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Research Paper

Evaluation of reactive absorption and adsorption systems for post-combustion CO_2 capture applied to iron and steel industry

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HIGHLIGHTS

- Integration of Carbon Capture and Storage (CCS) technologies into iron and steel sector.
- Calcium looping has reduced CO_2 emissions as well as lower energy and cost penalties.
- Energy integration analysis for steel mill with carbon capture and storage.

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ABSTRACT

Reducing CO_2 emissions from energy sector and other fossil fuel-intensive industrial applications is of main importance today. The iron and steel industry is one of the largest industrial sources of CO_2 (about 6% of total CO_2 emissions). Two post-combustion CO_2 capture methods based on reactive gas-liquid and gas-solid systems are evaluated to be used in an integrated steel mill in conjunction with the plant sub-systems with the highest CO_2 emissions e.g., captive power plant, hot stoves, coke ovens, lime kilns, etc. The gas-liquid absorption using chemical solvents (e.g., alkanolamines) and Calcium Looping (CaL) are assessed. The carbon capture rate is set to be at least 90%. The paper evaluates a conventional size of integrated steel mill emphasizing the energy integration aspects and the influence of various carbon capture options on the overall steel mill performances. The evaluated designs (captive power plants and carbon capture units) were modelled and simulated, the results being used to assess the overall indicators. For comparison reason, various captive power plant configurations of integrated steel mill without carbon capture were also considered. The assessments show that CaL system has significant advantages compared not only to benchmark cases without capture but also to the gas-liquid absorption cases.

1. Introduction

In the attempt to reduce the greenhouse gas emissions in the fight against the climate change, the energy-intensive industries have to implement innovative low carbon technologies in the near future [1]. Improving the energy conversion efficiency is one crucial aspect but other potential solutions (e.g., application of carbon capture and storage methods) need also to be considered [2]. The iron and steel industry is one of the largest energy-consuming manufacturing sectors in the world accounting for about 10–15% of the total industrial primary energy consumption. The main energy source for the iron and steel production is based on fossil fuels (coal and natural gas). The CO_2 emissions from production of one tonne of steel in an integrated steel mill have been estimated on average at 2 tonne CO_2 [3].

Basically, there are two main routes for producing steel: the iron ore reduction using coke or natural gas and the steel scrap recycling. The main steel production process (accounting for about 70% globally) is based on iron ore reduction with coke through the Blast Furnace (BF) followed by an iron refining process in the Basic Oxygen Furnace (BOF). This production method is known as integrated steel mill. The rest 30% of global steel production is based on Electric Arc Furnace (EAF) method which uses steel scrap, steel recycling and iron from a Direct Reduced Iron (DRI) processes. All iron and steel manufacturing steps are highly energy intensive leading to significant fossil CO_2 emissions.

In the last half of century, the energy intensity for steel production has been significantly reduced from over 110 GJ energy input per tonne of steel produced in 1970s to about 20 GJ/t in 2012 [4,5]. Currently, the iron and steel industry is already operating close to its thermodynamic limits. Further energy optimisation and CO_2 emission reduction need to come from other innovative

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Nomenclature

List of acronyms

BOF	Basic Oxygen Furnace
BOFG	Basic Oxygen Furnace Gas
BF	Blast Furnace
BFG	Blast Furnace Gas
CaL	Calcium Looping
CCS	Carbon Capture and Storage
CCR	Carbon Capture Rate
CFB	Circulated Fluidised Bed
COG	Coke Oven Gas
CCGT	Combined Cycle Gas Turbine
DRI	Direct Reduced Iron
EAF	Electric Arc Furnace
EOR	Enhanced Oil Recovery
HP	High Pressure steam
HRC	Hot Rolled Coil
LP	Low Pressure steam
MP	Medium Pressure steam
MDEA	Methyl-DiEthanol-Amine
NG	Natural Gas
NGCC	Natural Gas Combined Cycle
SCI	Specific Capital Investment
ULCOS	Ultra Low CO_2 Steel-making

technologies. For instance, the ULCOS (Ultra Low CO_2 Steel-making) project represents a consortium of European companies and organisations from 15 European countries that have launched a cooperative research & development initiative to enable drastic reduction in CO_2 emissions from steel production [6]. Three of the breakthrough technologies investigated by ULCOS (top gas recycling blast furnace with CO_2 capture, HIsarna smelter technology and ULCORED process) incorporate CO_2 capture [7].

Iron and steel industry is heavily dependent on carbon-based fuels as reducing agents of iron ore; currently the carbon is coming mainly from fossil sources. CCS technologies have the potential to significantly reduce the greenhouse gas emissions and to permit the usage of fossil fuels as a bridge to future low carbon economy where the renewable will be the main energy source. The main CO_2 capture options are: post-combustion, pre-combustion and oxy-combustion [8,9]. Considering that an integrated steel mill has numerous CO_2 emission sources (the most important being the captive power plant, hot stoves, lime kilns, coke ovens), the post-combustion capture configuration seems to be the obvious choice [10]. The most mature carbon capture option is based on post-combustion method using reactive gas-liquid absorption using various chemical solvents (e.g., Methyl-DiEthanol-Amine - MDEA). The main drawbacks of chemical gas-liquid absorption are high energy duty for solvent regeneration (~3 MJ/kg CO_2) and operational aspects (solvent degradation, corrosion, etc.).

Other innovative carbon capture options which suit very well with energy intensive processes are chemical and calcium looping methods [11]. The main advantages of these technologies are: inherent CO_2 capture, high temperature heat recovery potential, easy integration in industrial applications like cement and steel industry. For instance, the Calcium Looping (CaL) option implies two Circulated Fluidised Bed (CFB) reactors where the following reactions take place [12]:

– Carbonation reactor:

$$CO_2 + CaO \leftrightarrow CaCO_3 \quad \Delta H = -178.2 \text{ kJ/mole} \tag{1}$$

– Calcination reactor:

$$CaCO_3 \leftrightarrow CaO + CO_2 \tag{2}$$

Both CaL reactors are operating at high temperature: the carbonation reactor at about 500–600 °C and the calcination reactor at about 900–980 °C. The high operating temperature of CaL system enables the high pressure steam generation with positive influence on overall energetic management of the steel mill. In addition, the spent calcium-based sorbent can be easily utilised in the steel mill (e.g., sinter production, basic oxygen furnace, ladle metallurgy) reducing the output of lime kilns which is an important CO_2 emitter.

This article evaluates a conventional size of integrated steel mill with 4 million tonnes Hot Rolled Coil (HRC) per year output with and without carbon capture. The steel mill design without carbon capture was considered as a benchmark case [3]. For the benchmark case (steel mill without carbon capture), various configurations were considered for the captive power plant to evaluate the potential CO_2 emission reduction via power block retrofit. The assessed post-combustion CO_2 capture options are based on reactive gas-liquid (MDEA) and gas-solid (CaL) configurations. Various carbon capture scenarios from the most important CO_2 emission sources within the steel mill (e.g., captive power plant, hot stoves, lime plant, coke ovens) were considered. The energy integration aspects and the influence of various carbon capture options and operational scenarios on the overall techno-economic and environmental performances were assessed. The evaluated designs with and without carbon capture were simulated using process flow modelling, the simulation results being used to assess the overall technical and environmental indicators (e.g., energy efficiency, ancillary consumptions, carbon capture rate, specific CO_2 emissions, CO_2 capture investment costs).

2. Description of integrated steel mills with and without carbon capture

The integrated steel mill plants have the following main sub-systems [3]: sinter plant, coke ovens, lime kilns, Blast Furnace (BF) & hot stoves, desulphurisation plant, Basic Oxygen Furnace (BOF), ladle metallurgy, continuous caster, hot rolling mills, captive power plant, air separation unit. The simplified layout of integrated steel mill plant is presented in Fig. 1.

The CO_2 capturing process was concentrated on the most important effluents of the integrated steel mill. As an illustrative example, Table 1 presents the specific CO_2 emissions per tonne of Hot Rolled Coil (HRC) for each sub-system of integrated steel mill [3]. As can be noticed, the most important CO_2 emitters within an integrated steel mill are: captive power plant, hot stoves, sinter plant, coke oven and lime kilns. For the investigated carbon capture designs, two post-combustion carbon capture methods were evaluated. The first carbon capture concept is using an absorption - desorption cycle using an aqueous solution of MDEA [13]. The conceptual layout of reactive gas-liquid absorption process is presented in Fig. 2.

CO_2 is captured in the absorption column by reacting with the chemical solvent according to the following reaction: