

The most effective techniques of industrial purification processes: a technical review

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Abstract

This paper reviews various separation techniques used in purification processes to remove pollutants like carbon dioxide and hydrogen sulfide from petroleum products. The most effective techniques include absorption, adsorption, cryogenic distillation, chemical looping combustion, and membrane separation. The study reviews over 100 published studies to assess their characteristics, benefits, and drawbacks. The choice of separation technology depends on ideal conditions, cost, efficiency, and energy required in the regeneration phase.

Keywords

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adsorption
low temperatures technique
CLC
membrane separation

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Key findings

- Different undesirable materials in natural gas cause unacceptable problems for the health and quality of the petroleum product.
- A comparison was made between the various methods used for separating the petroleum product pollutants (acid gases).

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1. Introduction

Fossil fuel is a popular energy source, with the overall power required expected to increase by at least a third and the quantity of electricity consumed – to double in five decades [1]. Common oil and natural gas, containing harmful components like carbon dioxide and hydrogen sulfide, can rapidly increase climate change due to their combustion and emission of the pollutants [2].

Gas separation technologies are crucial for extracting acid gases from natural gas, reducing carbon dioxide concentration to 2–3 mol.%, improving heating efficiency, preventing solid carbon dioxide hydrates, preventing corrosion, and reducing pipeline capacity with inert gas [3].

Acidic gas separation techniques include different technologies such as sorbents or solvents, cryogenics, membranes, and chemical looping combustion [4]. Chemical absorption is a common method for removing CO₂ and

H₂S from gas mixtures, involving CO₂ reactions with commonly used solvents like alkanolamine, where the purity of carbon dioxide typically exceeds 99.9% [5,6]. Cryogenic distillation is a preferred method for CO₂ capture, particularly for concentrations up to 10 mol.%, due to its lower environmental impact compared to chemical absorption. The cryogenic process's main drawback is that high-pressure cryogenic columns, due to the Joule-Thomson effect, can produce dry ice [7].

Membrane contactor technology is a widely used technique for capturing high CO₂ and H₂S concentrations due to its low-sized absorption unit and freedom from restrictions like foaming, channeling, and coalescence, making it an efficient and cost-effective method for CO₂ capture.

This study reviews various works on acid gas removal through various sweetening processes. It provides an overview of different types of sweetening processes, discusses their characteristics and advantages, and compares different separation and sweetening procedures.

The goal is to provide suggestions for choosing technologies or their combinations for various applications, ensuring an accurate and perfect choice for acid gas removal. The study also highlights the advantages of each process and its use.

2. Acid gas capture technologies and carbon storage

Marketing operations must consider economic, safety, environmental, and ecological factors. The process of CO₂ separation should be energy-efficient. Common processes for post-combustion removals include absorption, adsorption, cryogenic distillation, membrane separation, and chemical looping, as shown in Figure 1.

Carbon dioxide is separated and compressed to convert it into a liquid for storage and transportation. It can be stored permanently by injecting it into porous rocks or under the ocean's surface. Captured carbon dioxide is used to convert it into valuable materials, increasing oil extraction. It is also used in the manufacturing of synthetic or hydrogen-based hydrocarbon fuels, food and drink processing, agriculture, medicine, pulp and paper steel (injection to metal casting), the petroleum industries (urea manufacturing, fuels), and water treatment [8,9].

2.1. Absorption

Absorption is an essential process for acid gas extraction from a gas mixture and involves dissolving undesired gases such as CO₂ in a solvent [10]. Standard-packed columns are commonly used in absorption processes in refineries, petrochemical facilities, natural gas manufacturing, and chemical processes, as illustrated in Figure 2.

The acid mixture is fed into the absorption column (absorber), in which the solution captures CO₂ or H₂S. The acidic-rich mixture is supplied into a heat exchanger to raise the temperature of the solution, then to a regenerator column to remove the acid gases.

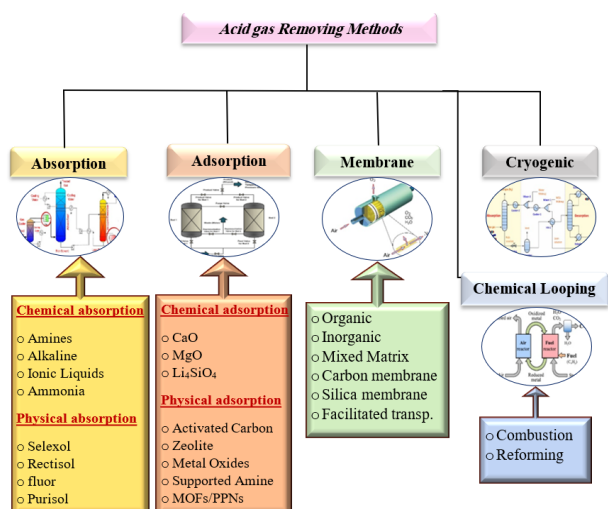


Figure 1 Overview of acid gas capture technologies.

The absorption process involves returning lean absorbent to the absorber after cooling, enhancing separation efficiency. This process offers affordable raw materials, low heat capacity, fast kinetics, high CO₂ adsorption capacity, high selectivity, and stability under extensive cycling under thermal, chemical, and mechanical conditions; for these reasons, it is widely used [11]. Absorption technologies involve two main categories: chemical and physical absorption.

2.1.1. Chemical absorption

Chemical absorption is a process where acid gases in a gas stream react with a solvent to create an intermediate product, eliminating acid gases from the exit flue gas. Efficient absorption-based CO₂ collection relies on choosing solutions with ideal thermal and physical characteristics as well as acid-base equalization processes in alkaline liquids [12]. Gas streams with high gas amounts and lower CO₂ partial pressures require numerous chemical solvents, increasing the cost of funds and energy. Chemical absorption includes the following solvents:

Amines group. Amine solutions are commonly used in absorption processes due to their strong absorption of carbon dioxide and excellent selection of acidic gases. However, they have disadvantages such as apparatus corrosion, high energy requirements during regeneration, and solvent losses due to evaporation. To overcome these issues, some developments include using mixed amine compounds instead of individual ones, minimizing circulation rate, and reducing energy during regeneration [13].

Three types of amine solutions exist, primary (monoethanolamine-MEA), secondary (diethanolamine-DEA), and tertiary (methyldiethanol amine-MDEA), each with unique characteristics such as absorption, corroding, reactivity, and selectivity of acidic gases.

MEA and DEA are widely used commercially for chemical-based adsorption due to their affordability, good interaction, and impressive absorption capacity [14].

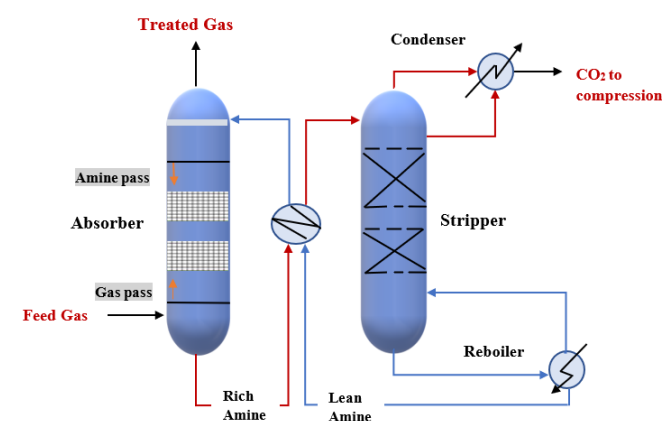


Figure 2 Schematic diagram of the absorption process.

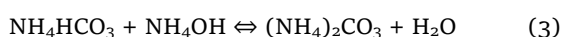
MEA and H₂O react to absorb CO₂ from gas streams, producing amine protonate, bicarbonate, and carbamate. MEA reacts faster with CO₂ than MDEA, but MDEA has a larger absorption ability and faster regeneration time [15].

Experiments show that blending amine with specific solvents improves separation efficiency and energy consumption in desorbed columns. Combining MEA solvent with methanol increases carbon dioxide extraction, uses less energy, and thus reduces regenerative heat duty [16]. Exxon Research and Engineering Company invented 2-amino-2-methyl-1-propanol (AMP), an amine-hindering compound [17].

Artanto et al. found a successful substitute for MEA, a blend of 25 wt.% from 2-amino-2-methyl-1-propanol (AMP) and 5 wt.% Piperazine (PZ). They noticed that PZ has a low chemical attraction, is 50 times faster than MEA, and has minimal regeneration capacity [18].

MDEA is used to capture H₂S and CO₂ when both acid gases are present, while DEA is typically used for H₂S alone due to its preference for H₂S over CO₂ [19]. R. Idem et al. [20] demonstrated lower energy consumption and reduced circulating rates for amine mixtures with a mixture ratio of 1/4 (MDEA/MEA) in a monoamine system with similar total amine contents using pilot carbon dioxide capture units. The Khurmala field research in Iraqi Kurdistan was focused on gas sweetening, examining essential amine process parameters like circulation rate and amine content. The study found that using DEA (35% w/w) was the most recommended approach [21].

Ammonia solution. Ammonia is a cost-effective solvent substitute for MEA due to its excellent carbon dioxide absorption, lower corrosiveness, and less deterioration sensitivity. The reaction between NH₃ and CO₂ initially produces carbamate due to ammonia availability. In the last stage, bicarbonate compounds form with decreased NH₃ content, as shown in equations (1–3) [22]. Bicarbonate production is preferred due to its lower breakdown heat compared to carbonate.



Zhu et al. found that increasing the ammonia content can enhance the separation efficiency to 99% [23]. Aqueous ammonia is a suitable choice for CO₂ separation due to its numerous advantages, including the ability to eliminate SO_x, NO_x, and mercury from flue gas, and the possibility of using the byproducts as fertilizers. In a coal-powered power plant, using aqueous ammonia reduces energy costs and CO₂ separation costs significantly, making it an efficient solution [24].

Ionic liquid. Ionic liquids (IL) have modest vapor pressure, excellent thermal conductivity, high polarity,

non-toxicity, and ability to regulate carbon dioxide solubility and specificity, but their poor operational capacity hinders their widespread use in carbon capture [25]. Fluorination can enhance the absorption rate of anions, including those with long alkyl chains or non-fluorinated substituents with carbonyls, esters, or ether groups [26].

Ionic liquids can be applied through physical or chemical processes, with the physical absorption method being most effective for capturing acid gases from natural gas, particularly carbon dioxide with a high content and pressure of around 14.5 psi, due to their low vapor pressures and reduced solvent loss issues [27].

The IL molecule, which contains an amino-function component called a task-specific ionic liquid (TSIL), can interact with CO₂ in chemical ionic liquid absorption. The study found that TSIL has a higher physical absorbance for carbon dioxide than IL due to its viscosity, attributed to the hydrogen bond between cation and anion [28].

2.1.2. Physical absorption

The process involves using physical solvents to absorb acidic gases without chemical reactions, removing carbon dioxide and hydrogen sulfide. Water is the most suitable solvent, along with pure absorbers like methanol, N-methyl-2-pyrrolidone, dimethyl ether, and solvents like Ipfexol™, Fluor™, Purisol™, Sulfinol™, and Morphysorb™ [12]. The partial pressure of acid gases significantly impacts separation efficiency, as increased pressure leads to improved performance while decreasing the physical solvent circulation rate [29]. Physical absorption often requires significantly lower regeneration power due to weak interactions between the solvent and the absorbed gas.

2.2. Adsorption

Adsorption is the attraction between particles, ions, or atoms and a solid surface, regardless of their state. Solid adsorption may be a more effective method for capturing acid gas due to its superior gas-liquid contacting area, low CO₂ loading, and less corrosion. Solid adsorption may be a better option for capturing acid gas due to its lower energy required in the regeneration step, superior selection and operating capacity, affordable price, and greater theoretical temperature of the operation band (usually ranging from room temperature to 700 °C) [30].

Figure 3 demonstrates a typical scheme for the adsorption process of acid gas over permeable solid materials. Adsorption and regeneration are the two major processes, which work in cycles. The feed gas is supplied to a solid adsorbent surface, which selectively adsorbs CO₂ until equilibrium is reached. Active adsorbents include CaO, alkali silicates, zeolites, carbon activated, carbon nanotubes, carbon nanofibers, graphene, and molecular sieves [31, 32]. Adsorbents can be regenerated through vacuum-swing adsorption, pressure-swing adsorption, or a combination of vacuum-pressure swing

adsorption [33]. Adsorbents can be physical or chemical, depending on the materials used.

2.2.1. Chemical adsorbent

Chemisorption is an adsorption process involving the reaction between improved surfaces and adsorbed materials, including amino groups, metal oxides, and double salts, which are high-temperature adsorbents [34].

The regeneration step, typically at elevated temperatures, reverses the chemical reaction path by freezing amine compounds to form a solid layer for acidic gas absorption. Molecular basket sorbent (MBS) is another substance that works as a sorbent, made of polyethyleneimine (PEI), a new amine sorbent using a unique nanoporosity polymer [29].

A carbonation reactor regenerates an adsorb column by converting metal oxides like CaO into metal carbonates like CaCO₃ at 649.85 °C and 849.85 °C, thereby creating a suitable storage stream [35].

2.2.2. Physical adsorbent

Physical adsorption (physisorption) is another method for adsorbing acid gases without chemical reactions, using a normal solid surface. It relies on weak van der Waals forces and uses substances like alumina, zeolites, carbon-based materials, porous polymer networks, and covalent organic frameworks (COFs) to prepare the solid bed for the separation process [36]. Zeolites, crystalline aluminosilicates, are effective for CO₂ extraction due to their strong adsorption properties, but their shape and charge density are weakened by water, weakening the bonding [37]. MOFs, formed by metal ions and chemical ligands, are easy to develop and synthesize and have high porosity and specific pore characteristics. Zhou's group studied MOFs' ability to capture carbon dioxide, finding that they have remarkable CO₂ adsorption capabilities for pure CO₂, but their absorption capabilities decrease when in contact with a gas mixture [38, 39].

The pressure swing procedure is used for adsorption and deactivation, utilizing a decrease in pressure to desorb carbon dioxide trapped under high pressure from solids.

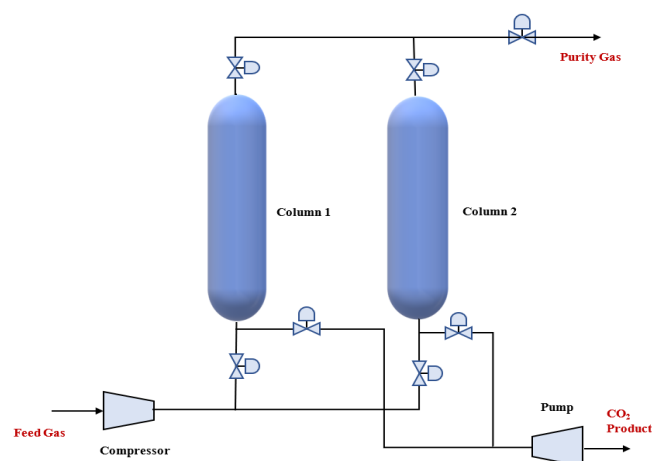


Figure 3 Diagram of the acid gas adsorption process.

The temperature is reduced during adsorption and increased during desorption, using a reverse strategy, indicating that absorption capacity increases with increasing CO₂ partial pressure and temperature.

2.3. Cryogenic distillation

The cryogenic method involves the condensation, separation, and purification of CO₂ from a gas mixture at low temperatures, with the freezing point for pure CO₂ being 195.5 K at atmospheric pressure. Figure 4 describes the cryogenic procedure. A pre-cooler cools feed gas, which is then cooled by a heat exchanger to low temperatures. Several vapor-liquid contact devices (such as trays or packing) are present in the column.

The distillation column receives the cooled feed gas, with topping and bottom products making up most element steam. A partial condenser removes methane separated at the top, ensuring efficient distillation. The distillation column collects condensed CO₂ at its base, which is vaporized using reboiler heat before returning to the column.

The remaining CO₂ stream is separated, and the separator is used to extract the cleaned CO₂ product [40]. This approach outperforms previously used separation technologies in CO₂ extraction by 99.17% [41]. This process allows for the direct production of liquid CO₂ through pumping, allowing for high-pressure storage and sequestration of components [42,43].

The low-temperature method is not widely used in separation due to its high operating costs and high energy requirements during the cryogenic process [44]. The experiment showed a significant reduction in energy consumption, methane losses, and size demands when using amplified hybrid cryogenic distillation systems.

2.4. Chemical looping combustion (CLC)

The proposed method is a highly energy-efficient alternative for capturing acidic gas, enabling the natural separation of CO₂ and water from the gas stream [45]. The CLC process involves two reactors: an air reactor and a fuel reactor, as shown in Figure 5. The air reactor's oxygen-containing "O₂ carrier" oxidizes metal particles like iron, manganese, or copper, forming metal oxides.

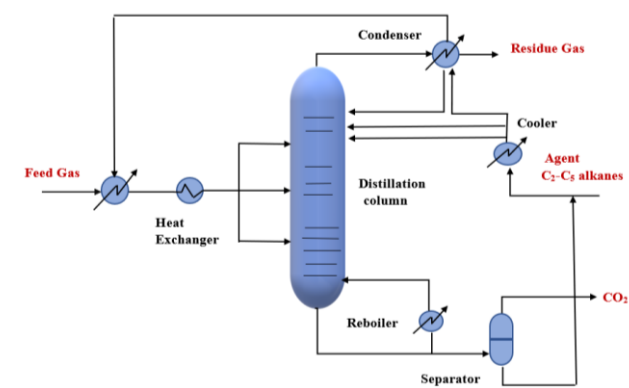


Figure 4 Cryogenic Distillation procedure. Adapted with permission from [40] © 2018 Elsevier Ltd. All rights reserved.

These are sent to the fuel reactor, where they react with the fuel. During combustion, metal oxides reduce, releasing CO₂ and H₂O along with energy. Purified CO₂ can be obtained by condensing flue gas [46]. The oxygen is diverted via fuel and air reactors, facilitated by oxygen carriers between two units to prevent nitrogen from being released into combustion exhaust. The primary barrier to scaling up the CLC procedure is the lack of suitable efficient oxygen carriers (OCs) [47].

A recent study emphasized the importance of the O₂ carrier in improving the performance of the CLC process. The researchers used density functional theory (DFT) to study the electronic and structural properties of materials and identify basic microscopic mechanisms, aiming to design an O₂ carrier with high performance in separation [48]. High-pressure functioning is crucial for optimal performance, but it may also benefit carbon capture and storage technology, with recent energy assessments showing that calcium-looping post-combustion procedures can only experience a six to eight percent power loss [49].

Since 2004, continuous studies on gaseous fuel have been conducted, revealing multiple applications of CLC. Solid fuels have also been extensively studied due to their significant contribution to carbon dioxide emissions [50]. The research reviews various types of municipal solid waste (MSW) and discusses reactor designs used for CLC, with fluidized bed reactors being the preferred choice due to their ability to achieve significant and homogenous solid-gas mass transfer [51]. Bio-mass fuels can achieve zero emissions and mitigate environmental impacts throughout their life cycle [52].

2.5. Membrane separation

Membranes, porous or semi-permeable filters, are effective in extracting carbon dioxide from gas mixtures. They consist of organic (like polymeric membranes) or inorganic materials (like carbon, ceramic, zeolite, metallic materials, etc.), and can be categorized into matrix mix membranes, which are derived from various substances [53].

The membrane's working principle is the pressure difference across the membrane contactor, produced by pushing the gas stream or generating suction.

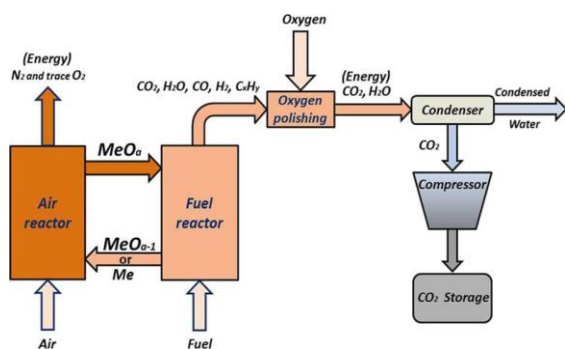


Figure 5 Overview of Chemical looping combustion (CLC). Reproduced from [45] © 2020 Elsevier B.V.

The acid gas product's quality is determined by selectivity and penetration, influenced by material choice [54].

Membrane technology is widely utilized in industries due to its effectiveness, simplicity, high selectivity, penetrability, energy efficiency, continuity, ease of control, easy scale-up, flexible design, and environmental friendliness [55,56]. High-pressure post-combustion procedures like integrated gasification combined cycles are more suitable for membranes in reality. Schlumberger and PETRONAS successfully constructed and operated the CYANARA PN-1 acid gas extraction membrane unit at Malaysia's Terengganu Gas Terminal in 2017 [57].

The membrane process involves the adhesion of gas molecules to the membrane's high-pressure side, transiting through the membrane's internal compartment, and ultimately ending on the low-pressure side of the membrane, as illustrated in Figure 6.

The membrane's pores should remain dry and open for optimal performance, ensuring a broad contact area (Figure 7a). This is achieved by selecting an absorbent solution with high surface tension and a membrane with larger hydrophobicity. The material used for absorption must also strongly and selectively attract the gas for successful separation [58].

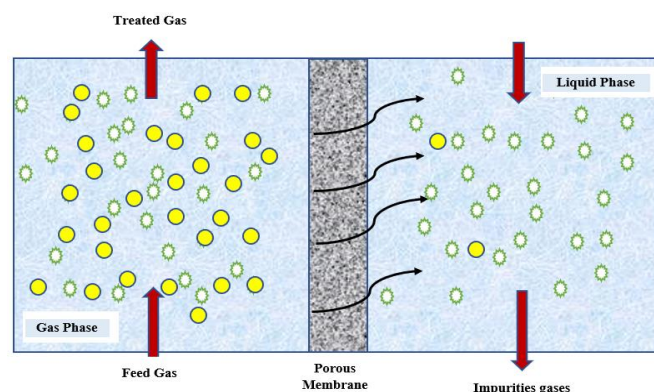


Figure 6 Schematic of the mechanism of membrane penetration. Reproduced from [53] © 2022 Elsevier Ltd. All rights reserved.

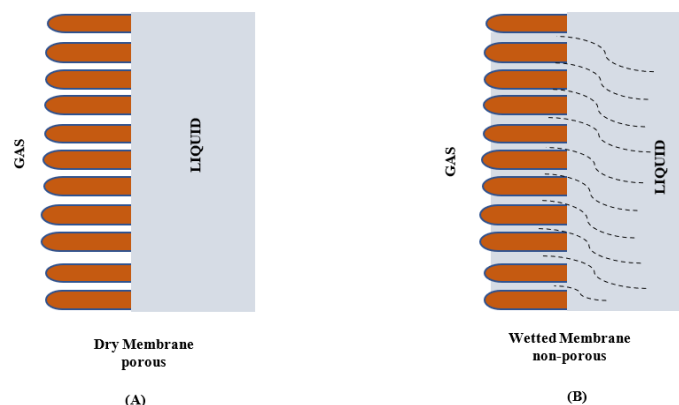


Figure 7 Schematic for porous and non-porous membranes. Reproduced from [56] © 2021 Elsevier B.V. All rights reserved.

2.5.1. Polymeric membranes

Polymeric membranes are widely used due to their high performance, affordability, and simplicity in manufacturing, making them easier to manage than inorganic membranes [59]. Polymeric materials like cellulose acetate, polyimide, polysulfones, and perfluoro polymer are widely used for gas separation, with polyimide and cellulose acetate being the most commonly used commercial membranes [60].

Zhang et al. pointed out that a polyimide membrane effectively separates CO₂ from natural gas [61]. Trifluoromethyl group-containing polyimides are highly selective towards penetration for various gases, and can be solubilized in various organic solutions, attracting attention for their potential applications [62]. Glassy polymers, including polyimide, may experience physical degradation, potentially reducing gas rates and decreasing permeability and selectivity in the long run [63]. Farrokhara and Dorosti studied polysulfones, highlighting their superior mechanical properties, thermal and chemical stability, and ease of membrane processing [64]. Fabien Porcheron's team compared polymeric membranes like polypropylene (PP), nylon, polytetrafluoroethylene (PTFE), and polyvinylidene fluoride (PVDF), finding that they were hydrophobic. However, after a week, the contact angle of nylon and PVDF decreased to 0°, especially at high temperatures [65].

Fashandi et al. utilized polyvinyl chloride (PVC) for CO₂ capture due to its affordability, hydrophobicity, and suitable structure, achieving high absorption efficiency through spindle optimization [66].

2.5.2. Ceramic membrane

Ceramic membranes offer superior thermal and chemical resilience compared to polymeric membranes, making them suitable for over a hundred purification processes [67,68]. The Deca-Dodecasil 3 Rhombohedral (T) zeolite demonstrated excellent selection and porosity for CO₂/CH₄ in various zeolite-based inorganic membranes [69,70]. Metal oxides, specifically Al₂O₃ and SiO₂, are used as additional materials to create these membranes. The membrane's hydrophilic surfaces, containing OH groups, are a result of a wetted membrane, as depicted in Figure 7b. To address the issue, fluoroalkyl silane can be applied to the outer surface of ceramic membranes, resulting in higher interfacial porosity and larger gas permeability than those of the polymers due to decreased hydroxyl group content, as shown in Figure 8. To enhance surface properties, it is essential to manage conditions during the process, such as polymer concentration, coagulant type, vapor exposure time, and temperature [71]. The hydrophobic Al₂O₃ hollow fiber membranes were prepared from an Al₂O₃/PES solution [72].

A hollow fiber membrane (HFM) is crucial in a membrane contactor (MC) device for successful separation, allowing two phases to exchange components directly

without mixing, as shown in Figure 9. In this device, the gas mixture flows inside the hydrophobic membrane while another absorbent, which is either water or amine, flows on the other side to complete the purification process.

The membrane conductor system uses the hydrophobic HFM system to adsorb the acid gas from the gas mixture by passing the absorbent such as water or amine flowing from the other side of the device to complete the purification process [74]. Table 1 summarizes the studies that have been applied in membrane separation processes and their properties, as well as applications for a variety of membranes.

2.5.3. Mixed-matrix membrane (MMM)

MMM, or a hybrid membrane, enhances ceramic and polymeric membranes, increasing efficiency in the gas separation applications. Its ease of manufacture and cross-Robeson's upper boundaries make it preferred over polymeric membranes due to improved gas selection and penetration [75, 76].

Goh et al. analyzed gas transport specifications, preparation methods, and challenges for Metal-organic frameworks (MOFs) to identify potential additives in mixed matrix membranes to enhance gas separation efficiency and address marketing issues [77].

Mixed matrix membranes can incorporate inorganic micro- or nanoparticles into a polymer framework, improving its physical, thermal, and mechanical properties. However, these membranes are expensive, fragile, and are not commercially accessible [78].

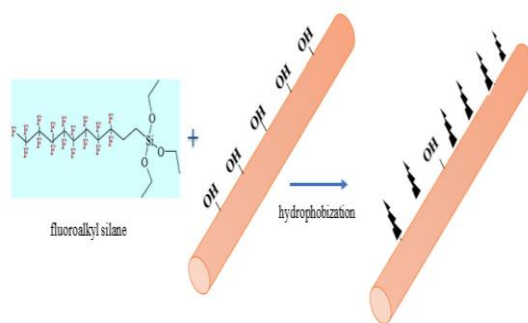


Figure 8 The hydrophobization process. Adapted with permission [73] © 2021 Elsevier B.V. All rights reserved.

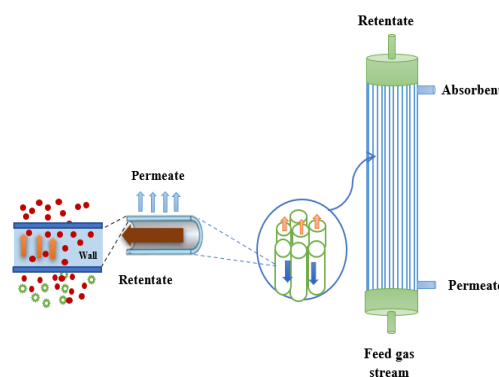


Figure 9 Schematic membrane contactor module with hollow fiber membrane according to the counter-current module and longitudinal flow on the shell side.

3. Compendium

Carbon capture involves various methods, requiring technological and financial considerations such as gas mixture composition, purification, plant fees, economic analysis, infomercial expertise, process serviceability, and flexibility. Table 2 outlines the differences in separation technologies, their properties, advantages, and drawbacks, with appropriate references. This helps in selecting the most suitable method for carbon separation.

4. Limitations

This article discusses various methods for purifying pollutants in petroleum products, including active methods for separating undesirable compounds like CO₂ and H₂S. These methods aim to produce clean products with high calorific value and less pollution, particularly after combustion. Each type has unique characteristics, advantages, and disadvantages, with the main choice based on the concentration of acid gas in the gas mixture.

5. Conclusion

Recent advancements in technology have shown promise in reducing CO₂ emissions, but each technology has unique operational requirements, benefits, and disadvantages.

– Chemical absorption is more efficient than physical absorption, with amine compounds accounting for 90% of CO₂ capture. Despite challenges like high energy regeneration, corrosion, and degradation, innovations like mixing amine compounds can reduce circulation rate and energy during regeneration, making them a viable alternative.

- The evaluation of the potential benefits of absorbents, including ionic liquid, alkaline absorbents, and mixes, should not be limited to alkanol amines.
- Adsorption is a promising method for carbon capture, offering energy-efficient regeneration, increased working capacity, and low cost. It operates well in high pressures and cold temperatures. Chemically altered adsorbents, like amine-based ones, have excellent sorption capacities, moisture resistance, and CO₂ selection.
- Cryogenic separation offers superior CO₂ extraction (99.17%) but requires high energy due to low temperatures during the condensation stage.
- The primary objectives for chemical looping combustion should be to improve the durability of metal oxides and establish showcase facilities.
- The membrane separation method presents the possibility of reducing operating costs, especially with the improvement of the membrane materials to resist extreme temperatures, degradation, and pollutants.

The reduction of acid gas emissions in energy technologies, particularly high-power fossil-fueled ones, necessitates significant research and development to capture, store, and utilize CO₂ effectively using sustainable, industrially feasible, and cost-effective technologies.

• Supplementary materials

No supplementary materials are available.

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Table 1 Characterization and properties of the membrane separation process.

Membrane used	Application	Absorbent	Modification method	Comment	Contact angle (°)	Ref.
CHFMs	MD	–	modified via dip-coating with PMHS/TEOS hybrid solution	the surface-modified CHFMs demonstrated the capability of processing feed solution with a saltiness of 35,000 ppm and 6.7 L/m ² h of flow	08.2–124.1	[79]
Silica sand CHFMs	MD	–	(FAS17) and (PVDF-HFP)	fabricate (SCHFM) to minimize wetting and make good membranes for seawater treatment with high-purity	water (167), red palm oil (157), and ethanol (146.1).	[80]
PVDF-SiO ₂	CO ₂ capture	Water & DEA	C ₁₉ H ₄₂ O ₃ Si	achieved good CO ₂ absorption flux and long-term in the MC	159.3	[81]
Alumina membrane	(MMM)	silica aerogel	bis(trimethylsilyl)hexane (BTMSH), tetraethyl orthosilicate (TEOS)	the composite membrane was utilized three times for one-day cycles of CO ₂ absorption and ran constantly for at least 3 days	150	[82]
Kaolin HFM	CO ₂ capture	water	FAS	modified kaolin-HFM having a very hydrophobic surface	142	[83]

Note: CHFMs – ceramic hollow fiber membrane; MD – membrane distillation; PVDF – Polyvinylidene fluoride; MMM mixed matrix membrane; HFM – hollow fiber membrane; FAS – perfluorodecyltriethoxysilane; SiO₂ – silicon dioxide; DEA – diethanolamine; C₁₉H₄₂O₃Si – hexadecyltrimethoxysilane.

Table 2 Comparison between the separation technologies and their properties.

Separation technology	Materials	Advantages	Disadvantages	Scale-up capability	Ref.
absorption	absorbent (aqueous-alkanolamine, ammonia, Selexol, etc.)	<ul style="list-style-type: none"> - some solvents are cheap; - large absorption of CO₂ (the amine method is estimated to capture 85–95% of the CO₂ in flue gas with a purity above 99.95%; - safe absorbent; - no effect on the environment (no hazardous). 	<ul style="list-style-type: none"> - high thermal decomposition solvent losses; - highly energetic usage when regenerating solvent; - requires high pressure; - cost is elevated (chemical absorption). 	industrial	[84–90]
adsorption	adsorbent (Alumina, Zeolite, CaO, MgO)	<ul style="list-style-type: none"> - sorbents are fairly inexpensive; - CO₂ capture 80–95%; - minimal waste creation; - decrease in pressure and adsorbent loss; - safe adsorbent (no corrosion). 	<ul style="list-style-type: none"> - the lower quality of the CO₂ that is extracted; - the process is slow; - after some time, the solid bed needs to be activated. 	industrial	[91–94]
cryogenic distillation	low temperature	<ul style="list-style-type: none"> - no requirement for chemicals or solutions; - usage that can easily enhance to industrial scale; - high capture efficiency 99.17%. 	<ul style="list-style-type: none"> - significant financial cost; - the amount of energy should be high (for refrigeration), the chemical industry uses approximately 40% of its energy to achieve the high purity of acidic gas removal needs; - to prevent blockage by crystallization, gas stream humidity reduction is necessary before chilling. 	pilot, industrial	[95–97]
chemical looping composition	- air&fuel reactor; - metal oxide.	<ul style="list-style-type: none"> - cost is low; - purity almost 99.96%; - necessary to work under elevated pressure. 	<ul style="list-style-type: none"> - absorbents made of compound oxides; - adjustments to the process design for effective and reliable oxygen-carrier substance; - high pressure. 	<ul style="list-style-type: none"> - power generation sector; - pilot (under investigation). 	[98–101]
membrane separation	organic, inorganic, hybrid membrane	<ul style="list-style-type: none"> - a very easy process; - CO₂ capture 80–95%; - it was Continuous, steady-state technology; - fixable parts and modularity. 	<ul style="list-style-type: none"> - high manufacturing costs for innovative membranes - energy intensive because it is crucial to absorb the heat of flue gas. 	experimental, industrial	[102–105]

● Author contributions

Conceptualization: I.H.S., F.Y.A.
 Data curation: I.H.S.
 Formal Analysis: I.H.S., F.Y.A.
 Funding acquisition: I.H.S., F.Y.A.
 Investigation: I.H.S.
 Methodology: I.H.S.
 Project administration: I.H.S.
 Resources: I.H.S.
 Software: I.H.S.
 Supervision: I.H.S.
 Validation: I.H.S., F.Y.A.
 Visualization: I.H.S.
 Writing – original draft: I.H.S.
 Writing – review & editing: I.H.S.

● Conflict of interest

The authors declare no conflict of interest.

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