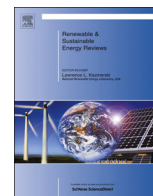




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## A journey into the process and engineering aspects of carbon capture technologies

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## ABSTRACT

Atmospheric warming due to greenhouse gases has become a serious global concern. Extensive efforts are being made to combat this phenomenon through Carbon Capture as carbon dioxide is its major contributor. In this work, a comprehensive review has been made on various Carbon Capture methodologies including adsorption, absorption, membrane separation, Chemical Looping Combustion, cryogenic separation with focus on their process chemistry, critical process parameters, contactor configurations, kinetics, thermodynamics, process development and scale-up. The challenges at the research and development stages have also been identified so as to provide the future directions for research.

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**Abbreviations:** AAP, agglomeration and attrition of particles;  $A_c$ , adsorption cycle; Apl.F, application formulated; APOC, analytical proof of concept; AR, air reactor; ARR, auto reduction reactor; BESs, bioelectrochemical systems; BFB, batch fluidized bed; BN, boron nitride; BPOB, basic principles observed; BR-MPBR, biomass retention-membrane photo bio reactor; BS, bench scale; BZX, binderless zeolite 13X; CASU, cryogenic air separation unit; CASU-PB, cryogenic air separation unit-packed bed; CC, CO<sub>2</sub> capture; CCI, combined cycles integrated; CDCL, coal direct chemical looping; CLAS, chemical-looping air separation; CLC, chemical looping combustion; CLOU, chemical-looping with oxygen uncoupling; CLP, calcium looping process; CMBS, circulating moving bed system; C-MPBR, carbonation-membrane photo bio reactor; CnC, counter current; CnC-MBR, counter-current moving bed reactors; Con-O, continuous operation; CPDm, component prototype demonstration; CPDt, component prototype development; CRS, condensed rotational separation;  $D_c$ , desorption cycle; DOCPB, dynamically operated cryogenic packed-bed; ESA, electric swing adsorption; FAC, fine activated carbon; FBR, fluidized bed reactor;  $F_{inlet}$ , feed inlet conditions; FPSC, free piston stirling cooler; FR, fuel reactor; FRR, fiber to resin ratio; FSCD, full-scale commercial deployment; GP, gas permeation; HCM, honeycomb monolith; HTC, hydro talcite; ICC, inlet CO<sub>2</sub> concentration; IFBR, interconnected fluidized-bed reactors; IPA, isopropanol amine;  $L_a$ , liquid flow area; LCT, laboratory component testing; LS, lab scale; MBA, moving bed adsorber; MCFC, molten carbonate fuel cells; MCR, max. compression ratio (per stage); MEA, methyl ethyl amine; MECs, microbial electrolysis cells; MEDC, microbial electrolysysis cell; MOF, metal oxide framework; MS, microwave synthesis;  $M_xO_y$ , oxidized form of metal oxide;  $M_xO_{y-1}$ , reduced form of metal oxide; N, absorption rate; NDC, non-dispersive contact; NPC10, nitrogen enriched porous carbons; OC, oxygen carrier; OFC-I, 1st generation oxyfuel combustion; OFC-II, 2nd generation oxy-fuel combustion; OFC-III, 3rd generation oxy-fuel combustion; PBR, packed-bed reactor; PEG, poly ethylene glycol; PEI, poly ethylene imine;  $P_{exit}$ , product exit conditions; Post-CCC, post-combustion CC; PP, partial pressures; Pre-CCC, pre-combustion CC; PSA, pressure swing adsorption; PSD, pilot scale demonstration; RPBR, rotary packed bed reactor; SAFB, sound assisted fluidized bed; SC, semi continuous; SLM, supportive liquid membranes; S-P, selectivity and permeability; SPM, substituted polymer membranes; SSCD, sub-scale commercial demonstration; STCR, steam-to-carbon ratio; STS, solvothermal synthesis; TSA, temperature swing adsorption; VPSA, vacuum pressure swing adsorption; ZIF, zeolitic imidazolate frameworks; ZX, zeolite 13X

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## 1. Introduction

The first meeting of United Nations Framework Convention on Climate Change (UNFCCC) held in 1992 had triggered for global concern on climate change due to GHG emissions. The global warming due to carbon dioxide emissions has been receiving worldwide attention to mitigate its adverse effect on the climate in terms of temperature rise, continuous rise in sea level, increasing occurrence of storms and floods. The main focus is on developing novel processes for carbon dioxide capture (CC) [1–4]. It has been predicted by the International Panel of Climate Change (IPCC) that by the year 2100, the atmospheric content of CO<sub>2</sub> shall reach 570 ppmv, rise in sea level of 3.8 m and a rise in global mean temperature of about 2 °C with very serious consequences on environment [5–8]. Coal continues to be the main fuel for power generation worldwide and hence integrating CC with power generation through pre and/or post-combustion options is on the main agenda [9,10].

The relationship between the CO<sub>2</sub> emissions (CD) with the population (*P*), economic development (represented by gross domestic product, GDP), energy production (*E*), carbon based fuels used for energy production (*C*) and CO<sub>2</sub> sinks (SCO<sub>2</sub>), expressed by the modified Kaya's identity [11]:

$$CD = P \frac{GDP}{P} \frac{E}{GDP} \frac{C}{E} - S_{CO_2} \quad (1)$$

It shows that the three feasible ways to reduce the CO<sub>2</sub> emissions viz., increase of energy efficiency (*E*/GDP), change of the fossil fuels to non-carbon forms of energy (for e.g., renewable and nuclear energy) and to create CO<sub>2</sub> sinks with the help of CC technology [12,13]. It can be achieved through technological options like pre-combustion removal of CO<sub>2</sub> from the fuel, post-combustion removal of CO<sub>2</sub> from the flue gases, oxyfuel combustion (OFC) to provide CO<sub>2</sub> at a high concentration in the flue gases, chemical looping and clathrate hydrate processes [14–16]. The presence of CO<sub>2</sub> at a relatively higher concentration and at a higher pressure in a pre-combustion option make them economically, thermodynamically and kinetically more attractive. Post-combustion CC though expensive is advantageous in that it can be successfully integrated to the existing power generation plants to enhance their efficiency with simultaneous CC. Oxyfuel combustion (OFC) CC is the latest of all technologies and is yet to be commercialized. By employing pure oxygen, the undesirable gases like NO<sub>x</sub> are minimized and

CO<sub>2</sub> concentration is enhanced. It can be operated at high pressures reducing the cost of CC. It, however, suffers from drawbacks like the need for expensive cryogenic air separation unit, higher material requirement and high temperatures for handling flue gases and their recirculation [17–19].

The post-combustion options for the CC are adsorption, absorption (physical and chemical), membrane and cryogenic separations (Fig. 2). Absorption based CC employs physical or chemical interactions between the CO<sub>2</sub> and the absorbent. Solvents like rectisol, selexol, etc. are employed for physical absorption [14]. For chemical absorption, solvents like amines, alcohols and their compatible blends, liquid ammonia and alkalis like NaOH, K<sub>2</sub>CO<sub>3</sub>, and Na<sub>2</sub>CO<sub>3</sub> are employed. Chemical absorption is widely employed due to higher capture efficiencies even at low concentrations of CO<sub>2</sub> and higher selectivity's [20–26]. Adsorption attaches gas or liquid on solid adsorbents which then could be regenerated by the application of temperature swing, pressure or vacuum swing. Adsorbents like activated carbon, alumina, metal oxides, zeolites and phosphates [14,27–30], metal organic frameworks [31–34], microporous carbons and polymers [35–39] and modified amines [40–42] are employed. CC could also be achieved through membranes separation of CO<sub>2</sub> from flue gases constituents due to its difference in permeability and selectivity. Organic (polymeric) and inorganic (ceramic, carbon, zeolite, metallic, etc.) membranes are employed for separation. Membrane also acts as a contacting device for the gas and the solvent moving in counter-current fashion with CO<sub>2</sub> getting selectively absorbed on the membrane matrix [15,43,44]. The advantages of the membrane technology are high product purity, low cost, continuous processing with very low start up time while the disadvantages could be non-attractiveness at low CO<sub>2</sub> concentrations and high flue gas temperatures and membrane fouling. Novel and effective membranes can be developed by incorporating functional groups like amines, combination of different and compatible membrane materials and manufacture of biomimetic configurations [45–47].

The fourth technical option of CC is cryogenic separation involving the compression and cooling of gas mixture with CO<sub>2</sub> at various levels to facilitate phase change of the CO<sub>2</sub> along with other constituents which can then be separated using distillation. The advantages of this process are that no chemical absorbent is needed, can be operated at atmospheric pressure and its compatibility with both pre- and oxy-combustion CC with easy transport of liquid CO<sub>2</sub> formed. Its drawbacks are its feasibility at high CO<sub>2</sub> concentrations (> 50%), formation of ice or solid CO<sub>2</sub> clathrates in the presence of water vapor leading to serious plugging, pressure

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