

CO₂ Removal from CH₄ by using Cellulose Acetate (CA) Membrane in Comparison with Adsorption, Absorption and Cryogenic Processes: A Case Study

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Conflicts of Interest

There are no conflicts to declare.

ABSTRACT

Natural gas is a homogenous liquid of low viscosity and low density or it may also be defined as a complex mixture of combustible hydrocarbon gases and impurities such as carbon dioxide, vapour, sulfur, hydrogen, and nitrogen. In order to fulfill the pipeline and environmental standards, these impurities must be removed. The major cause of climate change is carbon and sulphur emissions such as CO₂ and H₂S. For these impurities, the pipeline requirements are: <2% CO₂, <4ppm H₂S and <0.1g/m³ H₂O. Based on disadvantages in conventional processes, such as high energy consumption, complex processing and high capital cost, the development of membrane separation technique is highly compact, energetic, environmentally friendly, flexible, and possibly cost-effective than already well-established technologies. This study recommends the separation of CO₂ from CH₄ through membrane technology and introduces the cellulose acetate (CA) membrane in comparison with other established separation techniques including as absorption, adsorption, and cryogenic techniques and also suggests some ideas about current signs of progress in CA membranes such as enhanced permeability and selectivity. This study also emphasizes the modification of the cellulose acetate membrane and also outlines the essential distinctions, characteristics, and conditions of operation for the membrane process and other CO₂ removal approaches.

Keywords: CO₂ SEPARATION, MEMBRANE GAS SEPARATION, CELLULOSE ACETATE (CA) MEMBRANE.

1. Introduction

The burning of petroleum fuel, coal gas, and natural gas streams is the major source of CO₂ emission. CO₂ gas decreases the natural gas efficiency

and making it corrosive owing to its acidity, reducing the calorific value of gas streams, and causing the problem in gas storage and transport issues (Solomon S.Q.D et al., 2012). (C. A. McMillan et al., 2005). The

greenhouse effect also occurs due to the presence of water vapour and CO₂ in natural gas. The concentration of water vapor does not rely directly on human activity but temperature and other factors effects human health (Blasing, T.J et al., 2009) (Hongqun Yang et al., 2008) (Paola Bernardo et al. 2013). CO₂ is the main source of the greenhouse effect, representing 77% of the human greenhouse effect contribution in the last twenty years (26 to 30% of all CO₂ emissions). The burning of fossil fuels produced the main anthropogenic carbon dioxide emissions. Fuel such as coal (12–15 mol-% CO₂) and natural gas rely on the level of CO₂ in flue gases (1-2 mol- % CO₂). Therefore, it is timely need to separate CO₂ from CH₄. In petroleum industries, the greenhouse impact has been significantly improved by the separation of CO₂ from exhaust gases (Paola Bernardo et al., 2013) (Chaffee, A.L et al., 2007). Many ways have been used before CO₂ is compressed and delivered in gas streams for the mitigation of these challenges. On the other hand, CO₂ can be utilized as an e-oil recovery agent, which can be injected into the reservoir to enhance reservoir productivity (C. A. McMillan et al. 2005) (Farrar, C et al., 1999) (Yoro, K et al., 2016). Natural gas is also known as methane (CH₄). Studies have been done in recent years to look for effective gas separation membrane structures, membrane casting methods, and the membrane module. It was also noticed that with the passage of time, the efficiency of the membrane reduced owing to the plasticization problem but still there are many ways to improve it which are also briefly discussed in CA membrane section. Membrane can be affirmed as a very aggressive CO₂ extraction technology from CH₄ (Chaffee, A.L et al., 2007) (Songolzadeh M et al., 2014).

Table 1: The main greenhouse gases and their concentration [10, 11].

Compound	Preindustrial concentration (ppmv)	Atmospheric lifetime (years)	Main human activity source	GWP
Water Vapor	0.5	1960-200	Petroleum and natural Gas	-10-3 5×10 ⁻⁴
Carbon dioxide (CO ₂)	280	~100	Renewables, concrete production, and land utilization.	1
Methane (CH ₄)	0.715	12	Petroleum energy, fields of rice, dumping trash and cattle	25
Hydrogen Sulfide (H ₂ S)	20-40	Few hours	Petroleum, natural gas, pulp and paper manufacturing	16300
Perfluoromethane (CF ₄)	0.00007	49,000	While production of Aluminum	7000
Perfluoroethane (C ₂ F ₆)	0 0.000005	9,500	Production of aluminum.	10000
Sulfur hexafluoride (SF ₆)	0 0.00000918	3,600	Dielectric fluid	23,300

Whenever fuel is burnt, the amount of CO₂ generated is based on the percentage of carbon available in the fuel. The heat content or the energy produced in the combustion of a fuel is governed mostly by the fuel's carbon and hydrogen content (Dantas T.L.P et al., 2011) (Tsotsis et al., 2002). While burning, heats are created by combining carbon and hydrogen with oxygen (Budd P et al., 2005). CH₄ is more energy-efficient compared to other fuels and hence has a comparatively lower CO₂-to-energy proportion. The heat value of

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water and other components such as sulfur and non-combustible impurities in certain fuel reduces and the CO₂ concentration increases. The energy they generate when combusted from differing fuels emits varying amounts of carbon dioxide (CO₂). Compare the quantity of CO₂ emitted for each unit of energy or heat contents to evaluate releases across fuels (Mohammadi A et al., 2013) (Worrell E et al., 2001).

Table 2: Pounds of CO₂ emitted per million British thermal units (Btu) of energy for various fuels

Fuels	CO ₂ released/Btu
Natural gas (CH ₄)	132.0
Propane (C ₃ H ₈)	155.0
Petroleum	165.7
Crude oil and petroleum diesel	173.9
Subbituminous (Coal)	218.0
Anthracite (Coal)	229.1
Bituminous (Coal)	207.0
lignite (Coal)	216.5

Worldwide CO₂ emission from energy consumption has been steadily increased between 1751 and 2020. Figure 1 illustrates that the greatest proportion of CO₂ emissions in power generation plants (55% of world Emissions of CO₂), transport (23%), and industries (19%). The two largest CO₂ emission sectors include exhaust gasses and petroleum refineries (petrochemical) while the cement industry provides around 5% to global anthropical CO₂ emissions. Petrochemical industrials also account for a substantial part of CO₂ emissions, for example, the emission of around 21 tonnes/year from the petrochemical industry in Iran and Pakistan alone (Yang, Z.X et al., 2008) (Kim, Y et al., 2005).

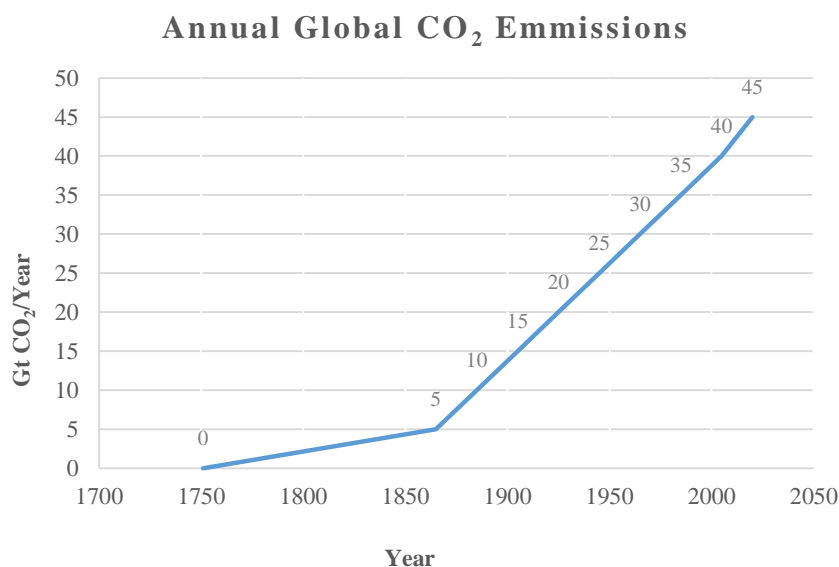


Figure 1: Global CO₂ grown emissions from fossil fuel combustion emitted in the over years

According to the IGPPC (Inter governmental Panel on Climate Change), the air may cover up to 583 ppmv CO₂ by 2021, bringing a 1.9°C rise in mean global temperatures and 38m rising sea level accordingly (Kim, Y et al., 2005). Considering that the earth's average temperature is continuing to increase, the IGPPC has declared that worldwide GHG emissions must be reduced by 50% to 80% by 2050 to prevent catastrophic global warming effects (Lin, H et al.,). The most promising technique for reducing CO₂ emissions from fossil

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fuel sources to the environment is carbon capture and storing (CCS) via a membrane. CO₂ extracted from flue gases may also be utilized in enhanced oil recovery (EOR) activities, which include injecting CO₂ into petroleum reservoirs to improve oil mobility and reservoir recovery (Cecopierigomez, M et al., 2007) (Christodoulou A et al., 2018).

This case study provides a brief overview of the membrane technology, followed by updates on membrane technology and advancements in membrane design for CO₂ extraction from exhaust gases. This study concentrates mainly on the ideas to modify membrane for their efficiency, such as assisted cellulose acetate membrane and mixed polymer membranes, which produce better separations than basic polymeric membranes. In this study, other separation strategies are also explored and compared (Pires, J et al., 2011) (J. G. J. Olivier et al., 2014).

Separation Techniques for CO₂ Removal

Table 3: Comparison between CO₂ separation techniques

Separation Techniques	Comparison
Membrane	The absorption of CO ₂ across the membrane is increased. Changes in a polymeric material can enhance solubility, and raising free space volume can promote CO ₂ diffusion. The addition of bulk substitute groups, improved membrane casting techniques, and annealing conditions may enhance the free volume (J. G. J. Olivier et al., 2014).
Sorbents	Sorbents fit well for low-to-medium feed contents of the desired component (J. G. J. Olivier et al., 2014).
Solvents	CO ₂ selectable solvents were studied for use as components in fluid separations as solvent extraction, mainly neutral solvents that switch from CO ₂ to ionic species (Howard Herzog et al., 2009).
Cryogenics	The cryogenic approach cannot be utilized for the extraction of CO ₂ from streams such as gas from coal-fired or natural gas plants, because of the comparatively tiny amounts of CO ₂ in these sources, And the energy necessary to transmit the stream to zero cryogenic application temperatures would be uneconomical for the whole process (Knapik, R.C et al., 2019).

Adsorption for large-scale removal of CO₂ from the exhaust gas is not currently considered to be attractive due to its small capacity and CO₂ selectivity. The Figure 1 also compares the different separation technologies with those already in operation worldwide and observed from literature and research that recently membrane technology is extensively active in the removal of CO₂-based natural gas (Loeb S et al., 1962) (Kosinov, N et al., 2016).

Currently used processes for CO₂ Separation

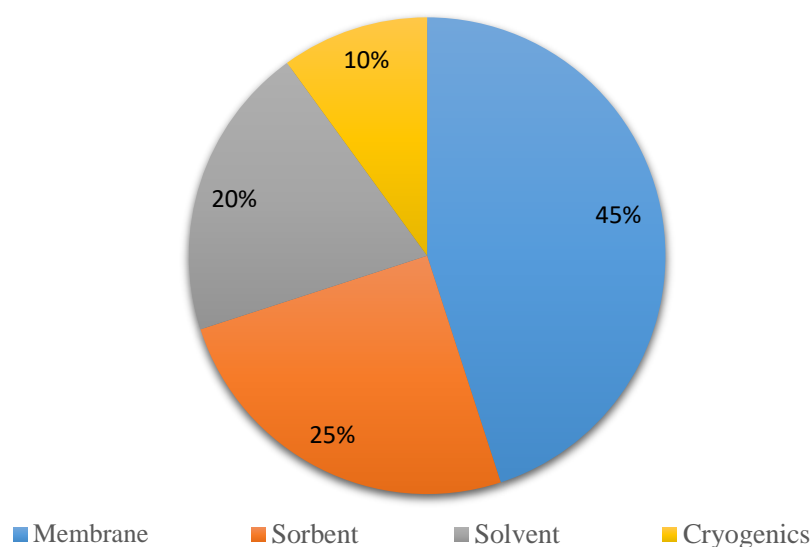


Figure 2: Overview chart of comparison separations techniques with membrane separation

Various other techniques for CO₂ gas separation also have been used in previous studies other than Membrane (cellulose acetate membrane) such as absorption process, adsorption process, and cryogenic process, but these techniques are failed to purify gas or capture CO₂ in good quality and good quantity due to their drawbacks (Gnanasekaran, D at al., 2012). The solvents in these processes' results corrosion as well as erosion since the technology for large-scale removal of CO₂ from flue gas is not yet deemed desirable. Further, existing adsorbents have limited capacity and CO₂ selectivity. The table below clearly highlights the drawbacks of the separation techniques other than the membrane approach (Ghalei, B et al., 2007) (C. Joly et al., 1997).

Table 4: Drawbacks of processes other than Membrane technique

Process	Drawback
Absorption process	Absorption causes environmental hazards
Adsorption process	Less cost-effectiveness, Loading capacity decreases with increasing temperature.
Cryogenic process	Using this method reduces overall plant efficiency and increases the probability of unit operations obstruction.

2. Membrane Technology

The membrane technology is relatively new approaches compared to other separation approaches which were started four decades ago. The earliest case studies on membranes and osmosis retrieve the central phase of the 18th century when Nollet found that a pig's vesicle transmits ethanol in contact with a combination of water-ethanol on one side as well pure water on the other. The relationship among both osmotic and a cellulose acetate membrane was believed to be known initially to Nollet (Yong, W.F et al., 2021) (Rhim H rt al., 1975). The permeation is the sum of the diffusion factor and the sorbent factor. A

kinetic description that reflects the ambient circumstances of the permeable molecules is the diffusion parameter. The coefficient of sorption relates the concentration of components in the fluid phase to the polymer phase. The solubility of gases in the polymeric cellulose acetate (CA) membrane phase may be identified with thermodynamics. The diffusion coefficient is usually affected more than the sorption coefficient by changes in membrane material, as in equation (1) (Lee KH et al., 1986) (Clarizia, P.B et al., 2013).

$$\frac{P}{l} = \frac{Q}{(A\Delta P)} \quad (1)$$

As in the previous discussion, it was said that Graham with Loeb, and Sourirajan created the concept of membrane separation in 1866 by presenting an anisotropic membrane that further reinforces this field. Throughout the 1980s and 1990s Separex, Gneron, and Cynara contributed much to the technical and commercial purification of gas (Knapik, R.C et al., 2019) (Tong, Z et al., 2021). These advancements make membrane gas separation a competitive instrument in the industrial sector. This technique is now commonly utilized in the natural gas pulverizing industries to eliminate CO₂ (Btddeder, K.W et al., 1995).

This method relies on separation methods, including separation with diffusion and molecular sieving (Farrar, C et al., 1999). Removal of CO₂ in the membrane happens when the radius of a pore is shorter than the mean free route of gas molecules; molecules collide with pore walls more than with each other, then accumulate and reflect in a random direction. Different median free pathways of gas molecules, which depend on their molecular weight. The contact of gas molecules that are deposited with the pores relies on surface diffusion (Tong, Z et al., 2021) (Xu, J et al., 2018).

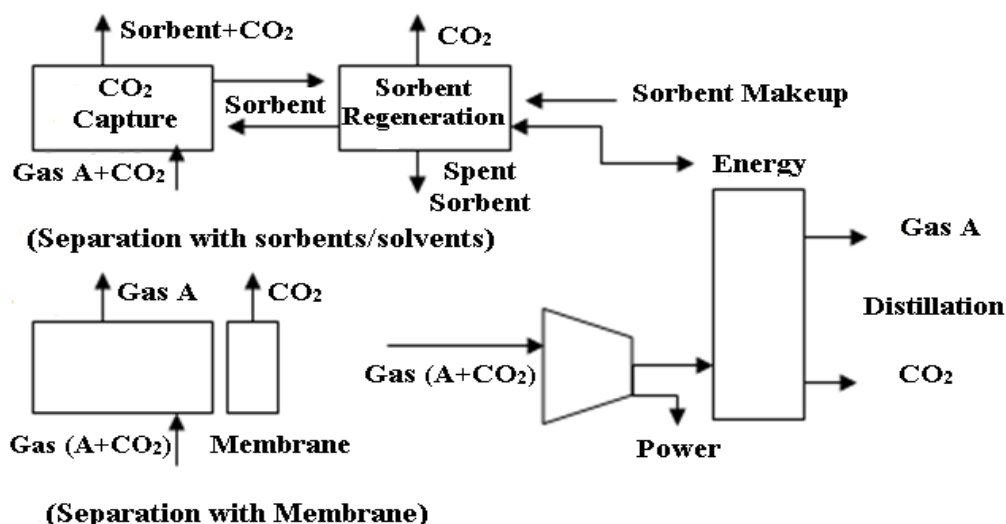


Figure 3: Schematic design for the removal of CO₂ with different steps in the cycle

The membrane CO₂ removal unit had several clear regeneration approaches and increased temperature while maintaining almost constant pressure and heating of the solid via the Joule action and this shows that CA membrane is usually dense (Baker, J.G et al., 1995) (Junaidi, M.U.M at al., 2013). CO₂ emissions by natural gas are ~25.7% less than oil and coal. Natural gas has an excellent fossil fuel background. It emits

significantly less greenhouse emission than petroleum or coal while using this fossil fuel. However, we can't argue that it's environmentally friendly (Fick, A et al., 1995) (Yave, W et al., 2010) (Le Blanc et al., 2009). In natural gas there are the lowest carbon dioxide emissions, thus it is better to use the CA membrane to retrieve the rest of the CO₂ from that lowest carrier efficiently (Allen, J.G et al., 2016).

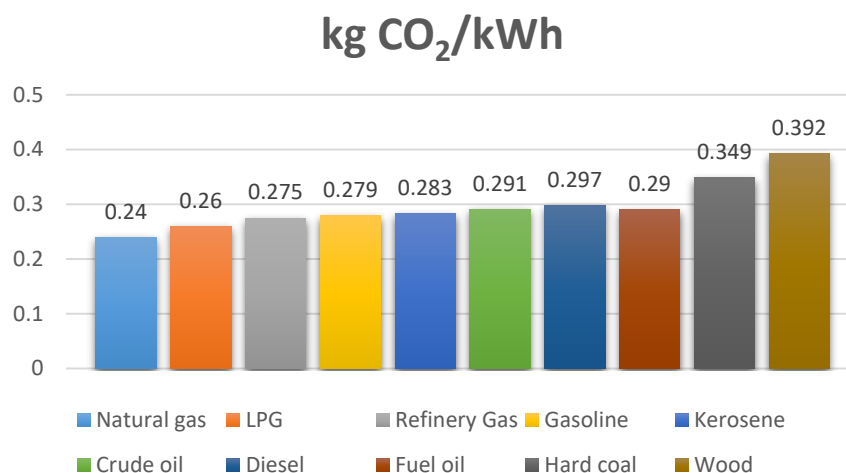


Figure 4: CO₂ content kg/kWh in Natural gas and other materials before separation process through the membrane

Cellulose Acetate (CA) Membrane

CA membrane was initially developed for reverse osmosis but is currently the most robust carbon rinse membrane available. Due to the glassy structure in CA membrane, this membrane is more efficient than polysulfone membrane (PSF) because in CA plasticization property is less than PSF (Jiang, L et al., 2006). Furthermore, For CO₂ separation, cellulose acetate and its derivatives are employed. The membranes are formed by a thin selective skin layer with a less selective porous base. The porous substrate provides mechanical strength under high pressure (Xiaobo Dong et al., 2021) (Bake, R.W et al., 2002). This membrane type is known as a polymeric membrane. In CA membrane, the flow of CO₂ reduction is higher as compared to other asymmetric membranes but in time owing to plasticization effects less than other membranes. CO₂ separation polymeric membranes (CA) with high performance may be produced by maintaining higher solubility in the membrane and improving CO₂ diffusion across the membrane (Scholz, M et al., 2011) (Linfeng Leia et al., 2020). Modifications in polymer composition can enhance solubility, and expanding free space volume which can promote CO₂ diffusion. Inserting bulk substitution groups, improving membrane casting processes, and annealing conditions can help to enhance free volume (Quesada Cabrera et al., 2011) (Sazali, N et al., 2020).

Polyaniline, polypyrrole, and polyacrylates are examples of patented polymeric membranes as reported in previous studies. PSF is a chemically and thermally stable polymeric with good selectivity and permeability for gas separation but PSF has more plasticization than CA membrane (Isanejad, M et al., 2017) (Pak, S.H et al., 2016). The new applications focus more on CA polymeric membranes, this membrane is made up of a hard-glassy component and a soft rubbery segment. The structural core is made up of hard polymeric segments, while the soft or rubbery segments form a thin layer on the hard support. Due to the

thick skin layer and porosity, the resulting membranes exhibit excellent selectivity and permeability (Xi, Y.H et al., 2018) (Mubashir, M et al., 2018).

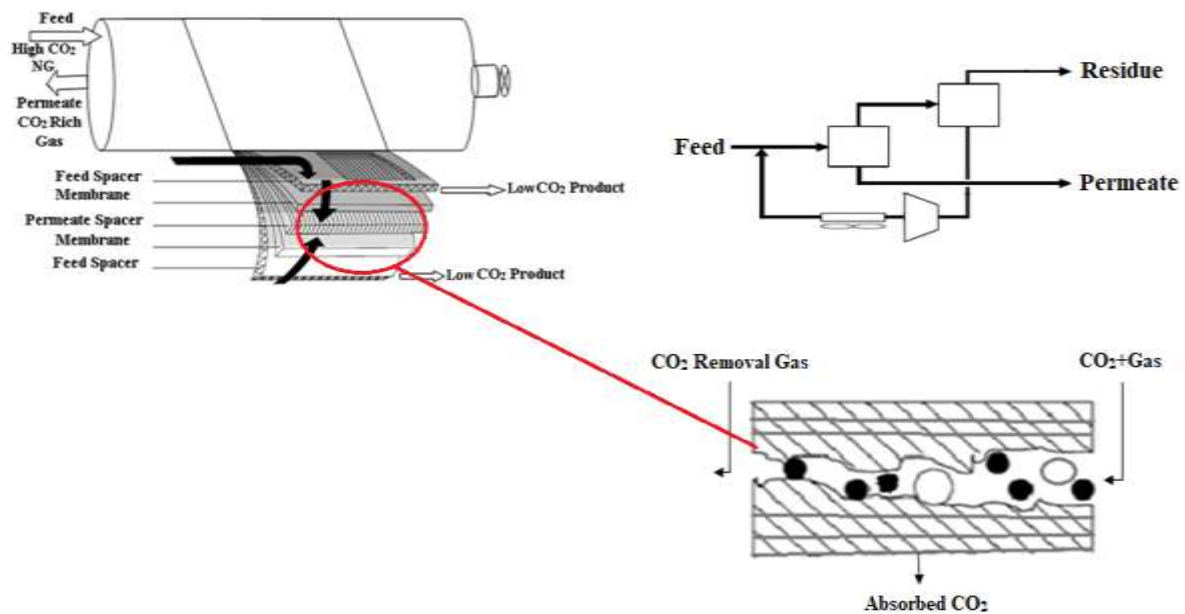


Figure 5: Spiral Wound Membrane Element CO₂ Removal Gas (Hamidreza Sanaeepur et al., 2019).

Two flat sheets with a dissolved or permeated spacer between arcs bonded together with three of their faces in a packing cabinet are within the circular pattern element. Feeding removes several of these packages, which are then coiled around a permeate pipe with their open ends facing the permeate tube (Ishigami, T et al., 2012). Feed Gas passes together with the membrane side through the separators. When the gas travels between the wrappers, the carbon dioxide, hydrogen sulphides, and other extremely porous materials are dissolving or penetrating the collector. There is just one exit for these dissolved or entered components, which means that component must be dissolved or permeated into that exit section (Jamil, A et al., 2018) (Wakui, T.A et al., 2020). The permeated gas passes into the pipeline through pores from which it travels and flows down and this continues as recycled process. Very thin hollow fibers are wrapped around a central pipe in a large design in hollow-fiber components. In this design, the two free ends of fiber eventually disintegrate on the side of the element (Salvatore F et al., 2021) (Stepan D. Bazhenov et al., 2018). Circular wounds in the membrane separation section can handle greater and less sensitive pressures and have a lengthy emphasizing the service in sweetening of natural gas. Elements with hollow fibers cannot tolerate greater, usually lesser pressures, but they can be modified with increasing solubility of a polymeric section of the membrane (Ahmed W. Ameen et al., 2020) (Can Zeng Liang et al., 2021).

CA is a natural plastic, which is produced from de-contaminated natural cellulose. Natural cellulose of the proper properties is formed initially from two sources, wood pulp, and cotton linters. In the production process, CA is produced by reacting natural cellulose with acetic anhydride, which occurs in flake (Hölter, J et al., 2011) (Meier, J et al., 2021) That flake is then converted into fine powder by grinding. CA in primary form cannot be treated as a thermoplastic. It can only be treated by liquefaction in a solvent and spinning. However, it can be treated by plastic treating techniques in compounded form. For CA granules or plastid, CA

has to be homogenized with a desirable combination of additives and plasticizer in order to melt or compounded to achieve granules (Juergen Puls et al., 2011) (Shuangping Xu et al., 2021).

3. Possible Research

1. There are many proposals for CO₂ separation, however, none have yet emerged as a clear energy efficiency champion. One approach is CO₂ removal selectively from conventional flue gas or separating O₂ from the air before burning might be beneficial, this would decrease the difficulties associated with separating CO₂ from the resultant effluent. There are variations on these subjects and more exotic options are offered. All of these CO₂ removal systems need gas separation techniques. Solvent methods, chemical adsorbents, and membrane separations are currently utilized to separate gases for CO₂ extraction. To maintain the solvent or drive efficient separation for CO₂ removal, all existing methods need a considerable amount of energy. Solubility research has revealed that the lowest energy necessary to carry out in any of these operations is considerably less than that utilized by today's membrane technology alone. If energy sources are to be part of a low-carbon dioxide system with minimal greenhouse gas emissions, research on effective, low-cost CO₂ capture technology will be necessary, and will be beneficial throughout transitions to alternative energy sources.

2. The impacts of plasticization can interfere with the generation of CO₂ removal. CO₂ capture polymeric (CA) membranes with high performance may be accomplished by increasing CO₂ solubility in the membrane and increasing CO₂ flow across the membrane. Changes in the chemistry of polymers and increased free space volume can enhance the solubility of CA membrane materials; casting and rinsing techniques can further enhance CO₂ and bulk material diffusion over the membrane region.

4. Conclusion

Recently, membrane-based gas separations are well stabilized and contend with cryogenic distillation, absorption, and pressure swing adsorption in chemical processing amenities. Based on overall economies, safety, environmental and technical considerations, membranes stay competitive as an alternative separation method. The main focus of research and development should be carried out on producing ideal CA membranes to fulfill the major reliability and durability standards for commercial processes. CA plastid is a high-performance polymer that combines novel manufacturing ideas with new membrane applications. From case study, it is found that CA membrane has the efficiency to reduce CO₂ from CH₄ < 2% CO₂, < 4 ppm H₂S and < 0.1 g/m³ H₂O and due to glassy structure, CA membrane has high transparency, high mechanical strength and best resistance.

References

1. S.Q, Solomon S.Q.D., M.Manning. Book Reviews. South African Geographical Journal. 2012; 91(2): 103-104.
2. C. A. McMillan G.A.K., and D. V. Spitzley. Greenhouse Gases. University of Michigan, Ann Arbor, Mich, USA. 2005.
3. Blasing, T.J. Recent Greenhouse Gas Concentrations. USDepartment of Energy, 2009. 32 Editions.
4. Hongqun Yang, Z.X.a.M.F. Progress in carbon dioxide separation and capture: A review. Journal of Environmental Sciences. 2008; 20: 14-27.
5. Paola Bernardo, G.C. 30 Years of Membrane Technology for Gas Separation. Chemical Engineering Transactions. 2013; 32: 1999-2004.
6. Chaffee, A.L. CO₂ capture by adsorption: Materials and process development. International Journal of Greenhouse Gas Control. 2007; 1(1): 11-18.
7. Farrar, C., J. Neil, and J. Howle. Magmatic Carbon Dioxide Emissions at Mammoth Mountain, California. USGS Water Resources Investigation Report. 1999: 98-4217.
8. Yoro, K. and P. Sekoai. The Potential of CO₂ Capture and Storage Technology in South Africa's Coal-Fired Thermal Power Plants. Environments. 2016; 3(4).
9. Songolzadeh M. Carbon dioxide separation from flue gases: a technological review emphasizing reduction in greenhouse gas emissions. Scientific World Journal. 2014: 828131.
10. Dantas T.L.P. Carbon dioxide–nitrogen separation through pressure swing adsorption. Chemical Engineering Journal. 2011; 172(2-3): 698-704.
11. Tsotsis, J.G.S.M.a.T.T. Catalytic Membranes and Membrane Reactors. Wiley-VCH Verlag Gmb H. 2002.
12. Budd P. Gas separation membranes from polymers of intrinsic microporosity. Journal of Membrane Science. 2005; 251(1-2): 263-269.
13. Mohammadi A. What is energy efficiency and emission reduction potential in the Iranian petrochemical industry? International Journal of Greenhouse Gas Control. 2013; 12: 460-471.
14. Worrell E, L.P., Martin N., Hendriks C., and Meida L. O. Carbon dioxide emissions from the global cement industry. Annual Review of Energy and the Environment. 2001; 26: 303– 329.
15. Yang, Z.X., M.F. Progress in carbon dioxide separation and capture: A review. Journal of Environmental Sciences. 2008; 20: 14–27.
16. Kim, Y., Park H., and Y. Lee. Gas separation properties of carbon molecular sieve membranes derived from polyimide/polyvinylpyrrolidone blends: effect of the molecular weight of polyvinylpyrrolidone. Journal of Membrane Science. 2005; 251(1-2): 159-167.
17. Kim, Y., H. Park, and Y. Lee. Preparation and characterization of carbon molecular sieve membranes derived from BTDA–ODA polyimide and their gas separation properties. Journal of Membrane Science. 2005; 255(1-2): 265-273.

18. Lin, H. and B.D. Freeman, Materials selection guidelines for membranes that remove CO₂ from gas mixtures. *Journal of Molecular Structure*. 2005; 739(1-3): 57-74.
19. Cecopierigomez, M., J. Palaciosalquisira, and J. Dominguez. On the limits of gas separation in CO₂/CH₄, N₂/CH₄ and CO₂/N₂ binary mixtures using polyimide membranes. *Journal of Membrane Science*. 2007; 293(1-2): 53-65.
20. Christodoulou A., D.H. Impacts of climate change on transport - A focus on airports, seaports and inland waterways. EUR 28896 EN. Publications Office of the European Union, Luxembourg. 2018.
21. Pires, J.C.M. Recent developments on carbon capture and storage: An overview. *Chemical Engineering Research and Design*. 2011; 89(9): 1446-1460.
22. J. G. J. Olivier, G.J.M., and J. A. H. W. Trends in global CO₂ emissions. Tech. Rep., PBL Netherlands Environmental Assessment Agency. Ispra, Italy. 2014; 1490.
23. Howard Herzog, J.M.a.A.H. Advanced Post-Combustion CO₂ Capture. Tech. Rep., Clean Air Task Force. Doris Duke Foundation. 2009.
24. Knapik, R.C.A.E. Carbon Dioxide Separation Technologies. *Arch. Min. Sci.* 2019; 64: 487-498.
25. Loeb S, S.S. High flow porous membranes for separating water from saline solutions. United States Patents. 1962; US3133132.
26. Kosinov, N. Recent developments in zeolite membranes for gas separation. *Journal of Membrane Science*. 2016; 499: 65-79.
27. Gnanasekaran, D. and B.S.R. Reddy. Cost effective poly(urethane-imide)-POSS membranes for environmental and energy-related processes. *Clean Technologies and Environmental Policy*. 2012; 15(2): 383-389.
28. Ghalei, B. and M.-A. Semsarzadeh, A Novel Nano Structured Blend Membrane for Gas Separation. *Macromolecular Symposia*. 200; 249-250(1): 330-335.
29. C. Joly, S.G.a.J.C.S. Sol-gel polyimide-silica composite membrane: gas transport properties. *Journal of Membrane Science*. 1997; 130: 63-74.
30. Yong, W.F. and H. Zhang. Recent advances in polymer blend membranes for gas separation and pervaporation. *Progress in Materials Science*. 2021; 116.
31. Rhim H, H.S. Transport of Capillary Condensate. *ournal of Colloid and Interface Scienc*. 1975; 52: 174-181.
32. Lee KH, H.S. The Transport of Condensable Vapors through a Microporous Vycor Glass Membrane. *Journal of Colloid and Interface Science*. 1986; 110: 544-555.
33. Clarizia, P.B.a.G. 30 Years of Membrane Technology for Gas Separation. *Chemical Engineering Transactions*. 2013; 32: 1999-2004.
34. Tong, Z. and A.K. Sekizkardes, Recent Developments in High-Performance Membranes for CO₂ Separation. *Membranes (Basel)*. 2021; 11(2).

35. Bdddeker, K.W. Commentary: Tracing membrane science. *Journal of Membrane Science*. 1995; 100: 65-68.
36. Farrar, C., J. Neil, and J. Howle. Magmatic Carbon Dioxide Emissions at Mammoth Mountain California. USGS Water Resources Investigation Report. 1999: 98-4217.
37. Xu, J. Recent advances on the membrane processes for CO₂ separation. *Chinese Journal of Chemical Engineering*. 2018; 26(11): 2280-2291.
38. Baker, J.G.W.a.R.W. The solution-diffusion model: a review. *Journal of Membrane Science*. 1995; 107: 1-21.
39. Junaidi, M.U.M. Carbon dioxide removal from methane by using polysulfone/SAPO-44 mixed matrix membranes. *Fuel Processing Technology*. 2013; 112: 1-6.
40. Fick, A. On liquid diffusion. *Journal of Membrane Science*. 1995; 100: 33-38.
41. Yave, W., A. Car, and K.-V. Peinemann. Nanostructured membrane material designed for carbon dioxide separation. *Journal of Membrane Science*. 2010; 350(1-2): 124-129.
42. LeBlanc, D.R.C.a.S.E. *Process Systems Analysis and Control*. McGraw-Hill's Chemical Engineering Series. 2009; Third Edition.
43. Allen, J.G. Associations of Cognitive Function Scores with Carbon Dioxide, Ventilation, and Volatile Organic Compound Exposures in Office Workers: A Controlled Exposure Study of Green and Conventional Office Environments. *Environ Health Perspect*. 2016; 124(6): 805-12.
44. Jiang, L., T. Chung, and S. Kulprathipanja. An investigation to revitalize the separation performance of hollow fibers with a thin mixed matrix composite skin for gas separation. *Journal of Membrane Science*. 2006; 276(1-2): 113-125.
45. Xiaobo Dong, D.L.a.T.A.L.H. Polymers and Solvents Used in Membrane Fabrication: A Review Focusing on Sustainable Membrane Development. *Membranes*. 2021; 11: 1-25.
46. Bake, R.W. Future Directions of Membrane Gas Separation Technology. *Ind. Eng. Chem. Res*. 2002; 41: 1393-1411.
47. Scholz, M., M. Wessling, and J. Balster. Chapter 5. Design of Membrane Modules for Gas Separations. 2011: 125-149.
48. Linfeng Leia, L.B.a.A.L. Carbon membranes for CO₂ removal: Status and perspectives from materials to processes. *Chemical Engineering Journal*. 2020; 401: 126084.
49. Quesada Cabrera, R. Nanomechanical and structural properties of native cellulose under compressive stress. *Biomacromolecules*; 2011; 12(6): 2178-83.
50. Sazali, N. A review of the application of carbon-based membranes to hydrogen separation. *J Mater Sci*. 2020; 55: 11052–11070.
51. Isanejad, M., N. Azizi, and T. Mohammadi. Pebax membrane for CO₂/CH₄ separation: Effects of various solvents on morphology and performance. *Journal of Applied Polymer Science*. 2017; 134(9).

52. Pak, S.-H. Preparation of Cellulose Acetate Hollow-Fiber Membranes for CO₂/CH₄ Separation. *Environmental Engineering Science*. 2016; 33(1): 17-24.
53. Xi, Y.-H. Graphene-based membranes with uniform 2D nanochannels for precise sieving of mono-/multi-valent metal ions. *Journal of Membrane Science*. 2018; 550: 208-218.
54. Mubashir, M. Efficient CO₂/N₂ and CO₂/CH₄ separation using NH₂-MIL-53(Al)/cellulose acetate (CA) mixed matrix membranes. *Separation and Purification Technology*. 2018; 199: 140-151.
55. Hamidreza Sanaeepur, R.A., Mehdi Sinaei and Ali Kargari. Pebax-Modified Cellulose Acetate Membrane for CO₂/N₂ Separation. *Journal of Membrane Science and Research*. 2019; 5: 25-32.
56. Ishigami, T. Fouling reduction of reverse osmosis membrane by surface modification via layer-by-layer assembly. *Separation and Purification Technology*. 2012; 99: 1-7.
57. Jamil, A., P.C. Oh, and A.M. Shariff. Polyetherimide-montmorillonite mixed matrix hollow fibre membranes: Effect of inorganic/organic montmorillonite on CO₂/CH₄ separation. *Separation and Purification Technology*. 2018; 206: 256-267.
58. Wakui, T.A.a.Y. Correlation between the Porosity and Permeability of a Polymer Filter Fabricated via CO₂-Assisted Polymer Compression. *Membranes*. 2020; 10: 1-10.
59. Salvatore F. Cannone, A.L.a.M.S. A Review on CO₂ Capture Technologies with Focus on CO₂-Enhanced Methane Recovery from Hydrates. *Energies*. 2021; 14: 1-32.
60. Stepan D. Bazhenov, A.V.B. and A.V.V. Gas-Liquid Hollow Fiber Membrane Contactors for Different Applications. *Fibers*. 2018; 6.
61. Ahmed W. Ameen, P.M.B.a.P.G. Superglassy Polymers to Treat Natural Gas by Hybrid Membrane/Amine Processes: Can Fillers Help. *Membranes*. 2020; 10: 1-24.
62. Can Zeng Liang, M.A.a.L.T.S.C. Ultra-strong polymeric hollow fiber membranes for saline dewatering and desalination. *Nature Communications*. 2021; 12: 1-11.
63. Hölter, J.P.A.a.W. Degradation of Cellulose Acetate-Based Materials: A Review. *Journal of Polymers and the Environment*. 2011; 1: 152-165.
64. Meier, J.W.a.M.A.R. A more sustainable synthesis approach for cellulose acetate using the DBU/CO₂ switchable solvent system. *Green Chem*. 2021; 23: 4410–4420.
65. Juergen Puls, S.A.W.a.D.H.I. Degradation of Cellulose Acetate-Based Materials: A Review. *J Polym Environ*. 2011; 9: 152–165.
66. Shuangping Xu, H.Z.a.H.J. Preparation and high CO₂/CH₄ selectivity of ZSM-5/Ethyl cellulose mixed matrix membranes. *Mater. Res. Express*. 2021; 8: 1-10.



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