Post Combustion Carbon Dioxide Capture

R.Y.D. Hansa, J.W. Devasurendra, M.I.P. Maduwantha, G.A.L. Madhuwantha, D.M.C.O. Ranaraja

Faculty of Technology, University of Sri Jayewardenepura

Abstract— Capturing CO2 from flue gas is one of the critical options to reduce greenhouse gas emission to the atmosphere for that post-combustion CO2 capturing technology is widely used in most industries. Although various CO2 capture technologies are available, chemical absorption and adsorption are currently believed to be the most applicable ones for post-combustion power plants and industries. As post-combustion CO2 capturing techniques, the operation of chemical absorption, physical absorption, membrane separation, cryogenic separation, and adsorption are studied in this paper. In the past decade, several studies have been involved in developing post-combustion CO2 capture from flue gas with high capturing capacity and desired economics. This post-combustion CO2 capture technology's significant concerns include CO2 capture efficiency, absorption rate, the energy required in regeneration, and capacity of the absorber. A variety of promising sorbents such as activated carbonaceous materials, zeolites, carbonates, and polymeric resins loaded with or without nitrogen functionality to remove CO2 from the flue gas streams have been reviewed. The primary concerns for selecting adsorbent, including cost, adsorption rate, CO2 adsorption capacity, and thermal stability, are evaluated in this paper.

Index Terms— Absorption, Adsorption, CO_2 capture, Post-combustion CO_2 capturing technologies.

—————————— ◆ ——————————

1 INTRODUCTION

Carbon dioxide (CO2) is considered a significant greenhouse gas, and fossil fuel-fired power plants are the primary emitting sources [1]. The ever-increasing concentrations of Carbon dioxide (CO2) in the atmosphere require humankind to consider ways of managing emissions of this greenhouse gas to the atmosphere. Since most of this Carbon dioxide (CO2) is produced by the combustion of fossil fuels and, simultaneously, the global energy demand produces more Carbon dioxide (CO2). It is essential to find ways to sequester it. There are three main Carbon dioxide (CO2) capture technologies available. They are pre-combustion, post-combustion, and Oxy-fuel combustion. Pre combustion is, capturing the Carbon dioxide (CO2) before the combustion process. This is a costly process. Oxy-fuel combustion is, from the air, taking only Oxygen (O2), and then Oxygen (O2) react with the fuel and less amount of flue gas emitting. Post-combustion is, without careering about the fuel and the air, do the combustion and After the combustion process, remove the Carbon dioxide (CO2) from the flue gas. There are also several options for post-combustion carbon capture from flue gas. They are Chemical absorption, Physical absorption, Membrane separation, Cryogenic separation, and Adsorption.

2 CARBON CAPTURE

2.1 Chemical absorption

chemical absorption is suitable for CO_2 capture for industrial flue gases. This process involves a reaction between CO_2 and a chemical solvent which forms a weak intermediate compound. This compound can be regenerated by applying heat producing the original solvent and a CO_2 stream. Here relatively pure CO_2 can be produced. Furthermore, the selectivity of this separation is high. monoethanolamine (MEA) is the most commonly used solvent for chemical absorption.

Acidic gases such as SO_2 and NO_2 can affect the performance of the system by forming heat stable salts with the solvent. Therefore, these gases should be removed before absorption. Also, a SO_2 concentration less than 110ppm is acceptable [2]. SO_2 removal takes place in a Flue Gas Desulphurization (FGD) unit. NO is removed using following methods,

- Selective Catalytic Reduction (SCR),
- Selective Non-catalytic Reduction (SCNR) or
- low NOx burners.

21

Absorption process is done in towers called scrubbers. The turbulent flow of the solvents promotes rapid CO_2 extraction from gas to the solvent. The density difference help in the liquid gas separation. The CO_2 mixed solvent is pumped to the stripper and exposed to steam [3]. The CO_2 recovering process takes place in the stripper by heating the solvent to de-absorb the purified CO_2. After stripping, the solvent is recirculated back into the scrubbers. Although water has the capability to absorb CO_2 than N_2, it cannot meet with the large-scale CO_2 absorption. A large quantity of water is required to fulfil the particular requirement [4]. CO_2 has a higher solubility in organic solvents than in water even at high pressures. Therefore, organic solvents are better for use at large scale CO_2 absorption [4, 5].

Organic solvents combine with CO_2 in the scrubber and release it at the higher temperatures in the stripper. Amines are water-soluble organic chemicals. Amines contain reactive nitrogen atoms. Monoethanolamine (MEA) is the workhorse amine in the CO_2 separation process. Rapid reaction, non-volatility and the cost effectiveness are properties of amines which are advantageous for this process. But it can cost higher construction expenses due to its corrosion abilities [6, 7].

The trace impurities in the flue gas can reduce solvent's performance. Amine solvents like MEA degrade on contact with certain impurities such as excess oxygen, Sulphur dioxide or nitrous oxides to form substances including heat stable salts. Part of the bottoms product from the stripper is sent to a re-claimer unit where the solvent is evaporated and returned leaving the nonvolatile solvent wastes. The temperature inside the absorber is between 40°C and 60°C. The rich solvent is heated in a cross-heat exchanger by regenerated lean solvent from the Stripper. It is then pumped to the top of the Stripper where it is regenerated at high temperatures (100°C-120°C) and at a pressure (1.5 – 2 atm). Heat is supplied by the re-boiler [6]. The regenerated solvent is pumped back to the Absorber using the cross-heat exchanger to reduce the temperature (Figure 1).
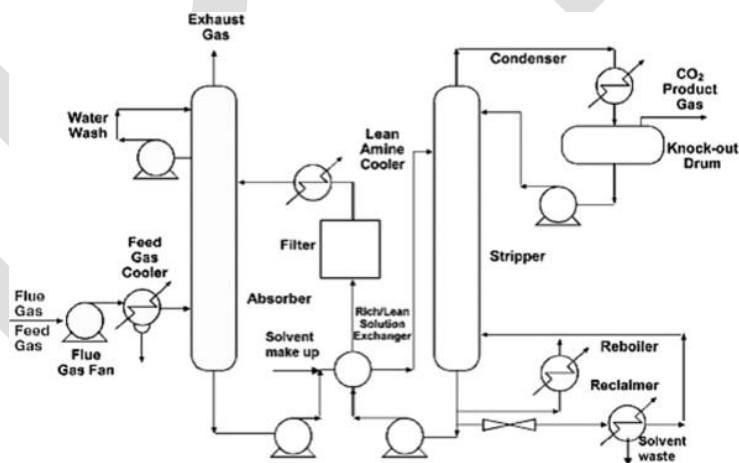

Figure 1: operational process structure of the absorption process [8]

2.2 Physical Absorption
Growing environmental issues after neutralization for global warming and climate change have motivated research activities to develop new models and processors for carbon dioxide capture (CO_2) from significant emitting sources. The Intergovernmental Panel on Climate Change (IPCC) 4th assessment report and some studies have stated that, as a result of anthropogenic CO2 emission, global atmospheric concentration has

increased from a preindustrial value of 280 ppm to 400 ppm in 2019 [9, 10]. Therefore, it is necessary for taking useful action regarding uncontrolled CO_2 emission to the atmosphere.

Among various technologies, some industries use the physical absorption method for CO_2 post-combustion capture. So, we have discussed further physical sorbent absorption in this section. Within the last few decades, researchers have involved in developing many physical sorbents to capture CO_2 from flue gas because it is essential to develop new technologies that will allow us to utilize the fossil fuels while controlling the emissions of greenhouse gases since it has become world's problem.

Physical absorption is a method Can be introduced as a physically dissolving gas in a physical solvent. It is generally considered to be based on Henry's law, which states that a dissolved gas loading in a physical solvent is proportional to the partial pressure of the gas. As shown in the gas-liquid equilibrium diagram (Figure 2), the physical solvent absorbs a given gas under conditions of high partial pressure in the gas phase and desorbs it under the condition of lower partial pressure [11]. Since a given gas is separated from the solvent using a driving force of a pressure difference, it is possible to remove and recover the gas with less energy.
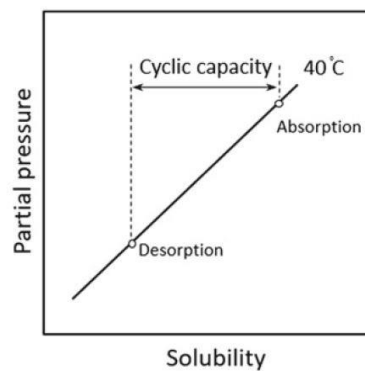

Figure 2: physical absorption[9]

As there many physical sorbents available in the market, we discuss only activated carbon base sorbents, Polymer-Based Sorbents, Zeolite-Based Sorbents, and Silica-Based Sorbents in this section for the removal of CO_2 from the flue gas stream [12].

Activated carbon-based sorbents

Activated carbon has been widely used for CO_2 capture due to its full availability, low cost, high thermal stability and low sensitivity to moisture are few reasons. But their applications are limited to treat high-pressure flue gas. Activated carbon-based sorbents can be categorized into weak CO_2 absorption material and high co2 absorption materials [13]. The absorption capacity of these materials can be enhanced by improving the surface area and pore structure. However, the main issue with activated carbon base sorbent is CO_2 absorption capacity decreases as the temperature increases.

Polymer-Based Sorbents

Polymeric based sorbents have been used for capture CO_2 in closed environments, such as aircraft, submarine, and space shuttles, under the concentration of $CO_2 < 1$ % [14]. However, the cost of these sorbents is too high for large-scale applications in the industry. Table 1 shows the CO_2 adsorption capacity of polymer-based solid sorbents.

Table 1. CO2 adsorption capacity of polymer-based solid sorbents [12]

Sorbent	Pore size (nm)	Pore volume (cm³/g)	BET surface area (m²/g)	Temperature T (K)	Presure p (atm)	Capacity (mol/g)
HSC*				313	1	0.91
TEPA-impregnated PMMA				343	0.15	14.03 (humid)
DBU-impregnated PMMA	20.3	0.58	94	298,338	0.1	3.0 (humid) 2.34 (humid)
PEI-impregnated PMMA				318	0.1	2.40 3.53 (humid)
PEI cross-linked with EP-coated fiber				303	1	6.30 (humid)
PEI cross-linked with ECH-coated fiber				303	1	4.12
Allylamine-grafted PAN fiber	3.08	0.0051	6.57	295	0.15	6.22

Zeolite-Based Sorbents

Natural and synthetic sorbents are widely used in industries gas separation and flue gas purification processes. The porous of Zeolite-based silicate frameworks has a negative charge within their pore structure, .which helps to separate CO_2 molecules via the molecular sieving effect. Table 2 shows the co_2 absorption capacities of various Zeolite-based sorbents.

Table 2: Absorption capacities of various zeolite-based sorbents [15]

Schemes	Material	CO₂ uptake
Structure and composition adjustment	CU-SSZ-13 H-SSZ-13	3.8 mmol g⁻¹ at 25°C. 1 bar 4.0 mmol g⁻¹ at 25°C. 1 bar 1.2 mmol g⁻¹ at 30°C. 1 bar

Cation exchange	Li-Rho Li-ZK-s Ca-A Zeolite Ca Sr2+ -SAPO 34 CHA and 13X	3.4 mmol g^{-1} at 25°C. 0.1 4.7 mmol g^{-1} at 25°C. 0.1 3.7mmol g^{-1} at 40°C. 15 bar 1.6 mmol g^{-1} at atroom temperature, 1bar 3.0mmol g^{-1} at 25°C. 1 bar 1.4 mmol g^{-1} at 200°C. 20
Amine modification	TEPA modified zeolite Y TEPA modified zeolite A G-SBA-15-NNN-(10)	2.6mmol g^{-1} at 60°C. 1 bar 3.8mmol g^{-1} at 25°C. 1 bar 2.2mmol g^{-1} at 40°C. 1 bar
Hybrid materials	SBA-3/cotton fiber	2.4mmol g^{-1} at 75°C. 1 bar

Silica-Based Sorbents

These sorbents have a high surface area, large pore volume, narrow pore size distribution, and excellent regeneration stability. According to literature, silica is mainly used as support, on which amines are added for capturing CO_2 [15]. Therefore, the research activities on silica-based CO_2 adsorbents are mostly focused on making different types of silica's-based sorbents with a high capacity of CO_2 absorption from flue gas. As there many silica-based sorbents, few of them are only used industrially by considering cost-effective and commercially availability. Table 3 shows silica-based CO_2 sorbents and their performance in CO_2 capture.

Table 3: Silica-based CO_2 sorbents and their performance in CO_2 capture [12]

Silica types	Surface Modifications	CO_2 uptakes
Conventional silica	PAA modified PEI modified	3.8mmol g^{-1} at 40°C. 1 bar 2.4mmol g^{-1} at 25^{0}C. 1 bar
Sillica hollow sphere	TEPA modified APTES & BTME modified MCFs PEI modified	4.4mmol g^{-1} at 110°C. 1 bar 1.7mmol g^{-1} at 0°C. 1 bar 6.0mmol g^{-1} at 85°C. 1 bar
Silica nanotube	Tertiaryamines modified	1.3mmol g^{-1} at 30°C. 1 bar
Chemical grafting	APS Grafted APMS grafted APTMS and Poly-L-alamine co-grafted	0.7mmol g^{-1} at 27°C. 1 bar 2.0mmol g^{-1} at 60°C. 1 bar 3.9mmol g^{-1} at 50°C. 1 bar

3.Membrane Separation

Membrane processes have been initially seldom considered within a post-combustion carbon dioxide capture framework. More traditional processes, particularly gas-liquid absorption in chemical solvents, are often considered as the most appropriate solution for the first generation of technologies [16]. Membrane separation might be a promising way with operating parameters beyond current technologies as they often have low energy consumption, low operational cost, small footprint and easy scale up and incorporation into existing technologies [17].

Membrane performs as a filter. It allows certain molecules to permeate through, while blocks other specific molecules from entering the membrane. Gas permeation flux across unit membrane area under unit pressure difference through unit membrane thickness is called permeability (mol s^{-1} m^{-2} Pa^{-1}) and the ratio of permeabilities of different gases through the same membrane is defined as selectivity. The gas separation mechanism varies from membrane to membrane. The selectivity of different gases may result from the difference in molecular size, affinity to membrane material, molecular weight, etc., depending on the gas and membrane of interest [18].

In order to recommend a membrane system for a specific gas separation process it should be proven that it can perform better separation or has better economics than other competing separation processes. Absorption, adsorption, and cryogenic distillation are widely adopted processes for large scale production when high purity and high recovery are required. Nevertheless, these processes are high energy consuming giving room for membrane systems to compete with these processes on an economical basis [19].

The flue gas mainly contains CO_2, H_2O and N_2. In here we discussed the CO_2 capturing using membrane arrangement. Post-combustion capture separates CO_2 at moderate temperatures and ambient atmosphere pressure. As a result, post-combustion capture has encountered much less difficulties and is therefore rather closer to practical application. The major challenge for post-combustion capture is the low CO_2 volumetric fraction in flue gas, that is, about 15%, which results in a low driving force of CO_2 permeation. The separation of CO_2 mainly relies on surface diffusion and solution diffusion, which is driven by the difference in adsorb-ability and solubility between the gases [18].

Schematically, the analysis of gas separation membrane processes for CO_2 capture depends on two different types of factors, which will be detailed in the next sections:

- a materials science aspect which addresses the evaluation of the intrinsic separation performances of the membrane. This topic typically requires the structure and/or the mass transfer mechanisms taking place in the membrane to be determined [16].
- a process engineering science aspect, which aims at the determination of the best design and operating conditions for a given membrane material. Classical tools of chemical engineering and separation science are used for this purpose [16].

Combining materials and process engineering considerations, the energy requirement and the size of the installation, the two-key data of technico-economical studies, can be finally obtained [16].

CO_2 is more likely to be favored by majority of the membrane materials via adsorption or absorption. Therefore, for post-combustion capture, CO_2 selective membranes are generally used. To capture CO_2 from flue gas, a membrane should satisfy a few requirements such as high CO_2 permeability, high CO_2 selectivity, high thermal and chemical stability and acceptable costs. So far, polymer-based membranes are the only commercially viable

type for CO_2 removal from flue gas. The membrane materials include cellulose acetate, polymides, polysulfone and polycarbonates. Table 4 shows the performance of several such membranes[18].

Table 4: CO_2/N_2 separation performance by polymer-based membranes.[18]

Membrane	Permeance[a] or Permeability[b] (mol s^{-1} m^{-2} Pa^{-1})	CO_2 /NO$_2$selectivity	Temperature (^{0}C)
Cellulose acetate	$2.48 \times 10{-}7$a	40.17	Not reported
Polymides-TMeCat	$6.30 \times 10{-}10$b	25	30
Polymides-TMMPD	$1.89 \times 10{-}9$b	17.1	Not reported
Polymides-IMDDM	$6.17 \times 10{-}10$b	18.1	Not reported
Polysulfone-HFPSF-oHBTMS	$3.31 \times 10{-}10$b	18.6	35
Polysulfone-HFPSFTMS	$3.47 \times 10{-}10$b	18	35
PolysulfoneTMPSFHBTMS	$2.27 \times 10{-}10$b	21.4	35
PolycarbonatesTMHFPC	$3.50 \times 10{-}10$b	15	35
Polycarbonates-FBPC	$4.76 \times 10{-}10$b	25.5	35
a Permeance b Permeability			

Selectivity larger than 20 was observed for all the polymer-based membranes with decent permeability. The high solubility of CO_2 in polymers ensures sufficient CO_2/N_2 selectivity. Furthermore, polymers with a high fractional free volume present excellent gas transport property.[18]

Mixed-matrix membrane is a new option to enhance the properties of polymeric membranes. The microstructure consists of an inorganic material in the form of micro- or nanoparticles in discrete phase incorporated into a continuous polymeric matrix. The addition of inorganic materials in a polymer matrix offers improved thermal and mechanical properties for aggressive environments and stabilizes the polymer membranes against the changes in chemical and physical environments. Carbon molecular sieves membranes also show interesting performance for CO_2 separation applications. Polyimide is the most used precursor for carbon membranes. Carbon membranes improved gas transport properties for light gases (molecular size smaller than 4.0–4.5Å) with thermal and chemical stability. The major disadvantages of mixed-matrix and carbon membranes that hinder their commercialization include brittleness and the high cost that is 1–3 orders of magnitude greater than polymeric membranes [18].

4.Cryogenic Separation

Cryogenic separation is also one of the physical processes, which is the Cryogenic separation produces liquid Carbon dioxide with under the high pressure [20, 21, 22]. Normally, a series of compression, refrigeration, and separation steps are using when the component of gas mixtures separating during the Cryogenic separation process [23]. Cryogenic separation is still not an economical process due to its variable high refrigeration cost. The high operating cost for cold production is the main limitation of the cryogenic separation process [24]. The simple process of the Cryogenic separator shows bellow in the Figure 3 [25].
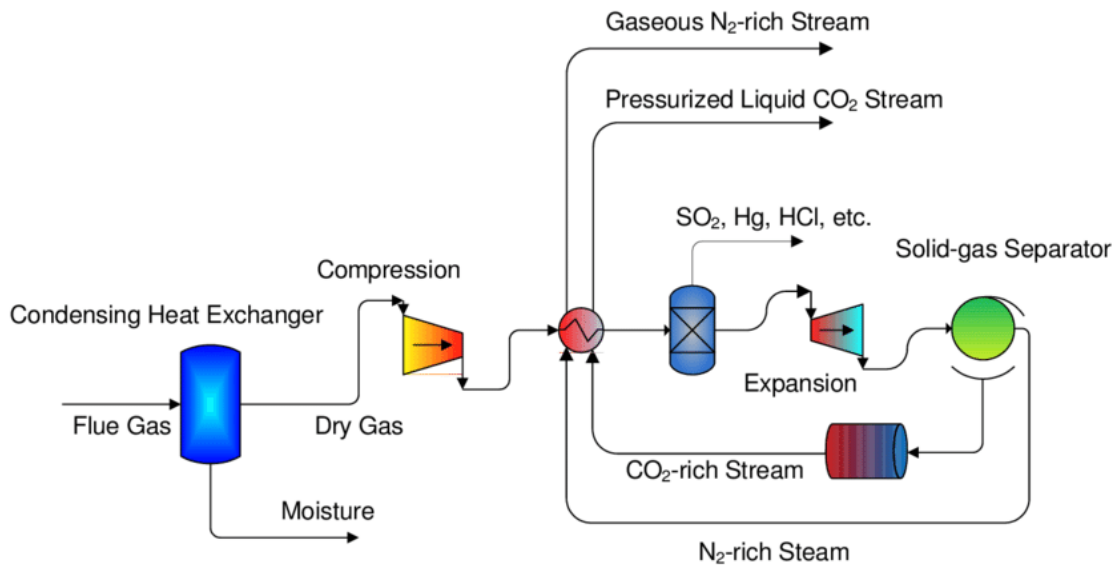
Figure 3: Simple schematic diagram of the cryogenic carbon capture process

Classification of cryogenic technologies: -

01. Conventional cryogenic methods: - liquid-vapor-based distillation and extractive distillation technologies
02. Nonconventional methods: - solid vapour desublimation-based separation, condensed contaminant centrifugal separation, successive release and recompression, and cryocoolers such as Stirling coolers
03. Hybrid technologies [26].

Advantages of cryogenic separation over chemical and adsorption-based processes: -

- Recurring consumable costs and secondary pollution of an industry can be avoided due to not use of chemicals and solvents. As well as solvent recovery plants are not required
- Makeup water supply and treatment are not required
- Process heating systems are not required
- Minimum corrosion potential
- There is no foaming potential
- Not need of winterization requirements for cold climates
- Pumping and storage of captured carbon dioxide are comfortable because of the cryogenic separation methods can capture carbon dioxide in a liquid form [26] [27].

5.Adsorption

Atmospheric CO_2 concentrations are rising due to anthropogenic emissions. Adsorption-Based CO_2 Capture Processes has motivated efforts to develop cost-effective and energy-efficient carbon capturing. Cyclic

adsorption-based CO_2 emission capture has emerged as a promising approach. There are mainly tree adsorption methods. They are pressure swing adsorption (PSA), vacuum swing adsorption (VSA), temperature swing adsorption (TSA) and electric temperature swing adsorption (ESA)[28]. PSA operates above atmospheric pressure, VSA happens at atmospheric pressure while desorption takes place under low pressure. During TSA, a desorber is heated by an external heat source. ESA is a type of TSA where electricity is used for fast desorption. In the moving process, adsorption and desorption happen alternatively to acquire high purity CO_2. This cycle is intermittent, and therefore a second set of the adsorber and the desorber is required to achieve continuous operation. Also, various solid adsorbents, which are classified into physical and chemical adsorbents, can be selected for capturing CO_2 in different applications.

As the Physical sorbents, zeolite 5A, zeolite 13X, activated carbon (AC) and silica gel have been widely investigated for adsorption-based CO_2 capture which is inexpensive, insensitive to moisture and with a large surface area. Several novel physical adsorbents, e.g. metal-organic framework (MOF), have attracted attention due to their large adsorption capacity and high gas selectivity. Nevertheless, their costs are relatively high compared to those of conventional adsorbents. As for chemical sorbents, amine-based materials are more advantageous due to their lower generation heat. **[29].**

Adsorption-based carbon capture is a material enabled technology. Porous materials including activated carbon, zeolites, and metal−organic frameworks, have been actively examined for use in CO_2 capture processes. Although capable cycle configurations are essential, the performance of cyclic adsorption processes depends heavily on the selection of adsorbent materials. layered double hydroxides (LDH), Zeolites and zeolites coated LDH composites are mainly used as the adsorption materials. CO_2 capture technologies have been lately implemented in many industries. However, the commercially mature technology to capture CO_2 remains an amine-based scrubbing, but its high cost and hazardous by-products force humankind to find out alternative technologies. [30]

The development of new solid adsorbents has flourished in the last decade. depending on their working temperature range the sorbents can be classified into high-temperature (> 400°C), intermediate-temperature (200–400°C), low-temperature (< 200°C) CO_2 adsorbents. layered double hydroxides (LDH) known as hydrotalcite-like compounds, are a class of layered materials which comprise mono or di and trivalent cations. In recently several researches have been dealing with the high potential of LDHs derived CO_2 adsorbents, especially conventional Mg-Al LDHs, which demonstrated excellent performance at high temperatures. Likewise, zeolites have also been subjected to further research for the adsorption of CO_2 due to their high stability, high capture capacity, low regeneration temperatures and over several adsorption-desorption cycles. Regarding sorbents working at an intermediate temperature range, recent studies have shown great potential from LDH coated zeolites. A significant increase in the adsorption of CO_2 was observed after the coating of LDH over a zeolite core at temperatures ranging from 35 to 300°C[28].

Conclusion

Carbon dioxide (CO_2) is the primary emitting source during the combustion of fossil fuel and it is a major

greenhouse gas. Therefore it is needed to control the emission of flue gas to the environment to minimize the greenhouse effect. Out of the three methods of capturing co2 such as pre-combustion, post-combustion and Oxy-fuel combustion, post-combustion can be considered as a more effective method. Among the post-combustion methods (Chemical absorption, Physical absorption, Membrane separation, Cryogenic separation and Adsorption), chemical absorption and physical adsorption are the most applicable ones for post-combustion power plants and industries. In chemical absorption, amines are used as a cost effective, rapidly reactive and non-volatile solvent. Adsorption-Based CO_2 Capture Processes has motivated efforts to develop cost-effective and energy-efficient carbon capturing.

As the Physical sorbents, zeolite 5A, zeolite 13X, activated carbon (AC) and silica gel have been widely us for adsorption-based CO_2 capture which is inexpensive, insensitive to moisture and with a large surface area.

The membrane separation process is also effective as it has low energy consumption, low operational cost, small footprint and easy scale up and incorporation into existing technologies

Although Cryogenic separation is having many advantages over chemical and adsorption based processes, it is not an economical process due to its variable high refrigeration cost. The high operating cost for cold production is the main limitation of the cryogenic separation process.

References

[1] U. S. P. R. Arachchige and M. C. Melaaen, "Aspen plus simulation of CO2 removal from coal and gas fired power plants," Energy Procedia, vol. 23, no. 1876, pp. 391–399, 2012, doi: 10.1016/j.egypro.2012.06.060.

[2]Mukherjee, A., Okolie, J. A., Abdelrasoul, A., Niu, C., & Dalai, A. K. (2019). Review of post-combustion carbon dioxide capture technologies using activated carbon. Journal of Environmental Sciences. doi:10.1016/j.jes.2019.03.014

[3] Merkel, T. C., Lin, H., Wei, X., & Baker, R. (2010). Power plant post-combustion carbon dioxide capture: An opportunity for membranes. Journal of Membrane Science, 359(1-2), 126–139. doi:10.1016/j.memsci.2009.10.041

[4] Oexmann, J., Kather, A., Linnenberg, S., &Liebenthal, U. (2012). Post-combustion CO2 capture: chemical absorption processes in coal-fired steam power plants. Greenhouse Gases: Science and Technology, 2(2), 80–98. doi:10.1002/ghg.1273.

[5] U.S.P.R. Arachchige, M. Muhammed, M.C. Melaaen, Optimization of post combustion carbon capture process-solvent selection. International Journal of Energy and Environment, 3, No. 6: 861-870, 2012.

[6] Wu, X., Yu, Y., Qin, Z., & Zhang, Z. (2014). The Advances of Post-combustion CO2 Capture with Chemical Solvents: Review and Guidelines. Energy Procedia, 63, 1339–1346. doi:10.1016/j.egypro.2014.11.143.

[7] U.S.P.R. Arachchige, M. Muhammed, M.C. Melaaen, "Optimized Carbon Dioxide Removal Model for Gas Fired Power Plant". European Journal of Scientific Research, 86, No. 3: 348-359, 2012.

[8] Wang, M., Lawal, A., Stephenson, P., Sidders, J., & Ramshaw, C. (2011). Post-combustion CO2 capture with chemical absorption: A state-of-the-art review. Chemical Engineering Research and

[9] R. Clement, E. Jensen, L. Prioretti, S. C. Maberly, and B. Gontero, "Diversity of CO_2 concentrating mechanisms and responses to CO_2 concentration in marine and freshwater diatoms," 2017, doi: 10.1093/jxb/erx035.

[10]A. Samanta, A. Zhao, G. K. H. Shimizu, P. Sarkar, and R. Gupta, "Post-Combustion CO_2 Capture Using Solid Sorbents : A Review," pp. 1438–1463, 2012.

[11]S. Nakao, K. Yogo, K. Goto, T. Kai, and H. Yamada, Springer briefs in energy.

[12]Y. Shi, Q. Liu, and Y. He, CO_2 Capture Using Solid Sorbents. 2015.

[13]C. Yu, C. Huang, and C. Tan, "A Review of CO_2 Capture by Absorption and Adsorption A Review of CO_2 Capture by Absorption and Adsorption," no. October 2012, 2015, doi: 10.4209/aaqr.2012.05.0132.

[14]A. Mathai and G. N. Karanikolos, "International Journal of Greenhouse Gas Control CO_2 capture adsorbents functionalized by amine – bearing polymers : A review," Int. J. Greenh. Gas Control, vol. 96, no. February, p. 103005, 2020, doi: 10.1016/j.ijggc.2020.103005.

[15]   J. Wang, L. Huang, and R. Yang, "Energy & Environmental Science," 2014, doi: 10.1039/C4EE01647E.

[16]B.Bouchra and F. Eric, "Membrane Separation Processes for Post-Combustion Carbon Dioxide Capture : State of the Art and Critical Overview," vol. 69, no. 6, 2014, doi: 10.2516/ogst/2013163.

[17] M. Kárászová et al., "Post-combustion carbon capture by membrane separation, Review," Sep. Purif. Technol., vol. 238, no. December, 2020, doi: 10.1016/j.seppur.2019.116448.

[18] G. Ji and M. Zhao, "Membrane Separation Technology in Carbon Capture," Recent Adv. Carbon Capture Storage, no. March, 2017, doi:

30

10.5772/65723.

[19] A. Alshehri, R. Khalilpour, A. Abbas, and Z. Lai, "Membrane systems engineering for post-combustion carbon capture," Energy Procedia, vol. 37, pp. 976–985, 2013, doi: 10.1016/j.egypro.2013.05.193.

[20] U. S. P. R. Arachchige, Carbon Dioxide Capture by Chemical Absorption: Energy Optimization and Analysis of Dynamic Viscosity of Solvents, Ph D thesis, University of South-Eastern Norway, ISBN: 978-82-7206-516-3. 2019.

[21] U.S.P.R. Arachchige, N. Aryal, M.C. Melaaen, Case study for flue gas separation of a coal fired power plant and parameters' effect on removal efficiency, Proceedings, APCRE'11 chemical engineering symposium, Beijing, China; 2011.

[22] U S. P. R. Arachchige, Dinesh K., and Morten C. M, Simulation of carbon dioxide capture for aluminium production process. International Journal of Modeling and Optimization (4-1), 43-50, 2014.

[23] G. Xu, F. Liang, Y. Yang, Y. Hu, K. Zhang, and W. Liu, "An improved CO2 separation and purification system based on cryogenic separation and distillation theory," Energies, vol. 7, no. 5, pp. 3484–3502, 2014, doi: 10.3390/en7053484.

[24] E. Knapik, P. Kosowski, and J. Stopa, "Cryogenic liquefaction and separation of CO2 using nitrogen removal unit cold energy," Chem. Eng. Res. Des., vol. 131, pp. 66–79, 2018, doi: 10.1016/j.cherd.2017.12.027.

[25] L. Baxter, A. Baxter, and S. Burt, "Cryogenic CO2 capture as a cost-effective CO2 capture process," 26th Annu. Int. Pittsburgh Coal Conf. 2009, PCC 2009, vol. 1, no. December, pp. 762–775, 2009.

[26] K. Maqsood, A. Mullick, A. Ali, K. Kargupta, and S. Ganguly, "Cryogenic carbon dioxide separation from natural gas: A review based on conventional and novel emerging technologies," Rev. Chem. Eng., vol. 30, no. 5, pp. 453–477, 2014, doi: 10.1515/revce-2014-0009.

[27] A. Hart and N. Gnanendran, "Cryogenic CO2 capture in natural gas," Energy Procedia, vol. 1, no. 1, pp. 697–706, 2009, doi: 10.1016/j.egypro.2009.01.092.

[28]   J. Park, H. O. RubieraLanda, Y. Kawajiri, M. J. Realff, R. P. Lively, and D. S. Sholl, "How Well Do Approximate Models of Adsorption-Based CO2 Capture Processes Predict Results of Detailed Process Models?," Ind. Eng. Chem. Res., vol. 59, no. 15, pp. 7097–7108, 2020, doi: 10.1021/acs.iecr.9b05363.

[29]   L. Jiang, A. Gonzalez-Diaz, J. Ling-Chin, A. P. Roskilly, and A. J. Smallbone, "Post-combustion CO2 capture from a natural gas combined cycle power plant using activated carbon adsorption," Appl. Energy, vol. 245, no. March, pp. 1–15, 2019, doi: 10.1016/j.apenergy.2019.04.006.

[30]   A. L. Chaffee, G. P. Knowles, Z. Liang, J. Zhang, P. Xiao, and P. A. Webley, "CO2 capture by adsorption: Materials and process development," Int. J. Greenh. Gas Control, vol. 1, no. 1, pp. 11–18, 2007, doi: 10.1016/S1750-5836(07)00031-X.