Based on the results of the present analysis, it can be stated that by employing CLC based technology over oxy-fuel combustion technology for CO₂ capture, approximately 44% of the energy can be saved. However, CLC is still a developing technology; oxy-fuel combustion may be the best short term measure for CO₂ capture with the CLC proving to be better in the longer term.

6. Conclusions

The present study focused on evaluating the Rankine cycle based power plant layout using CLC technology for NG, syngas, and lignite fuels in a 662 MW_{th} capacity power plant with different metal oxides for each case. In this study energy distribution from AR to FR and from AR to GR are studied in detail and for endothermic reactions of FR and GR. Since the energy required for these reactions are higher, a dedicated compressed fluid is required for supplying heat energy. Based on the thermodynamic analysis, it is observed that the net efficiency of lignite based plant with CO₂ capture and compression is 39.64%. This is ~4% higher than conventional syngas fuelled CLC power plant with CO₂ capture and compression. Whereas NG fuelled CLC power plant shows a net efficiency of 40.44%. It is also observed that CLC has specific advantages of lesser power consumption for auxiliaries and more steam production due to the availability of high grade energy. The results encourage the potential application of CLC for power generation even without CO₂ capture and compression. With continued development, the reliability and char combustion efficiency may increase further which will make CLC technology more attractive.

534
535
536
537
538
539
540
541
542
543
544
545
546
547
548
549
550
551
552
553
554
555
556
557
558
559
560
561
562
563
564
565

Ethical Approval

Not applicable.

Consent to Participate

Not applicable.

Consent to Publish

Not applicable.

Authors Contributions

SS has conceived the concept, data and written the manuscript, AC supported in generating the data for the present work, KK supervised the work and PSG also supervised and approved the work.

Funding

We have not received any funding for executing this work.

Competing Interests

We would like state here that we do not have any conflict of interest in publishing this work

Availability of data and materials

Data availability statements can take one of the following forms (or a combination of more than one if required for multiple datasets):

- The datasets analysed during the current study are available in the
 - IPCC (2014). Climate Change 2014: Synthesis Report.
https://www.ipcc.ch/site/assets/uploads/2018/02/SYR_AR5_FINAL_full.pdf.
We have accessed the web link on 24st June 2021.
 - IEA repository in the name of International Energy Agency (2020). Key World Energy Statistics, the web link is given below
https://iea.blob.core.windows.net/assets/1b7781df-5c93-492a-acd6-01fc90388b0f/Key_World_Energy_Statistics_2020.pdf. We have accessed the web link on 21st June 2021.
- All data generated during this study are included in this article itself

7. REFERENCES

- Abad A, Adánez J, García-Labiano F, de Diego LF, Gayán P, Celaya J (2007) Mapping of the range of operational conditions for Cu-, Fe- and Ni-based oxygen carriers in chemical-looping combustion. *Chem. Eng. Sci.* 62: 533-549. <https://doi.org/10.1016/j.ces.2006.09.019>
- Adánez J, Abad A, Garcia-Labiano F, Gayan P, de Diego LF (2012) Progress in Chemical-Looping Combustion and Reforming technologies. *Prog. Energ. Combust Sci.* 38:215-282. <https://doi.org/10.1016/j.pecs.2011.09.001>
- Adánez J, Abad A, Mendiara T, Gayán P, de Diego LF, García-Labiano F (2018) Chemical looping combustion of solid fuels. *Prog. Energy Comb. Sci.* 65: 6-66. <https://doi.org/10.1016/j.pecs.2017.07.005>
- Adánez J, Dueso C, de Diego LF, García-Labiano F, Gayán P, Abad A (2009) Methane combustion in a 500W_{th} chemical-looping combustion system using an impregnated Ni-based oxygen carrier. *Energy Fuels* 23:130–142. <https://doi.org/10.1021/ef8005146>
- Adánez, J, de Diego LF, García-Labiano F, Gayán P, Abad A, Palacios JM (2004) Selection of oxygen carriers for chemical-looping combustion. *Energy Fuels* 18:371–377. <https://doi.org/10.1021/ef0301452>
- Alvaro AJ, Paniagua IL, Fernandez CG, Carlier RN, Martín JR (2014) Energetic analysis of a syngas-fueled chemical-looping combustion combined cycle with integration of carbon dioxide sequestration. *Energy* 76: 694-703. <https://doi.org/10.1016/j.energy.2014.08.067>
- Andrus Jr. HE, Chiu JH, Edberg CD, Thibeault PR, Turek DG (2012) ALSTOM's Chemical Looping Combustion Prototype for CO₂ Capture from Existing Pulverized Coal-Fired Power Plants. United States. <https://doi.org/10.2172/1113766>
- Anheden M, Svedberg G (1998) Exergy analysis of chemical-looping combustion systems. *Energy Convers. Mgmt.* 39:1967-1980. [https://doi.org/10.1016/S0196-8904\(98\)00052-1](https://doi.org/10.1016/S0196-8904(98)00052-1)
- Basavaraja RJ, Jayanti S (2015) Viability of fuel switching of a gas-fired power plant operating in chemical looping combustion mode. *Energy* 81:213-221. <https://doi.org/10.1016/j.energy.2014.12.027>
- Berguerand N, Lyngfelt A (2008) Design and operation of a 10 kW_{th} chemical looping combustor for solid fuels – Testing with South African coal. *Fuel* 87: 2713–2726. <https://doi.org/10.1016/j.fuel.2008.03.008>
- Cuadrat A, Abad A, García-Labiano F, Gayán P, de Diego LF, Adánez J (2011) The use of ilmenite as oxygen-carrier in a 500 W_{th} Chemical-Looping Coal Combustion unit. *Int. J. Greenh. Gas Con.* 5:1630–1642. <https://doi.org/10.1016/j.ijggc.2011.09.010>
- Cuadrat A, Abad A, García-Labiano F, Gayán P, de Diego LF, Adánez J (2012) Relevance of the coal rank on the performance of the in situ gasification chemical-looping combustion. *Chem. Engg. J.* 195-196:91–102. <https://doi.org/10.1016/j.cej.2012.04.052>
- Erlach B, Schmidt M, Tsatsaronis G (2011) Comparison of carbon capture IGCC with pre-combustion decarbonisation and with chemical-looping combustion. *Energy* 36:3804-3815. <https://doi.org/10.1016/j.energy.2010.08.038>

609 Fan J, Zhu L, Hong H, Jiang Q, Jin H (2017) A thermodynamic and environmental
 610 performance of in-situ gasification of chemical looping combustion for power generation
 611 using ilmenite with different coals and comparison with other coal driven power
 612 technologies for CO₂ capture. *Energy* 119:1171-1180.
 613 <https://doi.org/10.1016/j.energy.2016.11.072>

614 Gayán P, Cabello A, Abad A, García-Labiano F, de Diego LF, Adánez J (2015) Development
 615 of Impregnated Oxygen Carriers at Industrial Scale for CH₄ Combustion in a Chemical
 616 Looping Combustion Process. *Proc, Brussels Sustainable Development Summit, Brussels,*
 617 *Belgium.*

618 Hansen J, Sato M, Ruedy R, Lo K, Lea DW, Medina-Elizade M (2006) Global temperature
 619 change. *Proc. Natl. Acad. Sci.* 103:14288-14293.
 620 <https://doi.org/10.1073/pnas.0606291103>

621 International Energy Agency (2020). Key World Energy Statistics,
 622 [https://iea.blob.core.windows.net/assets/1b7781df-5c93-492a-acd6-](https://iea.blob.core.windows.net/assets/1b7781df-5c93-492a-acd6-01fc90388b0f/Key_World_Energy_Statistics_2020.pdf)
 623 [01fc90388b0f/Key_World_Energy_Statistics_2020.pdf](https://iea.blob.core.windows.net/assets/1b7781df-5c93-492a-acd6-01fc90388b0f/Key_World_Energy_Statistics_2020.pdf). [accessed on 21st June 2021].

624 IPCC (2014). Climate Change 2014: Synthesis Report.
 625 <https://www.ipcc.ch/report/ar5/syr/>. [accessed on 24th June 2021].

626 Jayanti S, Saravan V, Seepana S (2012) Assessment of retrofitting possibility of an Indian
 627 pulverized coal boiler for operation with Indian coals in oxy-coal combustion mode with
 628 CO₂ sequestration. *Journal of power and energy. Proc. Inst. Mech. Eng. Part A* 226:1003-
 629 1013.<https://doi.org/10.1177%2F0957650912459465>

630 Ju Y, Lee C.H (2017) Evaluation of the energy efficiency of the shell coal gasification
 631 process by coal type. *Energy Convers, Manag.* 143:123–136.
 632 <https://doi.org/10.1016/j.enconman.2017.03.082>

633 Lewis WK, Gilliland ER (1954) Production of pure carbon dioxide, Patent 2665972.

634 Lyngfelt A, Leckner B (2015) A 1000 MW_{th} boiler for chemical-looping combustion of
 635 solid fuels – Discussion of design and costs. *Appl. Energy* 157: 475-487.
 636 <https://doi.org/10.1016/j.apenergy.2015.04.057>

637 Lyngfelt A, Thunman H (2005) Construction and 100 h of operational experience of a 10-
 638 kW chemical-looping combuston. In: Thomas DC, Benson SM, editors. Carbon dioxide
 639 capture for storage in deep geologic formations results from the CO₂ capture project, vol.
 640 1 chapter 36, Oxford, UK: Elsevier.
 641 https://www.co2captureproject.org/pdfs/advances_in_ccs_technology0409.pdf

642 Mukherjee S, Kumar P, Yang A, Fennell P (2015) Energy and exergy analysis of chemical
 643 looping combustion technology and comparison with pre-combustion and oxy-fuel
 644 combustion technologies for CO₂ capture. *J. Environ. Chem. Eng.* 3:2104–
 645 2114.<https://doi.org/10.1016/j.jece.2015.07.018>

646 Naqvi R (2006) Analysis of Natural Gas-Fired Power Cycles with Chemical Looping
 647 Combustion for CO₂ Capture. Dissertation, Norwegian University of Science and
 648 Technology, Trondheim.

649 Petrakopoulou F, Boyano A, Cabrera M, Tsatsaronis G (2011) Exergoeconomic and
 650 exergoenvironmental analyses of a combined cycle power plant with chemical looping
 651 technology. *Int. J. Greenh. Gas Con.* 5:475–482.
 652 <https://doi.org/10.1016/j.ijggc.2010.06.008>

653 Petriz-Prieto MA, Rico-Ramirez V, Gonzalez-Alatorre G, Gómez-Castrob FI, Diwekar UM
654 (2016) A comparative simulation study of power generation plants involving chemical
655 looping combustion systems, *Comput. Chem. Eng.* 84:434–445.
656 <https://doi.org/10.1016/j.compchemeng.2015.10.002>

657 Qi B, Xia Z, Huang G, Wang W (2019) Study of chemical looping co-gasification (CLCG) of
658 coal and rice husk with an iron-based oxygen carrier via solid-solid reactions. *J. Energy*
659 *Inst.* 92:382-390. <https://doi.org/10.1016/j.joei.2017.12.006>

660 Seepana S, Jayanti S (2012) Optimized enriched CO₂ recycle oxy-fuel combustion for high
661 ash coals. *Fuel* 102:32–40. <https://doi.org/10.1016/j.fuel.2009.04.029>

662 Seepana S, Rajavel M, Chakraborty A, Guruchandran PS (2018), A Methodology and
663 detailed layout for steam generation using chemical looping combustion process from
664 carbonaceous fuels, *Pat Appl No:* 201831026406 *date.* 16/07/2018.
665 <http://ipindiaservices.gov.in/PublicSearch/PublicationSearch/PatentDetails>

666 Shen Z, Huang H (2018) High-efficiency and pollution-controlling in-situ gasification
667 chemical looping combustion system by using CO₂ instead of steam as gasification agent.
668 *Chin. J. Chem. Eng.* 26:2368-2376. <https://doi.org/10.1016/j.cjche.2018.03.016>

669 Shijaz H, Attada Y, Patnaikuni VS, Vooradi R, Anne SB (2017) Analysis of integrated
670 gasification combined cycle power plant incorporating chemical looping combustion for
671 environment-friendly utilization of Indian coal. *Energy Convers. Manag.* 151:414–425.
672 <https://doi.org/10.1016/j.enconman.2017.08.075>

673 Ströhle J, Orth M, Epple B (2014) Design and operation of a 1 MW_{th} chemical looping plant.
674 *Appl. Energy* 113: 1490–1495. <https://doi.org/10.1016/j.apenergy.2013.09.008>

675 Watanabe H, Otaka M (2006) Numerical simulation of coal gasification in entrained flow
676 coal gasifier. *Fuel* 85:1935–1943. <https://doi.org/10.1016/j.fuel.2006.02.002>

677 Wolf J, Anheden M, Yan J (2001) Performance analysis of combined cycles with chemical
678 looping combustion for CO₂ capture. In: *Proceedings of the 18th Annual International*
679 *Pittsburg Coal Conference, Newcastle, Australia*, pp. 1122-1139.
680
681

Fig. 1 Schematic drawing of natural gas fuelled CLC based power plant layout for power generation.

Fig. 3 Schematic drawing of lignite fuelled CLC based power plant layout for power generation.

Table 1 Details of the fuel, air, and quantity of oxygen carriers for all cases.

Fuel Type	Natural gas (case 1)	Syngas (case 2)	Lignite (case 3)
Fuel supply to FR, kg/s	13.24	59.86	40.74
Air supply to AR, kg/s	273.25	203.21	283.25
Type of Metal oxide	NiO:Al ₂ O ₃	Fe ₂ O ₃ :Al ₂ O ₃	Ilmenite ore
Metal oxide ratio	60:40	60:40	-
Quantity of metal oxide to FR, kg/s	295.94	1411.6	1577.76

Table 2 Results of thermodynamic analysis of each stream for CLC based natural gas fired power plant.

Stream	P, bar	T, K	m, kg/s	h, kJ/kg
Natural gas				
F1	1	27.0	13.24	0
F2	1.5	48.15	13.24	40.97
F3	1.45	273.27	13.24	660.50
F4	1.4	800.0	13.24	2734.69
Fresh air				
A1	1	27.0	273.25	0.00
A2	1.5	66.03	273.25	81.21
A3	1.47	255.55	273.25	232.10
A4	1.45	600.0	273.25	611.50
Flue gas				
G1	1.2	900.0	66.07	1354.64
G2	1.18	316.58	66.07	405.75
G3	1.15	231.81	66.07	281.60
G4	1.13	110.58	66.07	113.4
G5	1.1	70.42	66.07	58.5
G6	1.05	56.39	66.07	33.4
Oxygen depleted air				
D1	1.15	1000.0	220.42	1064.10
D2	1.12	876.73	220.42	939.51
D3	1.1	466.18	220.42	469.17
D4	1.07	320.87	220.42	309.15
D5	1.05	280.26	220.42	265.75
D6	1.03	102.8	220.42	78.70
Steam/water				
S1	0.06	36.2	190.56	1992.43
S2	0.06	36.2	190.56	151.71
S3	21	36.3	190.56	153.93
S4	20.5	69.42	190.56	292.18
S5	20	97.30	190.56	409.13
S6	20	111.12	190.56	467.45
S7	18	123.00	190.56	517.65

S8	17.5	155.24	190.56	655.58
S9	17	160.37	219.32	677.76
S10	16	186.84	229.81	794.10
S11	225	184.61	229.81	794.10
S12	220	213.45	229.81	920.62
S13	215	249.56	229.81	1084.83
S14	210	281.54	229.81	1238.32
S15	200	331.08	229.81	1511.11
S16	190.8	544.43	229.81	3365.52
S17	35.4	309.72	211.55	3000.5
S18	33.6	540.32	211.55	3543.98
S19	5.18	296.0	180.06	3055.48
S20	0.06	36.2	161.73	2370.10
S21	35.4	308.9	18.267	3000.50
S22	20	471.9	10.494	3403.98
S23	10.5	382.2	10.494	3225.70
S24	5.2	296.3	10.494	3055.48
S25	0.7	104.8	8.415	2686.82
S26	0.3	70.1	9.918	2564.11
S27	35	218.0	18.267	934.58
S28	20	193.8	28.761	824.66
S29	5.2	131.0	10.494	550.81
S30	0.7	76.40	18.909	322.80
S31	0.3	42.80	28.827	180.05
S32	0.06	36.20	28.827	180.05

Table 3 Composition and calorific value of syngas for case 2 and case 3.

Components	Conventional syngas (case 2), vol % (dry)	iG-CLC based syngas (case 3), vol % (dry)
CO	59.39	38.75
H ₂	29.04	54.0
CO ₂	4.15	6.05
Others	7.42	1.2
Calorific value (LHV), kJ/kg	11060.22	15950.1

Table 4 Results of thermodynamic analysis of each stream for CLC based syngas fired power plant.

Stream	Pressure, bar	T, °C	m, kg/s	h, kJ/kg
Syngas fuel				
F1	1	27.0	59.86	0
F2	1.5	48.7	59.86	27.73
F3	1.45	274.03	59.86	318.5
F4	1.4	327.0	59.86	387.93
Fresh air				
A1	1.01	27.0	203.21	0.00
A2	1.5	63.0	203.21	36.45
A3	1.45	102.5	203.21	75.31
A4	1.4	700.0	203.21	725.77
Flue gas				
G1	1.2	950.0	99.15	1135.80
G2	1.18	291.07	99.15	290.00
G3	1.15	134.69	99.15	114.45
G4	1.13	105.11	99.15	82.5
G5	1.1	77.15	99.15	42.5
Oxygen depleted air				
D1	1.15	1000.0	163.93	1063.96
D2	1.12	847.85	163.93	908.00
D3	1.1	844.66	163.93	882.65
D4	1.07	100.34	163.93	76.30
Water/Stream				
S1	0.06	36.2	190.08	1992.43
S2	0.06	36.2	190.08	151.71
S3	21	36.3	190.08	153.93
S4	20.5	69.50	190.08	292.53
S5	20	97.18	190.08	408.58
S6	18	101.16	190.08	425.24
S7	17.5	134.07	190.08	564.72
S8	17	142.06	218.84	598.89
S9	16	170.28	229.33	719.09
S10	225	167.38	229.33	719.09
S11	220	196.39	229.33	845.87
S12	220	233.47	229.33	1010.43
S13	220	257.65	229.33	1121.91

S14	210	322.81	229.33	1487.57
S15	200	367.47	229.33	2163.29
S16	190.8	544.43	229.33	3365.52
S17	35.4	309.72	211.07	3000.5
S18	33.6	540.32	211.07	3543.98
S19	5.18	296.0	179.58	3055.48
S20	0.06	36.2	161.25	2370.10
S21	35.4	304.9	18.267	3000.50
S22	20	471.9	10.494	3403.98
S23	10.5	382.2	10.494	3225.70
S24	5.2	296.3	10.494	3055.48
S25	0.7	104.8	8.415	2686.82
S26	0.3	70.1	9.918	2564.11
S27	35	218.0	18.267	934.58
S28	20	193.8	28.761	824.66
S29	5.2	125.6	10.494	529.05
S30	0.7	76.40	18.909	322.80
S31	0.3	42.80	28.827	180.05
S32	0.06	36.20	28.827	180.05

Table 5 Proximate, ultimate analysis and heating value, LHV of lignite considered in the study (Cuadrat et al. 2012).

Property	Wt%
Moisture	12.5
Volatile Matter	28.7
Fixed carbon	33.6
Ash	25.2
C	45.4
H	2.5
N	0.5
S	5.2
O	8.6
LHV, kJ/kg	16250

Table 6 Moles of reactants of lignite fuel participated in gasification process and energy from each reaction during the iG-CLC process (case 3).

Mole of reactant	Reaction No	Energy from reaction, kJ/s
0.1816 kmol/s of CH ₄	(6)	+35065
0.1741 kmol/s of C	(8)	+30016
0.97 kmol/s of C	(9)	+273343
0.3826, kmol/s of CO	(10)	-15723

1. '+' indicates endothermic reaction
2. '-' indicates exothermic reaction

Table 7 Results of thermodynamic analysis of each stream in lignite and ilmenite ore based iG-CLC power plant.

Stream	P, bar	T, °C	m, kg/s	h, kJ/kg
SG1	1.20	870.00	64.30	1693.72
SG2	1.17	545.35	64.30	1025.77
SG3	1.14	341.67	64.30	609.33
SG4	1.11	276.39	64.30	480.57
SG5	1.07	125.00	64.30	186.64
SG6	1.01	27.00	52.67	0
F1	1.01	27	52.67	0
F2	1.50	48.7	52.67	43.23
F3	1.30	249.62	52.67	445.75
F4	1.25	327	52.67	602.94
A1	1.01	27.0	283.25	0.00
A2	1.5	63.0	283.25	36.45
A3	1.47	600.0	283.25	574.15
A4	1.44	700.0	283.25	725.77
G1	1.10	870.00	104.52	1185.56
G2	1.06	302.48	104.52	350.85
G3	1.04	147.28	104.52	148.03
G4	1.02	137.8	104.52	139.71
G5	120.00		70.56	1.5
D1	1.34	930.0	228.49	996.18
D2	1.3	703.86	228.49	742.77
D3	1.25	100.24	228.49	76.20
steam/water				
S1	0.06	36.2	213.97	1992.43
S2	0.06	36.2	213.97	151.71
S3	21	36.3	213.97	153.93
S4	20.5	65.80	213.97	277.06
S5	20	90.41	213.97	380.14
S6	18	111.40	213.97	468.47
S7	17.5	140.53	213.97	592.38
S8	17	146.99	242.73	619.90
S9	16	172.60	253.22	727.89
S10	225	169.39	253.22	727.89
S11	220	195.67	253.22	842.71
S12	220	229.42	253.22	991.74

S13	220	301.90	253.22	1336.29
S14	215	320.15	253.22	1442.03
S15	210	350.19	253.22	1670.68
S16	200	366.90	253.22	2082.14
S17	190.8	544.43	253.22	3365.52
S18	35.4	309.72	234.96	3000.5
S19	33.6	540.32	234.96	3543.98
S20	5.18	296.0	203.47	3055.48
S21	0.06	36.2	157.34	2370.10
S22	35.4	304.9	18.267	3000.50
S23	20	471.9	10.494	3403.98
S24	10.5	382.2	10.494	3225.70
S25	5.2	296.3	10.494	3055.48
S34	2	272	27.80	3015.2
S26	0.7	104.8	8.415	2686.82
S27	0.3	70.1	9.918	2564.11
S28	35	218.0	18.267	934.58
S29	20	193.8	28.761	824.66
S30	5.2	125.6	10.494	529.05
S31	0.7	76.40	18.909	322.80
S32	0.3	42.80	28.827	180.05
S33	0.06	36.20	28.827	180.05

Table 8 Summary of thermodynamic analysis of all CLC based power plant layouts using Rankine cycle.

Power production, kW	NG-PP	Syngas-CLC	iG-CLC
HP Turbine	83948.0	83710.8	91639.0
MP Turbine	97979.3	97661.8	108272.0
LP Turbine	118938.7	118493.2	115443.3
Total power generation	300866.1	299865.8	315354.3
Power consumption			
Air compression	11692.7	8725.9	12120.8
CO ₂ compression	12853.9	29945.8	24668.3
Water pumping	6917.4	6897.6	7560.8
Fuel pumping	698.9	2365.0	2976.2
Coal crushing, pulverizing and conveying	0.0	0.0	4500.0
Total power consumption	32163.0	47934.3	51826.2
Total useful output	267718.5	251931.5	262414.0
Total thermal input	662000.0	662000.0	662000.0
Gross efficiency, %	45.45	45.30	47.64
Net efficiency without CO ₂ capture & compression, %	42.53	42.58	43.53
Net efficiency with CO ₂ capture & compression, %	40.44	38.06	39.64

Table 9 Composition of flue gas at the exit of FR and concentration of CO₂ (dry) for all cases.

Components	Molar concentration, %		
	Case 1	Case 2	Case 3
CO ₂	33.33	63.54	44.8
H ₂ O	66.67	29.04	54.0
Others (N ₂ , SO _x , NO _x , etc)	-	7.42	1.2
CO ₂ (dry)	100	89.55	97.39

Table 10 Comparison of energy analysis of iG-CLC process with conventional PC fired power plant and retrofitted oxy-fuel combustion based PC fired power plant from literature.

Description	iG-CLC based power plant	Conventional power plant*	Retrofitted oxy-coal combustion power plant*
Power production, kW	315354.3	270900.0	273464.0
Auxiliary Power consumption, kW	51826.2	17896.0	94961.0
Total useful output, kW	262414.0	252914.0	178503.0
Total thermal input, kW	662000.0	662200.0	662200.0
Gross efficiency, %	47.64	40.91	41.3
Net efficiency without CO ₂ capture, %	43.53	-	31.22
Net efficiency with CO ₂ capture, %	39.64	38.19	26.96

* Indicates data taken from Jayanti et al. (2015)