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Carbon capture and utilisation technologies applied to energy conversion systems and other energy-intensive industrial applications

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ABSTRACT

Reducing the greenhouse gas emissions from heat and power sector as well as from other energy-intensive industrial applications is of paramount importance today. Various carbon capture technologies can be applied to reduce the CO_2 emissions from the polluting process industries. This paper is presenting, through various illustrative coal-based examples, the carbon capture, utilisation and storage (CCUS) technologies used to reduce the carbon footprint of the overall processes. The evaluations were focused on the conceptual design and the technical & environmental assessment of CCUS technologies with potential applications in power generation, iron & steel, cement and chemicals (including captured CO_2 utilisation for production of various chemicals e.g. methanol, substitute natural gas, synthetic fuel).

Two reactive gas-liquid and gas-solid methods were evaluated through illustrative examples. The first evaluated CO_2 capture option is based on gas-liquid absorption using chemical solvents (alkanolamines). The second capture option is based on calcium looping system. The carbon capture rate is set to 90%. Various coal-based processes were considered as illustrative examples e.g. combustion, gasification, cement production, integrated steel mill, coal to chemicals etc. The proposed conceptual designs were simulated; the mass & energy balances as well as the thermal integration tools were used to quantify the key technical and environmental performance indicators. The assessments show that CCUS technologies have significant advantages in reducing the environmental impact of energy-intensive industrial applications and simultaneously to produce useful products.

1. Introduction

The energy-intensive industrial applications (e.g. heat and power sector, metallurgy, petro-chemistry, cement production etc.) are facing fundamental changes in the attempt to reduce the greenhouse gas (GHG) emissions. Technical, economic and political measures are being used to curb the GHG emissions in the fight against climate change. For instance, European Union (EU) set binding targets for all member states to drastically reduce CO_2 emissions, improve energy efficiency and enhance renewable energy sources [1]. Carbon capture, utilisation and storage (C-CUS) technologies are promising solutions of changing the energy-intensive applications for transition to a low carbon economy [2].

The carbon capture from industrial processes can be done basically in three ways e.g. pre-, post- and oxy-combustion capture. Post-combustion capture is the most straight forward option, the flue gases resulted from the polluting process are treated for CO_2 capture (end of the pipe approach). The main penalising issue relating the post-combustion capture route lays in the fact that the CO_2 partial pressure in the flue gases is low; this aspect implies high energy consumption for the capture process [3]. Pre-combustion capture involves a partial oxidation process of the fuel (e.g. catalytic reforming, gasification) to produce syngas which then in subject to carbon capture producing a hydrogen-rich gas. The distinct advantage of pre-combustion capture vs. post-combustion capture is that the CO_2 partial pressure in the shifted syngas is high lowering significantly the energy consumption for the carbon capture process [4]. In addition, the pre-combustion route involves hydrogen production which then can be used for production of synthetic fuels/chemicals [5].

Oxy-combustion route involves using an oxygen-rich burning environment avoiding nitrogen contamination and therefore simplifying the carbon capture process. Important aspects to be considered here is the ancillary energy consumptions for cryogenic air separation as well as the retrofit of the boilers to withstand the oxy-fuel combustion [6]. As can be noticed, all three carbon capture approaches have pros and

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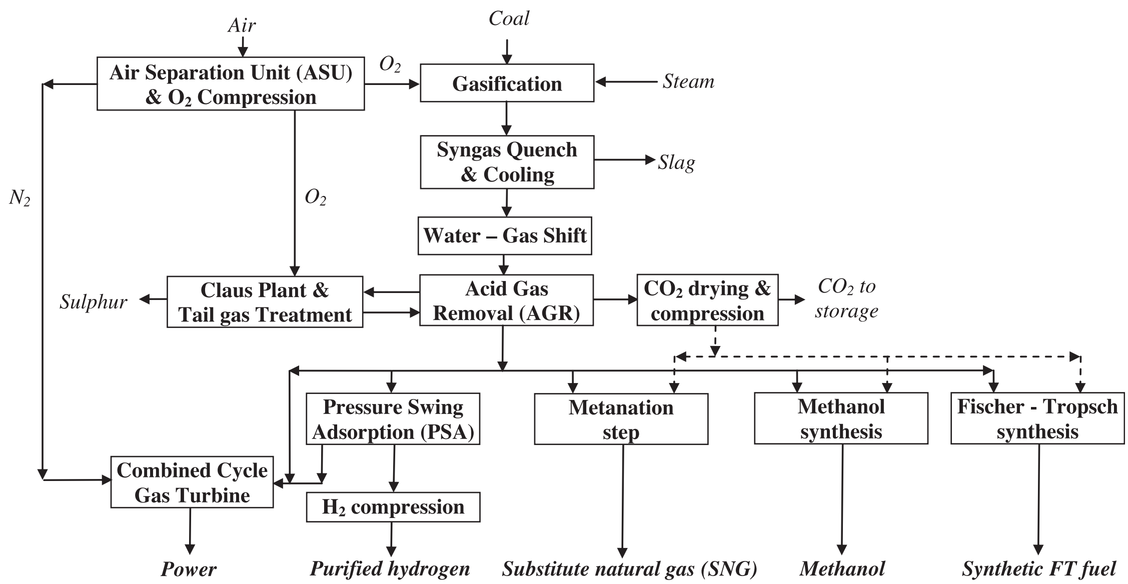

Fig. 1. Conceptual design of gasification-based poly-generation system with pre-combustion CO_2 capture.

cons, the situation became even more diverse when considering the particular processes subject for carbon capture [7].

This paper assesses two reactive gas-liquid and gas-solid systems to be applied in pre- and post-combustion capture configurations in various illustrative coal-based energy-intensive industrial applications. As evaluated industrial processes subject to decarbonisation, combustion and gasification power plants, integrated steel mill, cement production were considered [8–10]. In addition, for the pre-combustion CO_2 capture cases, the flexible energy-vector poly-generation scenarios were assessed for combined production of electricity and totally/partially energy carriers e.g. hydrogen, methanol, substitute natural gas (SNG), Fischer-Tropsch fuel. As an illustrative poly-generation system based on coal gasification process with pre-combustion CO_2 capture [11], Fig. 1 presents the conceptual layout of such a process.

As mentioned above, the syngas decarbonisation produces hydrogen which can be used as versatile chemical/energy carrier for developing low carbon applications [12]. For instance, various chemicals with energy value can be produced based on syngas as follows:

– Substitute natural gas (SNG):

$$CO + 3H_2 \rightarrow CH_4 + H_2O \quad (1)$$

– Methanol and dimethyl ether (DME):

$$2CO + 4H_2 \rightarrow 2CH_3OH \rightarrow CH_3OCH_3 + H_2O \quad (2)$$

– Fischer-Tropsch (FT) synthetic fuel:

$$nCO + \left(n + \frac{m}{2}\right)H_2 \rightarrow C_nH_m + nH_2O \quad (3)$$

Using this strategy of combining an energy conversion process with pre-combustion capture to produce hydrogen (to be used further for various energy applications including synthetic fuel production) the more direct but much more energy-intensive water electrolysis process can be avoided. Flexible energy vector poly-generation can bring important gains in term of overall plant energy efficiency [13] as an important innovative aspect of this work.

As evaluated carbon capture technologies, the chemical gas-liquid absorption using alkanolamines (e.g. methyl-diethanol-amine – MDEA) and the calcium looping (CaL) gas-solid system were assessed. The CO_2 capture gas-liquid absorption method is widely known in chemical sector (e.g. ammonia production) but its application in other industrial processes is rather new. Application of chemical scrubbing for CO_2 capture is done in a cycle, the gas to be treated is contacted with an aqueous solution of alkanolamine in the absorption column, the CO_2 rich solvent being then transferred in a separate column where heat in provided for CO_2 desorption and solvent regeneration (recycled back to the absorption stage). The main energy penalty of CO_2 capture by gas-liquid absorption process is represented by the heat duty for solvent regeneration (about 3 GJ/t CO_2) [14]. The conceptual layout of either pre- or post-combustion CO_2 capture based on gas-liquid absorption is presented in Fig. 2.

The calcium looping cycle for CO_2 capture is based on two interconnected circulated fluidised bed reactors [15]. In the first reactor (carbonation reactor), the gas to be treated is contacted with calcium-based sorbent, the formed calcium carbonate being then transferred in a second reactor (calcination reactor) where heat is provided (through oxy-fuel combustion) to decompose calcium carbonate into calcium oxide and CO_2. The main advantage of reactive calcium looping system in comparison to the chemical gas-liquid absorption is the high temperature heat recovery potential; the CaL reactors are operating at high temperature (500–1000 °C) in comparison to near ambient gas-liquid absorption columns [16]. The conceptual layout of CO_2 capture based on gas-liquid absorption is presented in Fig. 3.

The CaL cycle can be exploited in both pre- and post-combustion capture configurations. For instance, in case of pre-combustion CO_2 capture concept, the calcium-based sorbent is used to move the water gas shift equilibrium to the right:

$$CO + H_2O + CaO \leftrightarrow CaCO_3 + H_2 \quad (4)$$

2. Energy-intensive industrial applications, model assumptions, thermal integration

The following coal-based energy-intensive industrial applications with pre- and post-combustion CO_2 capture were assessed as illustrative cases:

Cases 1: Integrated gasification combined cycle (IGCC) power plants;
Cases 2: Super-critical pulverised coal (PC) power plants;
Cases 3: Integrated steel mills;
Cases 4: Cement production plants.