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REVIEW ARTICLE

CO_2 capture using membrane contactors: a systematic literature review

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Abstract With fossil fuel being the major source of energy, CO_2 emission levels need to be reduced to a minimal amount namely from anthropogenic sources. Energy consumption is expected to rise by 48% in the next 30 years, and global warming is becoming an alarming issue which needs to be addressed on a thorough technical basis. Nonetheless, exploring CO_2 capture using membrane contactor technology has shown great potential to be applied and utilised by industry to deal with post- and pre-combustion of CO_2. A systematic review of the literature has been conducted to analyse and assess CO_2 removal using membrane contactors for capturing techniques in industrial processes. The review began with a total of 2650 papers, which were obtained from three major databases, and then were excluded down to a final number of 525 papers following a defined set of criteria. The results showed that the use of hollow fibre membranes have demonstrated popularity, as well as the use of amine solvents for CO_2 removal. This current systematic review in CO_2 removal and capture is an important milestone in the synthesis of up to date research with the potential to serve as a benchmark databank for further research in similar areas of work. This study provides the first systematic enquiry in the evidence to research further sustainable methods to capture and separate CO_2.

Keywords CO_2 capture, preferred reporting items for systematic reviews and meta-analyses, membrane contactor, absorbent

1 Introduction

The global energy consumption has doubled since the year 1970 predominated by fossil-based fuels such as oil, natural gas and coal [1]. These conventional resources have accounted for more than 80% of the global primary energy consumption in 2015 [1]. The total energy consumption is expected to increase by up to one third by 2060, and electricity consumption is projected to double as well [1]. Energy from renewable sources and nuclear power are growing at a rapid rate of 2.6% and 2.3% per year, respectively. Nevertheless, the reliance on fossil fuels will not decline as it is forecasted that fossil fuels will represent 78% of the world's energy use by 2040 [2]. Fossil fueled power plants account for approximately 40% of the total CO_2 emissions, with coal fired power stations being the predominant contributor [3]. The combustion of these fossil fuels produces CO_2 at high rates which is recognised as the main greenhouse gas that contributes to climate change. The anthropogenic increase of atmospheric CO_2 concentration in the environment is projected to cause substantial fluctuations in the climate. It is estimated that approximately half of the existing CO_2 emissions are absorbed by the ocean and land ecosystems. However, sensitivity of climate and atmospheric CO_2 concentrations create the feedback carbon loop [4]. On the other hand, CO_2 has a growing potential for by-product end-use in both the industrial and energy production sectors. The utilisation of CO_2 as a by-product would reap economic benefits as well as simultaneously alleviate the concerns regarding global climate change [5].

There are currently three main technologies which have been developed and implemented to capture CO_2 from fossil fuel combustion plants. These are pre-, post- and

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oxyfuel combustion [6]. The latter comprises of burning the fuel with almost pure O_2 as an alternative to air. In order to regulate the flame temperature, some part of the flue gas is recycled back into the furnace/boiler segment [6]. The key purpose of using this technology is to produce a flue gas with a high concentration of CO_2 and water vapour; and consequently, remove the CO_2 from the flue gas by dehydration coupled with a low temperature purification process [6]. The pre-combustion technique is a mature technology and has been used in the chemical industry for over 90 years. Here, the primary fuel is processed with steam and air/oxygen to produce synthesis gas (mixture consisting mainly of H_2 and CO). Excess H_2 and CO_2 are produced by reacting steam and CO in a shift reactor. The CO_2 is then removed, typically by a physical or chemical absorption process, subsequently in a H_2-rich fuel which can be used in various applications, such as boilers, furnaces, gas turbines, engines and fuel cells [7,8]. Post-combustion is also often used to remove CO_2 which is produced from the flue gases generated by the combustion of the fuel in air. Normally a liquid solvent is used to obtain the small fraction of CO_2 (3%–15% by volume) which is present in the flue gas consisting mainly of N_2. Current post-combustion systems will often use an organic solvent, such as monoethanolomine (MEA), in a modern pulverised coal or natural gas combined cycle power plant [8,9].

Membrane contactor technology refers to tubular reactors that possess both chemical reaction and product separation units. This type of technology is widely applied in industries due to its lower capital costs and facilitation of the reaction in reaching equilibrium for the desired reaction. These reactors are the most applied in dehydrogenation reactions. H_2 molecules can permeate through the membrane and increase conversion and make the process more economically efficient. Due to this application, membrane contactor technology has gained great popularity in recent years for application in CO_2 capture, which has been demonstrated by the studies discussed in this paper. There are two common types of membrane contactors, inert and catalytic. The former reacts as a barrier, whereas in the latter the membrane is coated or compiled from a catalyst material so that can facilitate the reaction [10]. On the other hand, membrane adsorption refers to the phenomena of species separation within the membrane contactor due to the presence of functional groups of the membrane, or the sorbent utilised for the system. These are often applied in spent metal recovery and water treatment methods [11]. Membrane contractors promote contact between two phases through hydrophobic membranes and are mostly applied for industrial degassing of liquids and can also be categorised in hollow fibre membrane (HFM) contractors due to their arrangement and functionality.

Membrane-based systems for the removal of CO_2 have demonstrated great superiority over conventional ones, and it has become imperative that they overcome existing issues of CO_2 separation and removal in pre-combustion and post-combustion systems [12]. One of the noticeable advantages of a membrane contactor system is that the reaction and separation units of the process are combined to give a single unit. As a result, the need for additional separation units is eliminated, thus making the process greener and environmentally sustainable [13]. There are three main systems which are often used as membrane processes for CO_2 removal (Fig. 1). These are (a) non-dispersive contact via a microporous membrane; (b) gas permeation (using dense membranes); (c) supported liquid membranes. Non-dispersive membranes are often applied in post-combustion capture systems [14]. This type of membrane configuration has a high degree of operational flexibility because of the independent control of the gas and liquid flow rates, as well as an interfacial area which can be controlled and makes it easier to predict the performance of the membrane contactor. In addition, the modularity of the membrane contactors allows linear scale-up, and the system is compact and energy efficient. Issues

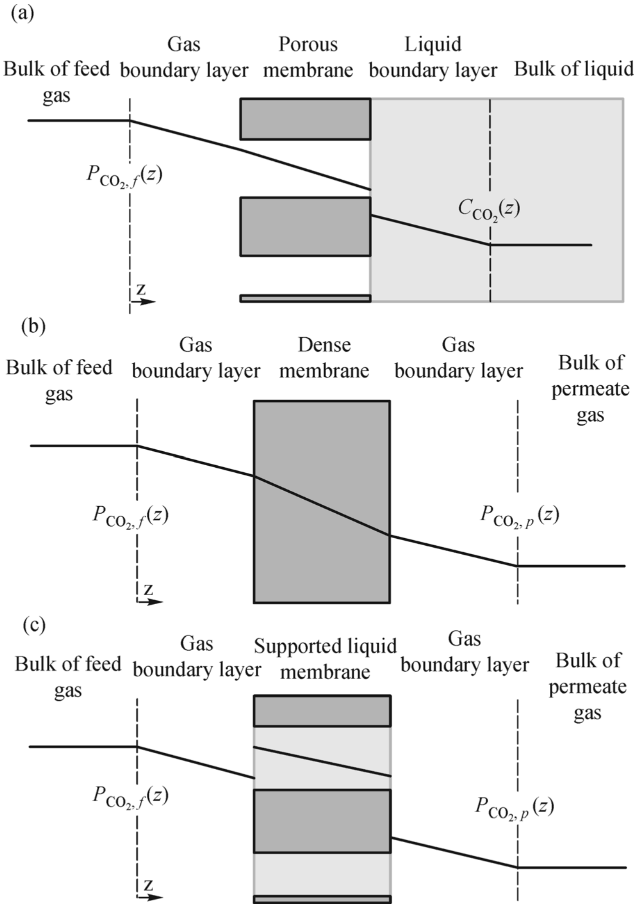

Fig. 1 Schematic of systems for CO_2 removal: (a) non-dispersive contact via a microporous membrane; (b) gas permeation; (c) supported liquid membranes. Reprinted with permission of Elsevier from [12].

regarding the flooding, channelling and entrainment are also avoided since the two phases flow on opposite sides. Furthermore, the mass transfer of CO_2 from the gas to the liquid phase does not have a large impact on the gas flow due to the low concentration of CO_2 in the gas phase [14]. Other membrane separation systems such as distillation, extraction and electrophoresis can also be utilised. Stripping is another common separation process where single or multiple components are absorbed from a liquid stream by a vapour stream for the separation of dilute volatile organic compounds from an aqueous solution [15,16].

In this work, a systematic literature review was conducted to inform the reader about all the published studies performed in the area of CO_2 removal using various membrane-type contactors. Figure 2 depicts how the use of membrane contactors for CO_2 removal has increased throughout the years and is predicted to continue to do so. A detailed description of the methodology is provided to deliver an insight into how the review was performed, based on the guidelines for conducting systematic literature reviews [17]. Subsequently, the methodology section is followed by the results and discussion to assess and analyse the findings of the study. To our knowledge this is the first systematic review in the topic of CO_2 removal using membrane-type contactors.

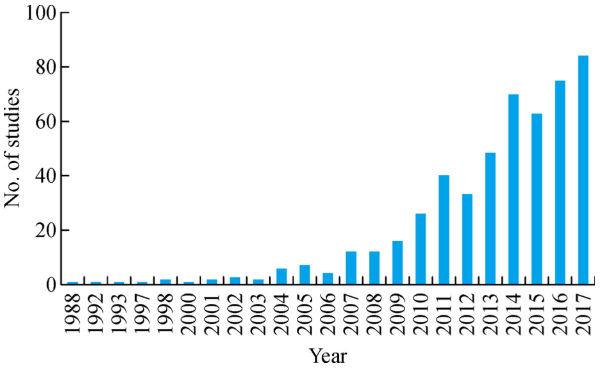

Fig. 2 Popularity of membrane contactors for CO_2 removal throughout the years.

2 Methods

A systematic enquiry was set by using a defined search strategy and run on the 8th January 2018 across three databases: Web of Science (WoS), Google Scholar and PubMed. This was done to gather peer-review articles, conference proceedings, editorial letters, books and grey literature with no language, time or geographical restrictions in our search. We imported all references to an EndNote library, removed duplicates and screened for relevance based on title and abstract.

2.1 Search strategy

A search strategy was devised using only "CO_2" and "membrane" in the title. Although a third keyword could have been added to refer to the process of isolating the CO_2, this was intentionally left out. This was done as many studies use for example a specific absorbent membrane type of membrane and hence, do not use words like capture, removal, separation or other synonyms as such to describe this. Similarly, instead of trying to gather a list of potential solvents used to absorb CO_2, we kept a few basic search terms and the search strategy simple. We then used the information from the collected studies to fill the knowledge gap around the type of membranes used so far by researchers in the area of CO_2 removal. Compared to systematic reviews performed in the field of healthcare where the titles can be longer and more descriptive, most engineering articles contain information in the title about the equipment and material(s) used.

2.2 Inclusion/exclusion criteria

Only studies that concerned the absorption of CO_2 in membrane contactor systems were included. For example, studies focusing on membrane systems for medical and nature applications were excluded. We adopted the widely recognised preferred reporting items for systematic reviews and meta-analyses (PRISMA) flowchart to demonstrate the steps in the undertaken methodology and results. Figure 3 details the PRISMA flowchart for this work.

2.3 Outcome analysis

Prior to conducting the review, we have considered the following items to be important variables in synthesising the research in this area: membrane material, contactor type, flow configuration, absorbent (molarity), wetting, average flux ($\mathrm{mol \cdot min^{-1} \cdot cm^{-2}}$), gas flowrate ($\mathrm{mol \cdot min^{-1}}$), liquid flowrate ($\mathrm{mL \cdot min^{-1}}$), CO_2 in inlet feed (%), CO_2 removal (%). The above information was extracted for each paper. Unless the average flux was provided by the authors, we have manually calculated it using the formula below:

$$\bar{f} = \frac{\text{inlet molecular flow}\left(\frac{\text{mol}}{\text{time}}\right) \times \text{conversion}(\%)}{\text{membrane surface area}}, \quad (1)$$

where the conversion (%) refers to the amount of CO_2 removed.

3 Results

We have identified 2650 studies through electronic

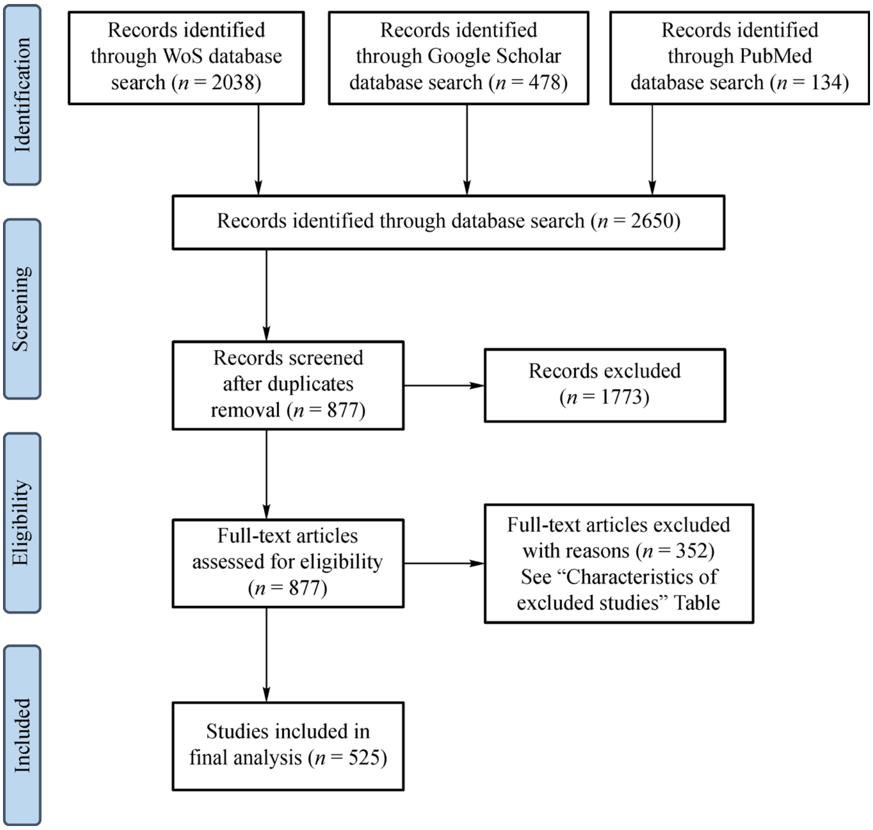

Fig. 3 The PRISMA flowchart of the methodology.

searches of WoS ($n = 2038$), Google Scholar ($n = 478$) and PubMed ($n = 134$). There were 341 removal of duplicated records. We have excluded 1773 through scanning titles and reading abstracts and retrieved a total of 877 full-text articles for further assessment. The 352 upon full-text did not meet the study criteria, and hence were subsequently removed. We included 525 studies in the final review.

3.1 Excluded studies

The excluded studies encompassed those that did not meet the criteria of using a membrane structured reactor. Of the total 877 studies, 122 of the papers had no text available or could not obtain access, leaving 755 studies. To keep the focus of this paper on published and established CO_2 membrane applications, non-peer-reviewed sources such as masters or doctoral degree theses were later excluded (17). Also, since patents do not provide scientific results, were also excluded (16). Lastly, as the aim of this paper was to compile data on CO_2 membranes, biological membranes, such as plant or animal-based membranes for CO_2 transfer were not included as they demonstrated applications in biological systems (17). CO_2 capture and separation has been of interest to many research possibilities, especially with novel membrane technologies. A further 181 studies discussed the potential application of new membranes into CO_2 capture by either theoretical modelling or conducting preliminary experiments to study the permeances of the membrane. However, they did not provide enough parameters to be included in the review as these new innovations need further research before they can be used for industrial capture applications.

3.2 Included studies

We have included 525 studies in this systematic review. There were 77 studies on computational modelling, where different programmes such as Aspen Plus, COMSOL, Aspen HYSYS and MATLAB were utilised to stimulate a preliminary application of CO_2 membrane capture. A total of 21 review papers that discussed existing membrane capture technologies, showcased a range of membrane from zeolites to polymeric to ionic liquid membranes (ILMs). Other studies ($n = 427$) varied between demonstrating an application of CO_2 membrane capture to small scale lab experiments to determine the potential of the proposed method. The remaining 427 studies were on.

3.3 Summary of main results

3.3.1 Membrane material

The porosity and pore size of the membrane are the most significant factors to take into consideration since the contact between the gas and liquid phases occur solely on the pores of the membrane. It is imperative to have a good chemical suitability between the membrane contactor and the solvent, as the absorption liquid determines the selectivity of the separation [12]. Figure 4 demonstrates the principle of CO_2 separation using a membrane. Here, the membrane determines the permeability and selectivity of the process and so the use of liquids is not required [18]. Gas permeation membrane technology is predominantly used in pre-combustion systems. However, such membranes are being developed for post-combustion systems as well. The use of supported liquid membranes for CO_2 removal have gained increasing attention due to ionic liquids being used as solvents. In this membrane configuration, the pores of the membrane are saturated with a liquid, or the liquid is supported on the surface of the membrane. Ionic liquids are mostly attractive in a membrane separation device due to their very low volatility which minimises solvent losses from the membrane [19].

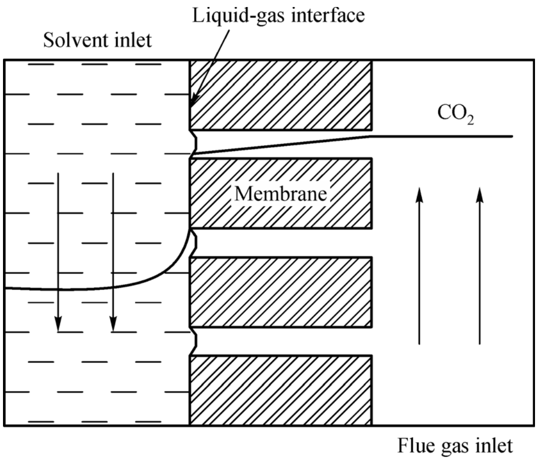

Fig. 4 Principle of CO_2 absorption using membranes. Reprinted with permission of Elsevier from [20].

The most popular type of membrane (28%) was found to be the hollow fibre (*n* = 149) [20–168]. Figure 5 shows a schematic of how absorption occurs in a HFM. The second most common membrane (15%) was observed to be mixed matrix membranes (MMMs) (*n* = 78) [169–246]. The average flux for these ranges from 3.95×10^{-3} to 1.8×10^{-12} $\mathrm{mol \cdot cm^{-2} \cdot min^{-1}}$. HFM work to imitate the function of pulmonary capillary bed packing function where the oxygenation can be optimised by manipulating the gas delivered to the oxygenator. HFM combines chemical absorption with membrane separating technology, allowing for higher selectivity and smaller dimensions (compared to typical separation columns) to be achieved. The mass transfer mechanism resembles that of the shell-tube heat exchanger, thus causing the concentration gradient to be the driving force. Since HMFs are modular systems, the interfacial area can be significantly increased and scale-up operations can become relatively simple when compared to conventional separation systems [247]. Due to their better performance, HFMs were one of the first membrane systems to be investigated for gas separation systems. This is also supported by the high number of studies testing HFM with relatively higher flux values. However, the flux values sit within a huge range, with the majority being in the lower end. This could be the result of membrane wetting, as membranes can become partially wet by the absorption liquid and significantly reduce performance.

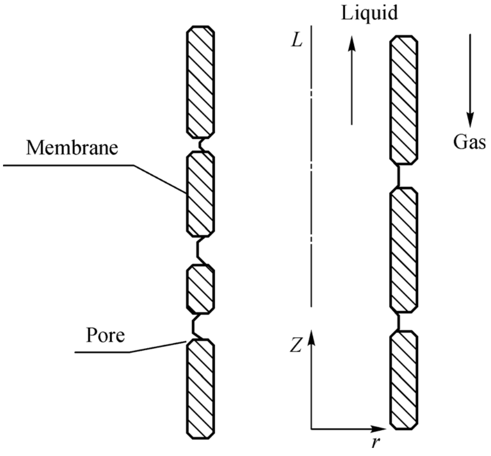

Fig. 5 Schematic showing how absorption occurs in a HFM. Reprinted with permission of Elsevier from [25].

MMMs combine the inorganic fillers with polymeric properties thus giving rise to a huge potential for gas separation industry. These have exhibited versatile performance, with different kind of solvents, ranging from water, ethanol, hydrochloric acid to amine solvents. Since this utilises polymeric properties, the majority of MMMs (3%) are made from different types of polymer materials but face commercialisation issues on a large scale. Metal-organic frameworks (MOFs, *n* = 14, 3%) [211,248–260] are one of the recent inventive solutions for CO_2 separation, with 14 studies exploring the potential. The physical characteristics such as high porosity and surface area along with adjustable pore size and versatile structural arrangement makes it an ideal membrane. The studies above have shown better results than conventional zeolites and polymeric membranes, in conjunction with different kinds of solvents (from alcohol to amine solvents). Poor mechanical properties along with thermal and chemical stability are amongst one of the major limitations of MOFs. Intercrystalline voids or any internal damage within the layers significantly reduces the membrane selectivity. As MOFs are a relatively new membrane advancement than zeolites or polymers and coupled with their limitation makes them a less popular choice amongst other types.

A total of 110 studies utilised polymeric membranes

(21%) [46,48,52,62,77,102,117,134,152,227,229,250, 261–358] or zeolites (*n* = 27, 5%) [359–385] and have been a major part of CO_2 separation. These membranes have been applied and used throughout industry for the last three decades and have shown great potential. The studies have shown enhanced performance of these membranes in hybrid and composite forms. The average flux ranged from 1.3×10^{-1} to 3.33×10^{-9} $mol \cdot cm^{-2} \cdot min^{-1}$, thus displaying a great potential. Furthermore, these can be applied with organic and inorganic solvents, making them more versatile, with water solvent displaying the best results. However, polymeric membranes are subject to mechanical and structural change over time, as well as low surface area per unit of volume, and results in low selectivity and permeability values on a large scale. This is supported by the lower range of flux values, where the majority lie under 1 $mol \cdot cm^{-2} \cdot min^{-1}$. The main current challenge is the plasticisation of suppression of polymer membranes along with the economic implication involved in increasing the membrane area to obtain higher flux values. To overcome this, many studies have experimented on hybrid polymer membranes by integrating them into other membrane structures. Peters et al. [302] studied acid gas sweetening using amine absorption and a two-polymer membrane structure and achieved a flux of 2.3×10^{-3} $mol \cdot cm^{-2} \cdot min^{-1}$. The value of flux refers to the performance of membrane and the effect it has on the molar flux of the membrane, considering the ratio of its permeability against the thickness. The membrane technology was reported to achieve a content of 2% CO_2 in the product gas as a final target, with a two-stage configuration for a purity of 90% CO_2 within the permeate stream of the second membrane stage. The flux of the membrane was also considered in the simulation environment exercises conducted. Though a good membrane performance was exhibited, the group also reported further work to evaluate the capital costs of the separation system and thus indicating the persistent challenge between price and performance. Zeolites have been extensively used as catalyst throughout the industry and have shown potential in membrane technology in the last twenty years but have not been as successful as novel MMMs or HFMs. These have exhibited average flux in the range of 1×10^{-2} to 3.02×10^{-6} $mol \cdot cm^{-2} \cdot min^{-1}$ and have displayed poor mass transfer within the membrane. Zeolites are desired for numerous reasons, the main one being the durability and economic cost, as well as their ability to work with different kinds of solvent [386]. However, further research is required to study and establish better reaction conditions to achieve better mass transfer within the system.

ILMs (*n* = 24, 4%) [112, 360, 387–408] are one of the recent advancements in membrane technology. They have a liquid component in the system which allows for the system to have a higher diffusivity, thus resulting better permeability as well allowing the system to be modified by adding on complexes to enhance the CO_2 solubility. Nevertheless, ILMs still need to be further developed to withstand high temperatures and demonstrate how their hydrodynamics work. This can explain why there only 23 (4%) studies on ILMs, with an average flux in the range of 1×10^{-3}–5.03×10^{-9} $mol \cdot m^{-2} \cdot s^{-1}$. Due to the great potential of ILMs, some studies have experimented on different ways forming ILMs. Karousos et al. [390] developed ILMs through physical inhibition of ionic liquid in ceramic tube, consisting of mesoporous separation layer. The group tested different types of ionic liquids but a flux of 8.1×10^{-7} $mol \cdot cm^{-2} \cdot s^{-1}$ was only exhibited by one type ionic liquid as well as being limited to high temperatures and CO_2 mole fractions. ILMs are yet to be successfully applied in industry for long-term systems. Most studies are focused on investigating support membranes, viscosity of ionic liquids and preparation methods. The upcoming and major challenges for ILMs can be summarised in the following points, thus reflecting the piqued interest but low popularity, due to that: 1) Adsorption capacity of ionic liquids in membrane separations; 2) ionic liquids although they show great performance promise, are toxic; 3) overcoming selectivity, stability and recycling issues; 4) finding an economically feasible method of ILM development and membrane set-up.

The flux range and the number of studies in this paper are higher than zeolite and MOFs, showing great promise and potential for CO_2 capture. There were 22% (*n* = 117) of studies [89,409–524] which tested different materials and belong in the 'other' category due to the vast variation in materials, such as ceramics, caesium incorporated, bio-catalytic membrane materials, and capillary membrane as well hybrid membrane forms of polymer and MMMs for example. The remaining 34 studies (6%) [525–546] have not conveyed any information relating to the membrane material. Figure 6 displays the percentage of studies utilising the various mentioned membranes.

3.3.2 Contactor type

There were three types of membrane contactors observed across the 525 studies: flat sheet (FS) (*n* = 79, 15%) [90, 93,98,117,127,137,180,181,187,193,199,212,218,222, 230,238–240,243–245,248,249,256,267,268,278,282, 284,287,289,302,305,312–315,317,321,323,324,326,329, 333,336,338,343–345,347,352,356,358,360,391,398,399, 404,408,422,426,438,449,450,453,465,467,476,481,500, 503,508,515,521,522,524,531,538,544], facilitated transport (FT) (*n* = 36, 6%) [21,32,50,86,135,136,188,272,276, 283,288,325,335,387–390,392–397,399–403,421, 423,431,468,482,510,517,518], and HFM (*n* = 176, 32%) [20,22–49,51–63,65–84,87–89,91,94–97,99–111,113–116,118–126,128–134,138–148,150–168,174,183–185,192,195–197,204,261,262,276,284,288,291–293,307,311,322,331,364,387,390,392,412,426,429,430, 434,435,439,489,492,507,516,519,527,528,530,535,540,

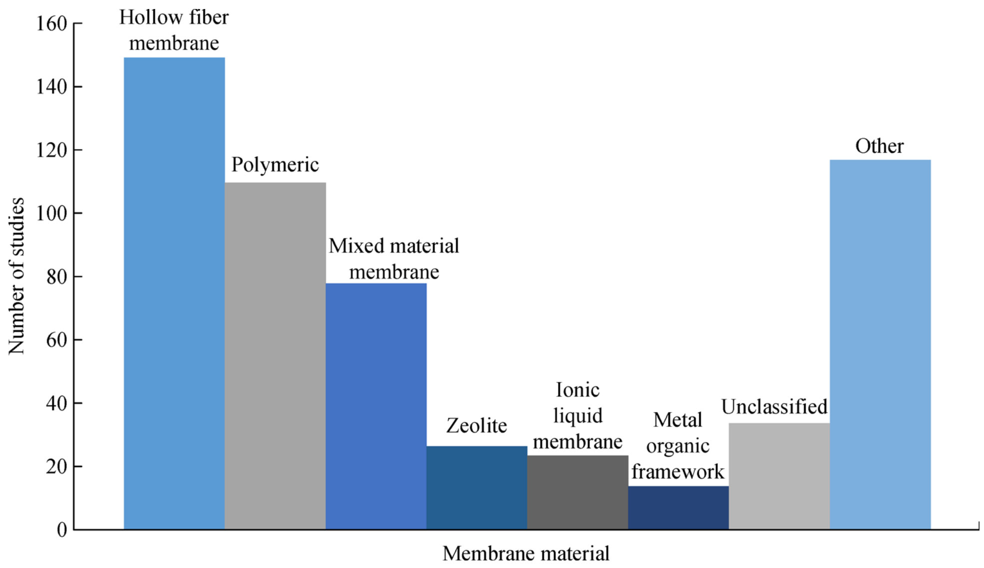

Fig. 6 Percentile of types of membranes utilised for CO_2 capture determined from this work.

541]. There were 175 (33%) studies that had other membrane contactor types (for example, water gas shift/membrane hybrid, and poly(ethylene oxide) based block copolymers contactors), which do not fit into the above mentioned categories [64,85,170–173,175,176,178, 179,182,189,191,194,200–203,206–211,231–233, 241,242,246,247,253,260,263–266,271,273,274, 277,279,281,283,285,286,290,295–301,303,304, 306,308–310,316,318–320,327,328,332,334,337, 339,340,342,346,348,350,351,353–355,357,359,361, 363,366,367,370–372,374–378,380,381,385,386,405–407,410,411,413–418,420,424–428,432,433,436,440, 442–448,451,454–458,460–462,464,466,469,470,472–475,477–480,483–488,490,491,493,494,497–499, 501,502,505,509,512–514,520,523,532,533,536,537, 539,542,545]. The remainder 72 studies (14%) did not contain any information on the membrane contactor type [92,112,149,169,177,186,190,198,205,213–217,219–221, 223–229,234–237,250–252,254,255,257–259,269,270, 275,280,294,330,341,349,362,365,368,369,373,379, 382–384,409,419,437,441,452,459,463,471,495,496,504, 506,511,525,526,529,534,543,546].

FT is also known in the application of supported liquid membranes, referring to ILMs in this review. The FT mechanism refers to a form of passive transport where external species are used to aid the transport. The molecules move across the membrane with the help of membrane proteins and the membrane possesses the ability to transport larger molecules. This is usually affected by the temperature, which is supported by the fact that ILMs have better stability, and thus can withstand higher temperatures, resulting in higher flux values. Concentration is another influential factor that affects the transport mechanism [547].

FS membrane configurations (Fig. 7) are most known for their application in bioreactors [548]. Hollow fibre reactor configurations (Fig. 8) provide higher fluxes and this is supported by review data presented in the supplementary material. HFM provide better gas permeability across the membrane, evidently supported by the number of studies utilising HFM. They are also easy to maintain with minimal pre-screening and requiring mild cleaning to maintain the fibre exterior. FS membrane configurations do not allow for the membrane to back pulse, and so the risk of membrane fouling increases because the impurities cannot be frequently removed [548]. However, FS is a common choice from a maintenance perspective because of the application of gravity flow, saving the systems from using effluent pumps thus saving cost and energy in operation [549]. They have a longer lifetime but are not commonly manufactured across industry, making the initial investment costly. The arrangement of FT membranes (Fig. 9) enables high selectivity and high flux as well as better stability. Fixed carrier membranes, where the ionic liquids were adsorbed on the support, exhibited better stability in terms of higher reaction pressures and temperatures, when compared to the flat liquid sheet membrane configuration. Hence, they have higher potential for recyclability. The reason being simply that adsorbed ionic liquids are stronger anchor on the support than the freely standing ionic liquids. Table S1 (cf. Electronic Supplementary Material) shows that higher flux values are exhibited by HFM, followed by FT and then FS.

3.3.3 Flow configuration

Figure 9 shows different types of flow configuration that were used across the studies: co-current (n = 117, 22%) [21–24,26,32,34,36–38,41,46,52,53,58,61,63–65,67,73,

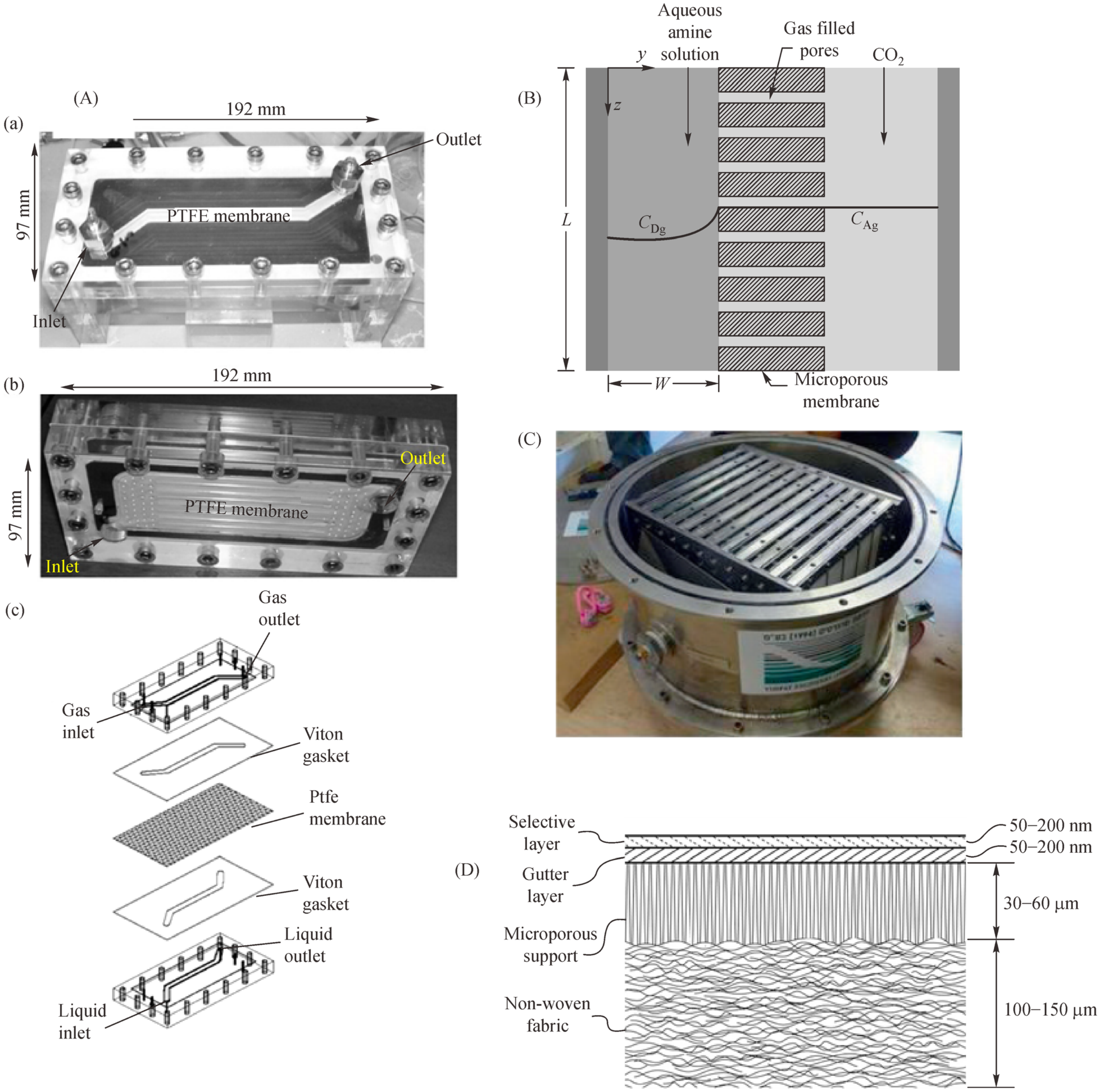

Fig. 7 (A) Flat membrane microstructured contactors: (a) picture of assembled device of the Polytetrafluoroethylene (PTFE) single channel contactor, (b) picture of the assembled device of the 8-channel PTFE contactor, (c) exploded schematic view of the single channel contactor. Reprinted with permission of ACS Publications from [321]; (B) schematic representation of absorption in hydrophobic FS membrane. Reprinted with permission of Elsevier from [422]; (C) FS pilot scale membrane module. Reprinted with permission of Elsevier from [282]; (D) schematic illustration of thin-film composite polaris membranes. Reprinted with permission of Elsevier from [323].

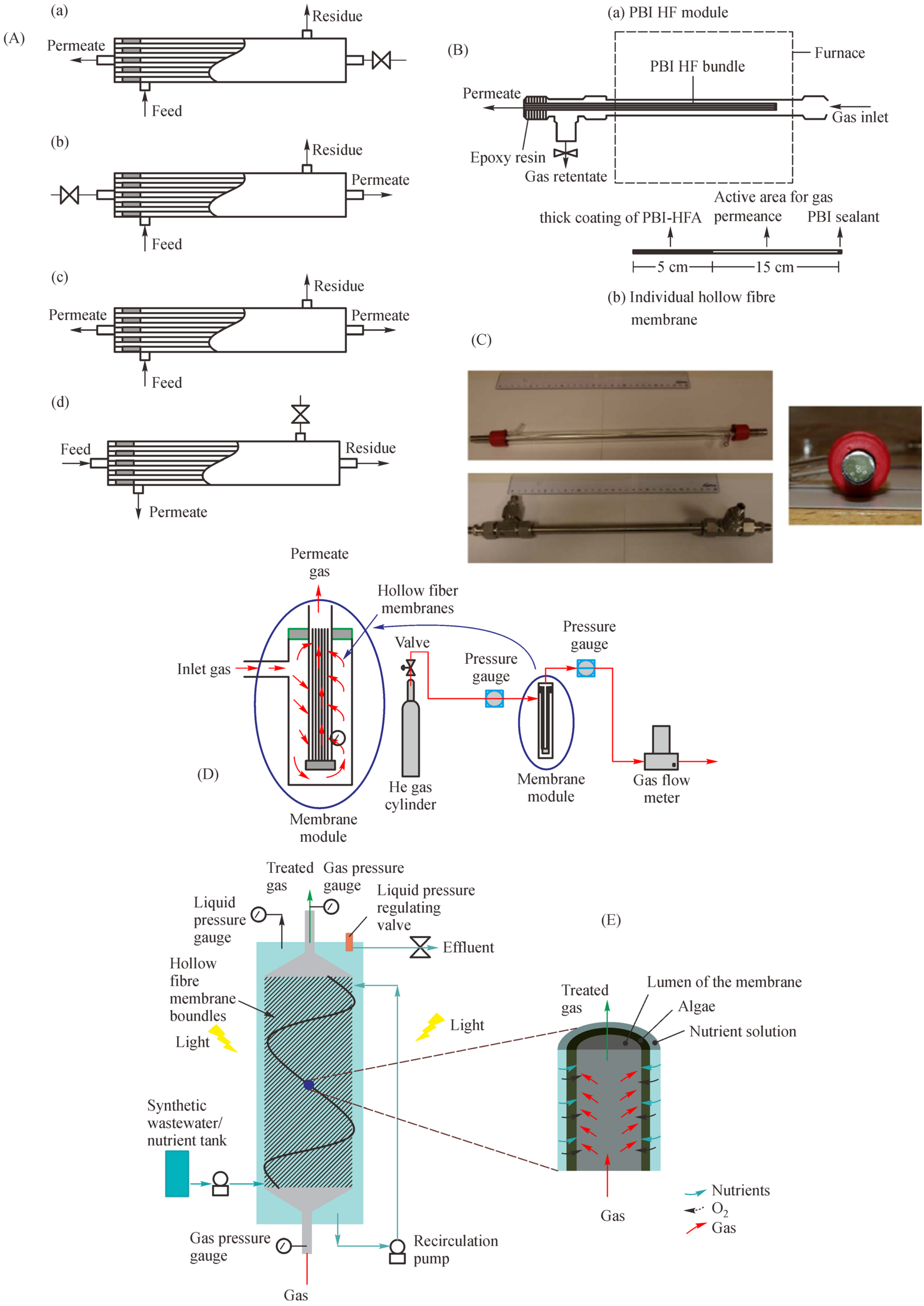

Fig. 8 (A) Configurations of membrane modules: (a) shell side feed, counter-current flow, (b) shell side feed, co-current flow, (c) shell side feed, counter-/co-current flow (permeate withdrawal from both ends of the fibre bores), (d) bore side feed, counter-current flow. Reprinted with permission of ACS Publications from [30]; (B) schematic representation of (a) polybenzimidazole (PBI) HFM module used for permeation at high temperature, (b) Individual HFM partially coated with polybenzimidazole-4,4′-(hexafluoroisopropylidene)bis (benzoic acid) (PBI-HFA) and lumen plugged with PBI sealant. Reprinted with permission of Elsevier from [63]; (C) hollow fibre modules for gas permeation experiments. Reprinted with permission of Elsevier from [56]; (D) schematic diagram of hollow fibre gas permeation test apparatus. Reprinted with permission of Elsevier from [61]; (E) schematic of the bench-scale HFM photo-bioreactor (HFMPB) system. Reprinted with permission of Wiley from [43].

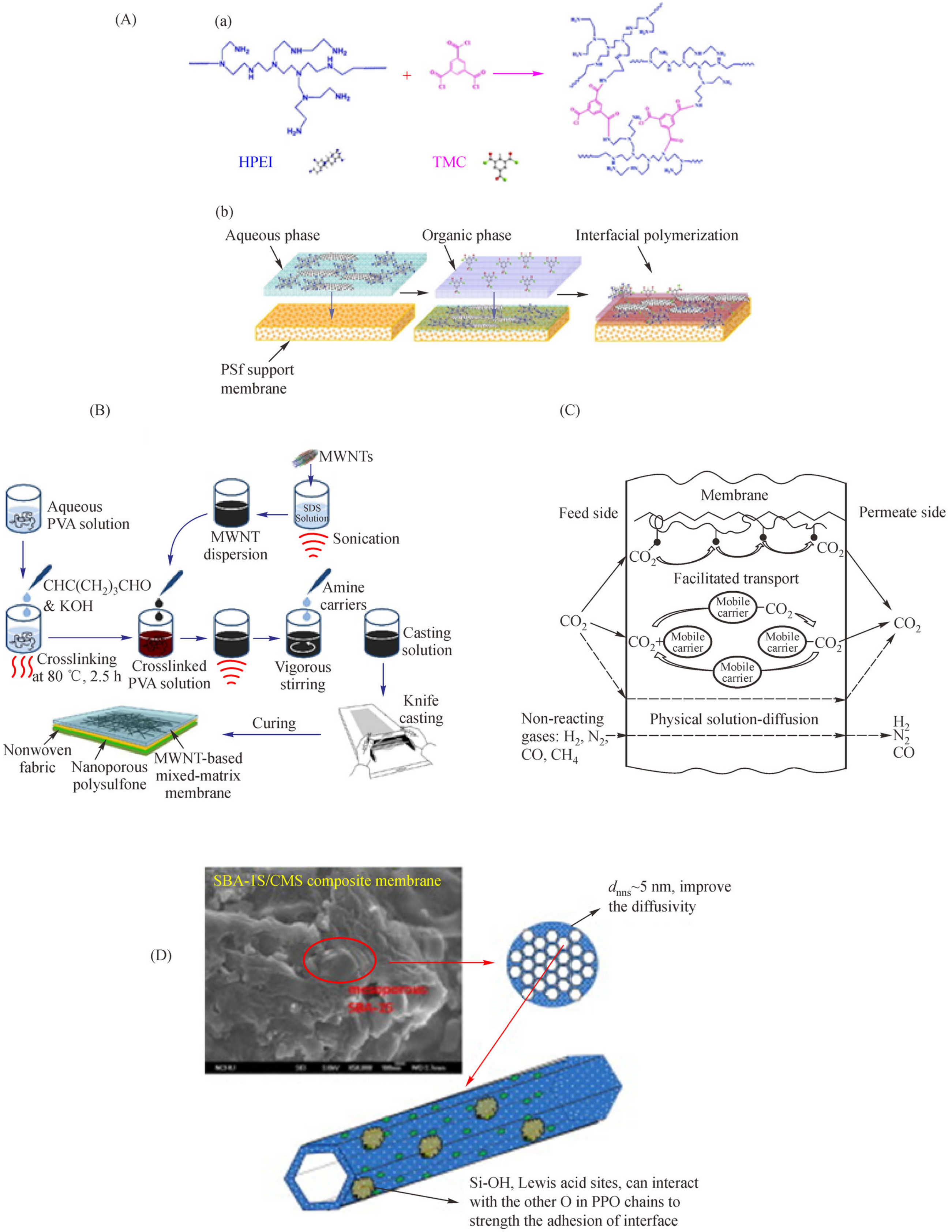

Fig. 9 (A) Schematic diagram of (a) the reaction between hyperbranched polyethylenimine (HPEI) and trimesoyl chloride (TMC), and (b) the fabrication process for the HPEI/graphene oxide-TMC composite membrane. Reprinted with permission of ACS Publications from [481]; (B) schematic of the preparation procedure for the MMM. Reprinted with permission of Elsevier from [449]; (C) schematic of gas permeation through a FT. Reprinted with permission of ACS Publications from [98]; (D) schematic of mesoporous silica sieve SBA-15/carbon molecular sieve composite membrane. Reprinted with permission of Elsevier from [283].

74,76,77,81,83,86,97,109–111,113,123,132,165–167, 171,177–179,182,195,217,226,236,238,241,242,244, 245,253,261,262,275,282,284,288,290,292,300,311,312, 314,319–322,327,336,338,344,346,347,356,357,359, 365–367,376,387,388,390,392,394,395,397,400,403, 407,408,410,412,419,422,424,434,446,447,462,468,472, 487,488,490,507,510,515,522,528,531,533,535,536,538, 546], counter current (n = 118, 22%) [20–22,24,25,27,30, 33,40,42,44,45,47–49,54,56–58,60,65,66,69,71,72,74,75, 80,82,85,87–89,91,98–102,104,105,108,113,115,117,119, 120,124,125,128,134,138,140–144,147,148,151,153,154, 156,157,160,161,163,168,186,187,196,197,249,263,278, 279,300,302,326,339,344,345,350,358,382,383,396,397, 411,413,418,421,428–430,433,439,453,458,461,465–467,470,477,489,505,509,514,516,520,521,526–528, 530,534,544], and cross flow (n = 41, 8%) [51,78,92,94–96,103,114,130,131,139,146,150,152,155,194,196,225, 287,293,308,322,323,333,344,351,353,406,413,417,432, 451,454,456,486,491,494,495,502,523,526]. The rest 258 studies (49%) contained no information regarding the flow configuration used [28,31,35,43,50,55,59,62,84,90,93, 106,107,112,116,118,121,122,126,127,129,133,135–137, 145,149,158,159,162,164,169,170,172–176,180,181, 183–185,188–193,198–216,218–224,227–235,237,239, 240,243,246,248,250–252,254–260,264–274,276,277, 280,281,283,285,286,289,291,294–298,299,301,303–307,309,310,313,315–318,324,325,328–332,334,335, 337,340–343,348,349,352,354,355,360–364,368–375, 377–381,384,385,389,391,393,398,399,401,402,404, 409,414,415,420,423,425–427,431,435–438,440–445, 448–450,452,455,457,459,460,463,464,469,471,473–476,478–485,492,493,496–501,503,504,506,508,511–513,517–519,524,525,529,532,537,539–543,545].

In many cases both co- and counter-current flow were studied to see the effect on mass transfer and membrane performance. Co-current and counter flow configurations are most utilised across various disciplines, due to the developed understanding of mass transfer phenomena. However, it is not possible to say whether one is better than the other. It can be summarised that these flow configurations provide better performance (with their respective membrane application) when compared to other types of flows. Studies that solely used co-current configuration displayed an average flux in the range of 1×10^{-1}–1.72×10^{-17} $mol \cdot cm^{-2} \cdot min^{-1}$ with the higher values corresponding to ILMs suggesting that co-current flow is better suited for ILMs.

The study of counter current flow was mostly exhibited in HFMs and displayed larger mass transfer range, 5.5×10^{-1}–8.7×10^{-11} $mol \cdot cm^{-2} \cdot min^{-1}$. This indicated the better performance to be due to better concentration gradients being established at the gas liquid interfaces. However, the lower flux value suggest that this flow is subjective to situation and experimental conditions. A flux of 8.7×10^{-11} $mol \cdot cm^{-2} \cdot min^{-1}$ was obtained at a lower gas flow rate and 0% N-Methyl-2-Pyrrolidone solvent. Counter current configuration seems to display better mass transfer rate with amine and salt solvent, with high and low inlet feed conditions. Some studies experiment with cross-flow, where the feed travels tangentially across the membrane. Theoretically, this provides better contact as there is more random contact between the membrane and the gas, but the results do not provide promising mass transfer. The flux range was between 2.94×10^{-4} and 1.2×10^{-12} $mol \cdot cm^{-2} \cdot min^{-1}$. However, these were tested with butanol and amine solvents. Further testing with different types of solvents could potentially provide a different result.

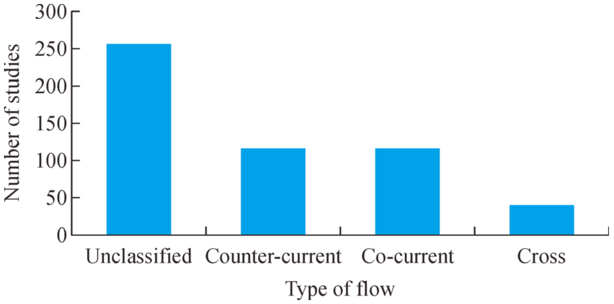

Fig. 10 Types of flows (by count) determined from the included studies.

3.3.4 Solvent (with molarity)

The solvent choice is an important factor in membrane separation, as it directly impacts the economic aspect of the process as well as aid to indentify the right low energy solution for CO_2 processing. Three distinctive types of solvents were found from the studies; amine solvents (n = 104, 20%) [20,21,25,32–34,36,37,39,40,42,49,51–53, 57,59,60,67,68,70,72,79,85,87,91–96,98,100,103,105, 107,109,114,115,119,120,122,124,125,129–131,138,140, 141,143,144,146,151–155,157,166,168,171,206,213, 217,233,241,263,271,276,287,288,296,300,302,309,310, 317,324,327,331,339,357,396,402,404,408,411,412,422, 425,434,439,453,458,469,476,491,498,503,505,521,529, 538]. CO_2 capture using amine solvents has been practiced since the 1950s and therefore is a well understood and developed process. This is supported by the number of studies testing CO_2 separation using amines solvents. Typical membrane separation operates at 60 °C, which makes it extremely desirable to be an energy efficient option. The flux for amine solvents range from 1.1×10^{-1}–1.75×10^{-16} $mol \cdot cm^{-2} \cdot min^{-1}$. For 1.1×10^{-1} $mol \cdot cm^{-2} \cdot min^{-1}$ an MEA solvent was used in a polymer matrix [288]. For 1.75×10^{-16} $mol \cdot cm^{-2} \cdot min^{-1}$ the group used same MEA solvent in FT membrane contactor with a feed inlet of 41% [21]. Large variation in flux ranges support the low absorption capacity of amine solvents as well as high reactivity, stability and thermal degradation issues.

There were 58 studies (11%) which utilised various kinds of inorganic solvents such as metal nitrates and silane [22,47,61,71,73,89,90,106,123,149,150,159,162, 170,172,173,192,195,200,207,208,229,237,239,240,245, 256,269,311,315,320,321,325,367,370,372,378,416,419, 420,424,427,444,448,450,452,456,460,473,478,492,501, 502,506,511,512,515,523], and amides (n = 44, 8%) [24, 26,63,82,99,101,133,139,176,184,187,197,198,209,216, 227,231,252,262,270,272,274,279,301,326,334,336,346, 347,349,351,352,379,385,395,400,401,407,465,467,474, 475,490,514]. Amide solvents are typically known for their use in pharmaceuticals and manufacturing materials such as Kevlar [550]. Their widespread application led to new and upcoming ideas for organic amide solvents for membrane operations. Particularly due to their relatively easy synthesis process as well introducing a huge variety of amide solvents possibilities that can be utilised. The flux values range from 9.66×10^{-5}–9.55×10^{-14} $\mathrm{mol \cdot cm^{-2} \cdot min^{-1}}$. Though amides are known to have comparatively better permeability and selectivity, further research is required to find the optimum operating conditions to achieve stable values of flux.

41 studies (8%) used water and ethanol solvents [38,55, 108,112,135,164,175,178,181,201,204,214,215,222,223, 238,242,246,260,278,285,298,304,307,318,328,329,335, 350,361,369,375,382,388,403,451,480,481,486,500,518]. It was found that 93 studies (18%) showcased the use of general organic solvents such as alcohols, acids and salts [23,27,30,31,44,46,48,62,65,66,75–78,80,84,88,102,116, 118,132,161,163,169,180,182,186,191,193,194,196,203, 196,210–212,218,221,225,228,235,236,243,248,249,257, 261,264,266,268,273,280,286,289,295,297,316,319,332, 340,342,348,352,355,360,365,377,387,389,391,397,399, 405,406,410,414,415,423,428,433,435,438,454,459,464, 479,482,487,494,508,517,519,521,522]. The use of organic solvents is preferred due to economic opportunities that arise as well as being more environmentally friendly, hence a considerable interest in organic solvents. The flux range between 3×10^{-3}–1.17×10^{-6} $\mathrm{mol \cdot cm^{-2} \cdot min^{-1}}$. As organic solvents do not provide high flux values, this might be linked to the membrane roughness and some structural changes a membrane can undergo when in contact with organic solvents [551]. The absorption efficiency of organic solvents is theoretically better than amine solvents. This is supported by a smaller flux range for studies that used organic solvents, indicating consistent behaviour. More recently, membrane contactors which utilise immobilised enzymes, such as carbonic anhydrase (CA), for effective CO_2 removal have been studied. For applications at low concentration CO_2 (< 1%, v/v) and near atmospheric reaction conditions, CA is the most efficient catalyst for CO_2 hydration and dehydration, with a turnover number of 10^6 $\mathrm{mol_{CO_2} \cdot mol^{-1}{}_{CA} \cdot s^{-1}}$. The reaction rate catalysed by CA is much faster than the rate at which CO_2 complexes with other solvents such as MEA [552,553].

The remaining 185 studies (35%) had no information about solvent types [28,29,35,41,43,45,50,54,56,58,64, 69,81,83,86,97,104,110,111,113,117,121,126–128,134, 136,137,142,145,147,148,156,158,160,165,167,174,177, 179,183,185,188–190,199,202,205,219,220,224,226,230, 232,234,244,250,251,253–255,258,259,265,267,275,277, 281–284,290–294,299,303,305,306,308,312–314,322, 323,330,333,337,338,341,343–345,353,354,356,358,359, 362–364,366,368,371,373,374,376,380,381,384,390, 392–394,398,409,413,417,418,421,426,429–432,436, 437,440–443,445–447,449,455,457,461–463,466,468, 470–472,477,483–485,488,489,493,495–497,499,504, 507,509,510,513,516,520,524–528,530–537,539–546]. Figure 11 shows a visual representation of the different types of solvents and the number of studies that utilised them. Inorganic membranes provide better flux values because organic solvents can cause denaturing of membranes at high temperature operations.

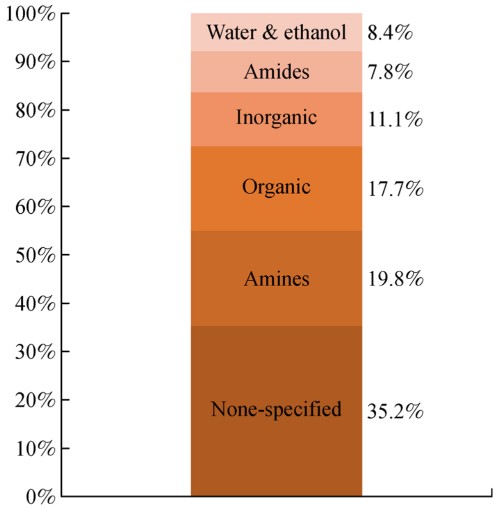

Fig. 11 Types of solvent used in the included studies.

3.3.5 Wetting

Wetting refers to the angle the solvent makes with the membrane, hence determining the solvent dispersion on the membrane surface. It was found that 8 studies (1.3%) used hydrophilic membranes [54,225,337,433,491,492, 515,522]. The majority of the studies (n = 341, 65%) exhibit a phobic behaviour between the solvent and the membrane [20,22–24,26,27,30,31,34–40,42,44,46–53,55, 56,58–69,71–78,80,82–86,88–91,94–109,111,114–118, 121–123,125,127,129,130–132,133,134,135,137,139, 141,143–146,151–157,159,161,163,164,166–171,174, 176–181,183–185,188–194,198–211,213,214,216–218, 222–224,226–228,230,233–36,238–240,242,244,246, 250,252, 253, 258, 261, 262, 264–270, 272–274, 276–283, 285,286,288–305,307–336,338–356,358–360,362,364, 365,368,376,377,380,383,384,393,394,400,405,408,410, 411,415,419,426–428,431,434,435,437,438,443,445, 447–451,453,454,456,458,459,463–467,472,473,475, 478–480,482,483,484–489,496,497,500–502,505, 506,508,513,514,516,517,519,521,523,524,528,533,538, 543]. One of the reasons for the low popularity of hydrophilic membranes is the low thermal and chemical stability of membranes, which in turn has an effect on the flux, demonstrated in Table S1, with the values ranging from 1.1×10^{-3}–1.2×10^{-10} $mol \cdot cm^{-2} \cdot s^{-1}$. Hydrophobic membranes have better thermal stability and along with lower transport resistance these makes them more appropriate for gas separation applications and a popular option for gas separation studies [554]. The remainder 176 studies (34%) had no information about wetting [21,25,28, 29,32,33,41,43,45,57,70,79,81,87,92,93,110,112,113,119, 120,124,126,128,136,138,140,142,147–150,158,160,162, 165,172,173,175,182,186,187,195–197,212,215,219–221,229,231,232,237,241,243,245,248,249,251,254–257, 259,260,263,271,275,284,287,306,357,361,363,366,367, 369–375,378,379,381,382,385,387–392,395–399,401–404,406,407,409,412–414,416–418,420–425,429, 430,432,436,439–442,444,446,452,455,457,460–462,468–471,474,476,477,481,490,493–495,498,499, 503,504,507,509–512,518,520,525–527,529–532,534–537,539–542,544–546].

3.3.6 Average flux

Molar flux is known as the amount of substance passing across the membrane, per unit of area and is one of the key parameters to evaluate the performance of a membrane. A higher indication of flux represents effective utilisation of the membrane surface. The flux values ranged from 10^{-17} to 10^{-13} $mol \cdot cm^{-2} \cdot min^{-1}$. In 10 studies (2%) the flux values were lower than 10^{-10} $mol \cdot cm^{-2} \cdot min^{-1}$ [21,65, 96,143,194,292,343,379,411,524], and 33 studies (6%) were in the range $10^{-10} \leqslant flux \leqslant 10^{-7}$ [51,63,68,79,100–102,112,149,155,163,215,224,235,267,295,314,326,380, 385,390,401,408,423,431,438,448,458,467,483,514,520, 522]. There were 257 studies (48%) which determined the average flux to be within $10^{-6} \leqslant flux \leqslant 10^{-4}$, [20,22–27,30, 31,33,34,36,40–42,44,46–49,55,60–62,66,67,69,72–78, 80–82,84,87–89,93,97,99,103–106,108,109,111,115,116, 118,123,127,129,131–134,137,139,145–148,150,152, 153,156,159,161,164,165,167,169,170,171–174,177–179,182–187,191–193,195,197,199–201,204,205,209–214,216–219,221–223,225,226,229–233,236,238–243, 246,248,256,261,262,265,266,270,271,273–275,278,279, 281,283,284,289–291,294,296–298,300–305,313,316–318,323–325,327,328,334,335,338–340,342,345–347, 349–355,357,359,361,365,367,370–372,375–378,381, 382,384,387–389,391,392,397,398,399,402,404–406, 410,414,416,417,419,420,422,425,427,428,432,433,439, 440,452,456,459,460,463,464,474–476,478–482,490–492,496–503,510–513,518,519,526,534] and 87 studies (17%) had the flux range of $10^{-3} \leqslant flux \leqslant 10^{-1}$ [32,38,50, 53,56,57,70,83,86,90,94,98,110,119,135,140–142,175, 176,180,181,188,198,206–208,220,237,252,255,257,264, 268,277,288,299,307,312,315,319,321,329,332,336,337, 341,348,356,358,362–364,369,373,374,393,395,396,407, 415,421,426,435,441,447,449–451,453,454,457,465,466, 469,484,486,488,505,506,508,515–517,521,523]. The remainder 138 studies (26%) contained no information on the flux [28,29,35,37,39,43,45,52,54,58,59,64,71,85, 91,92,95,107,113,114,117,120–122,124–126,128,130, 136,138,144,151,154,157,158,160,162,166,168,189,190, 196,202,203,227,228,234,244,245,249–251,253,254,258, 259,263,269,272,276,280,282,285–287,293,306,308–311,320,322,330,331,333,344,360,366,368,383,394,400, 403,409,412,413,418,424,429,430,434,436,437,442–446, 455,461,462,468,470–473,477,485,487,489,493–495, 504,507,509,525,527–533,535–546].

Figure 12 shows a visual representation of the flux ranges. Table S1 shows that the highest flux was exhibited by polymeric membranes (7.6×10^{-1} $mol \cdot cm^{-2} \cdot min^{-1}$). However, some ILM studies exhibited a relatively higher flux values when compared to conventional membranes such as polymeric membrane material. These are made up of microporous supports containing cation and anions. The arrangement and structure of these membrane allow for the vapour pressure to be neglected within the system, provide greater viscosity, reduce solubility and thus resulting in effective utilisation of the membrane. These recent studies on ILMs open a new research opportunity for gas separation processes. Some HFMs also displayed high flux in combination with amine solvents. The tubular and small capillary arrangement of these membranes allows the membrane to utilise the maximum surface area for CO_2 separation. However due to fouling and breaking issues, the best result is not always achieved.

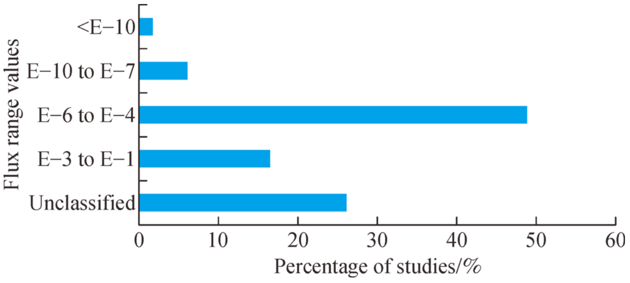

Fig. 12 Flux range percentages.

3.3.7 Gas and liquid flow rate

It was found that 17 studies (3%) had the gas flow rate under 10 $mL \cdot min^{-1}$ [21,44,54,63,88,118,127,157,186, 205,225,278,356,407,421,508,529], and 51 studies (10%) set the flow rate between 10 and 100 $mL \cdot min^{-1}$ [32,51, 59,73,77–79,81,90,98,101,104,115,156,187,188,200,209, 217,239,246,272,279,283,294,298,314,325,336,350,357, 358,365,372,382,414,423,427,433,449,459,469,472,474,475,492,517,518,520,524,529]. A further 43 studies (8%) set the gas flow rate in the range of 100 < flow < 1000 [25,27,37,38,40,47,49,60,70,72,73,76,85,104–106,115,122,128,131,134,150,152–154,161,162,167,195,285,321,327,364,397,402,417,423,439,469,479,515,521,522]. Thirteen studies (2%) set the flow rate to ≤1000 $\mathrm{mL\cdot min^{-1}}$ [87,94,96,139,143,146,151,166,168,266,302,428,467]. The remaining 406 studies (78%) contained no information on the flow rate [20,22–24,26,28–31,33–36,39,41–43,45,46,48,50,52,53,55–58,61,62,64–69,71,74,75,80,82–84,86,89,91–93,95,97,99,100,102,103,107–114,116,117,119,120,121,123–126,129,130,132,133,135–138,140–142,144,145,147–149,155,158–160,163–165,169–185,189–194,196–199,201–204,206–208,210–216,218–224,226–238,240–245,248–265,267–271,273–277,280–282,284,286–293,295–297,299–301,303–313,315–320,322–324,326,328–335,337–349,351–355,359–363,366–371,373–381,383–385,387–395,398–401,403–406,408–413,415,416,418–420,422,424–426,429–432,434–438,440–448,450–458,460–466,468,470,471,473,476–478,480–491,493–507,509–514,516,519,523,525–528,530–546].

It was found that 25 studies (5%) had the liquid flow rate under 10 $\mathrm{mL\cdot min^{-1}}$ [21,29,31,41,47,54,59,82,88,98,157,164,268,278,321,324–326,331,342,348,356,440,467,515]. Forty-two studies (8%) had the flow rate between 10–100 $\mathrm{mL\cdot min^{-1}}$ [25,29,32,44,49,65,74,76,77,79,85,87,96,101,106,110,118,128,131,146,151,153,154,156,161,162,166,195,217,246,272,279,298,357,397,432,433,440,447,467,474,520]. Thirty-eight studies (7%) had the flow rate in the range of 100 < flow ≤ 1000 [32,37,38,40,44,46,48,51,57,70,75–78,84,85,94,101,102,104,106,122,128,131,134,143,152,188,195,337,364,365,396,408,440,472,521,522], and 5 studies (1%) had the flow rate greater than 1000 $\mathrm{mL\cdot min^{-1}}$ [145,147,168,496,516]. However, 429 studies (82%) did not provide enough data [20,22–24,26–28,30,33–36,39,42,43,45,50,52,53,55,56,58,60–64,66–69,71–73,80,81,83,86,89–93,95,97,99,100,103,105,107–109,111–117,119,120,121,123–127,129,130,132,133,135–142,144,148–150,155,158–160,163,165,167,169–187,189–194,196–216,218–245,248–267,269,270,271,273–277,280–297,299–320,322,323,327–330,332–336,338–341,343–347,349–355,358,359–363,366–385,387–395,398–407,409,410–431,434–439,441–446,448–466,468–471,473,475–495,497–514,517–519,523–546]. The average gas and liquid flow rates ranged between 100–800 $\mathrm{mL\cdot min^{-1}}$. A general correlation between flow rates and flux can be deduced. Lower flow rates result in lower flux. This was the expected result since higher flowrate results in more contact with the membrane leading to higher flux, at any given concentration. However, these relationships do not necessarily hold on smaller preliminary lab scale experiments.

3.3.8 Feed CO_2 concentration

About a fifth of the studies 18%, (n = 94 studies) had the inlet feed at less than and including 20% [22,37–39,49,50,56,61,64,68–70,73,87,90,94,112,115,120,121,124,126,127,137,139,140,142,143,145,147,148,151,158,160–163,165,167,168,173,181,187,199,209,217,240,245,251,260,267,270,275,277,290,303,311,312,315,316,319,320,322,323,330,336,338,367,381,390,409,412,421,423,428–430,436,437,453,455,480,488,489,493,497,507,516,520–522,526,529,533]. There were 112 studies (21%) that set the inlet feed between 20%–50% [21,28,34,36,40,42,48,55,57,60,67,71,72,88,90,95–97,99,103,110,117,126,129,131,137,139,155–157,164,172,183,184,187,188,200,205,209,218,221,237,240,248,251,261,265,277,279,281,292,298–300,313,320,321,323,325,327,329,341,344,352,356–359,362,365,370,371,373,375,379,381,382,385,388–390,392,393,398,407,410,414,416,419,425,427,435,439,440,444,446,455,457,470,491,507,510,513–515,519,523,529,531,532,534,536]. For 63 studies (12%) the inlet feed composition was set between 50%–90% [27,30,40,55,71,79,88,90,92,95,97,99,126,132,139,146,172,183,184,200,213,218,221,237,248,251,281,291,298,314,320,341,359,362,371,373,375,379,381,382,388–390,392,393,398,407,410,414,416,425,427,435,440,457,507,510,513,514,523,524,528,529]. Four studies (1%) had inlet compositions up and including 100% and this was done to study the permeability and solubility of the membrane [54,79,92,266]. Figure 13 shows a visual representation of inlet CO_2

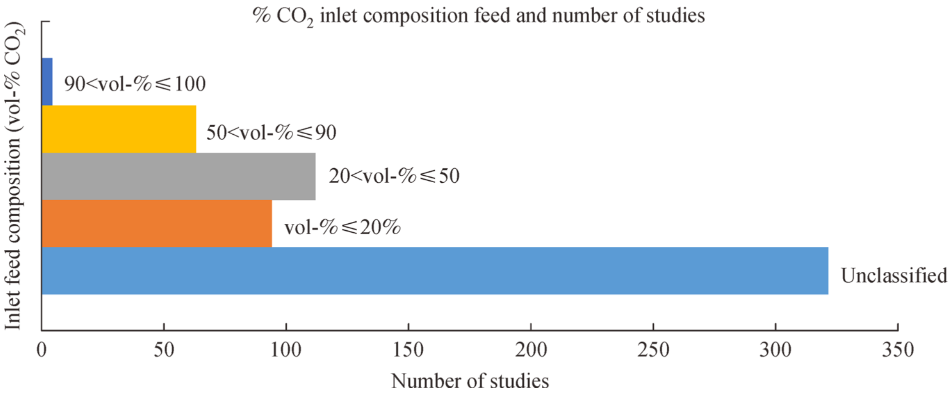

Fig. 13 The inlet feed of CO_2 concentration for the included studies.

ranges and the number of studies. The inlet feed CO_2 ranged from 1.8% to 100%, with many of the studies (142) keeping the inlet feed at the standard feed composition of industrial feed (between 14%–50%). As a lot of studies were lab scale experiments along with simulated models, 14%−50% provides a better representation of CO_2 capture feed. The remaining 322 studies (62%) had no information on the CO_2 feed [20,23–26,29,31–33,35,41,43–47,51–53,58,59,62,63,65,66,74–78,80–86,89,91,93,98,100–102,104–109,111,113,114,116,118,119,122,123,125,128,130,133–136,138,141,144,149,150,152–154,159,166,169–171,174–180,182,185,186,189–198,201–204,206–208,210–212,214–216,219,220,222–236,238,239,241–244,246,249,250,252,253–259,262–264,268,269,271–274,276,278,280,282–289,293–297,301,302,304–310,317,318,324,326,328,331–335,337,339,340,342,343,345–351, 353–355, 360, 361, 363, 364, 366, 368, 369, 372,374,376–378,380,383,384,387,391,394–397,399–405,406,408,411,413,415,417,418,420,422,424,426,431–434,438,441–443,445,447–452,454,456,458–462,463–469,471–479,481–487,490,492,494–496,498–506,508,509,511,512,517,518,525,527,530,535,537–546].

4 Quality of the evidence and bias assessment

Although we did not perform a quality assessment on the included studies, we could not identify a validated tool that can be used in the engineering field, in a similar way that various ones are being widely used for the appraisal of healthcare interventions. For the purposes of our study, we considered adequate that the conducted studies have undergone peer-review to publication. Potentially, it would be useful to perform future studies on the construction and validation of such quality assessment tools specifically for experimental and theoretical studies in membrane contactor systems. We did not assess conflicts of interests, such as industrial collaboration or funding, on any of these studies, but we consider these to be important aspects in checking for biases in the reported methods and results. Our review process was systematic in that we defined a search strategy, run it across three key databases where engineering work is published, with no language, time or geographical restrictions. At every stage at least two authors were independently screening and extracting data, reducing the potential for error. However, this impacted the duration of the overall process from the initial design, search, data extraction and reporting of the primary studies which took almost three years.

5 Implications for research and practice

The review highlights for the first time, the research evidence on the capture of CO_2 using various membrane systems. Although patents, books and conference proceedings were excluded from this review, the included peer-reviewed studies have indicated that HFMs are the most common practice of gas separation methods in industry, along with the use of inorganic solvents in these separation methods providing best results. From the 525 published research studies on the CO_2 capture using different membranes there are three types of membrane contactors identified: FS (15%), FT (6%), and hollow fibre (33%). The flow configuration was co-current in 22% of the studies and counter-current in 22%. Although three main solvent types were used: amines, amides, and water and ethanol solvents, there were inorganics such as metal nitrates and silane, general organic solvents such as alcohols, acids and salts (18%) also explored. The majority of studies (65%) favour a phobic behaviour between the solvent and the membrane and future studies should avoid hydrophilic membranes. The inclusion of more information around the membrane material, membrane contactor type, flow configuration and other identified parameters can lead to the design of better studies on optimally capturing higher concentrations. Future studies should try to address the issue of efficient CO_2 capture by using membranes tested under ILMs and facilitated membrane transport. ILMs and FT have advantages from a chemical and economical perspective. However, further research should focus on how to overcome the issue of thermal stability and lack of reliability on hydrodynamic application in industry.

6 Conclusions

This study started from 2650 papers down to 525 final included studies (shown in Fig. 2). This displays that membrane technology for CO_2 capture has attracted a lot of research attention from research in the past three decades. An efficient method for CO_2 post and pre-processing is yet to be established. Membrane carbon capture and storage, if established, can be operated in a continuous system as opposed to current adsorption and absorption of CO_2 in batch systems. Different kinds of membranes have been investigated to study how membrane systems can be applied and optimised on an industrial scale.

Polymeric membranes have low operating costs and zeolite membranes have high durability and recyclability making them both an attractive common starting place for investigations. Zeolites were initially preferred due to their durability of high temperatures and sorption-diffusion mechanism in separating CO_2. However, they cannot be widely applied due to high manufacturing costs, which may explain why they have only been tested in 5% of the studies. Some have proposed the solution of modifying the zeolite structures by integrating polymers and MMMs but that is yet to be researched further. Polymeric membranes were found to be very popular due to the range of structural possibilities they hold, as well as being economically feasible. ILMs were one of the least popular choices amongst the studies. Although recent advancements established them with better performance at low concentrations when compared to other membranes, ILMs are not widely applied because the membranes cannot withstand high temperatures, and the hydrodynamics of the membranes is yet to be properly understood.

The application of polymer membranes has transitioned into the use of MMMs where organic polymers are imbedded into inorganic casings. This structural arrangement provides higher flux and better separation performances than simple conventional polymer membranes. In 15% of the studies experiments were conducted with MMMs and found great potential. However, issues of incorrect solvent application and inconsistency in the flux values require further investigation. HFMs were found to be the most popular choice due to their versatility and wide range of applications. These are known for gas separation applications which may justify their use in 28% of the studies which experimented with different kinds of HFMs. The HFMs can have various configuration possibilities with different combinations of polymers and have gained a lot of interest as they display good performances. However, further research is required to overcome fouling issues and developing a more economical manufacturing and operating processes. Different kinds of amine solvents were found to be the most popular choice for the membrane studies (20%). Amine solvents have a high CO_2 capacity, low solvent degradation during the absorption and regeneration process, as well as exhibiting better tolerance for regeneration at high pressures. Counter-current flow was the most popular choice of flow configurations over concurrent flow as it provides a better thermodynamic environment and along with larger concentration gradients promotes gas separation. The main limitation of CO_2 membrane capture can be evaluated by a compromise between flux, membrane stability and economic implications. The systematic review of all of the studies in the CO_2 removal and capture is an important milestone in the synthesis of the most relevant and up to date research work. It also provides the additional value of serving as a rich databank for further research and benchmarking and in identifying areas of further research priority.

This study did not focus on papers that involved biological membrane for CO_2 transfer. This was done to keep the focus on CO_2 separation in the energy sector. Studies that modelled membrane systems using different computational programmes, the effect of programmes was not discussed, rather the flux and other parameters were included in the table (supplementary material). Future research should be focused around CO_2 capture using ILMs and facilitated membranes tested under organic and inorganic solvents to form a well-rounded evaluation of these membrane applications in industry, from a chemical and economical prospective. Stability issues of HFM should be investigated to better understand their potential to widely commercialised. Some research could be focused around optimising polymeric and zeolite CO_2 membrane separations systems or upgrading the existing systems into MMMs systems.

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References

1. Schiffer H W, Kober T, Panos E. World energy council's global energy scenarios to 2060. Magazine for Energy Industry, 2018, 42 (2): 91–102
2. Johansson T B, Patwardhan A P, Nakićenović N, Gomez Echeverri L. Global Energy Assessment: Toward A Sustainable Future. Cambridge UK and New York, Laxenburg, Austria: Cambridge University Press, and the International Institute for Applied Systems Analysis, 2012, 99–1257
3. Carapellucci R, Milazzo A. Membrane systems for CO_2 capture and their integration with gas turbine plants. Proceedings of the Institution of Mechanical Engineers. Part A, Journal of Power and Energy, 2003, 217(5): 505–517
4. Cox P M, Betts R A, Jones C D, Spall S A, Totterdell I J. Acceleration of global warming due to carbon-cycle feedbacks in a coupled climate model. Nature, 2000, 408(6809): 184–187
5. Koytsoumpa E I, Bergins C, Kakaras E. The CO_2 economy: review of CO_2 capture and reuse technologies. Journal of Supercritical Fluids, 2018, 132: 3–16
6. Stanger R, Wall T, Spörl R, Paneru M, Grathwohl S, Weidmann M, Scheffknecht G, McDonald D, Myöhänen K, Ritvanen J, Rahiala S, Hyppänen T, Mletzko J, Kather A, Santos S. Oxyfuel combustion for CO_2 capture in power plants. International Journal of Greenhouse Gas Control, 2015, 40: 55–125
7. Jansen D, Gazzani M, Manzolini G, Van Dijk E, Carbo M. Pre-combustion CO_2 capture. International Journal of Greenhouse Gas Control, 2015, 40: 167–187
8. Working Group III of the Intergovernmental Panel on Climate Change. IPCC Special Report on Carbon Dioxide Capture and Storage. Metz B, Davidson O, De Coninck H, eds. New York: Cambridge University Press, 2005, 431
9. Wang Y, Zhao L, Otto A, Robinius M, Stolten D. A review of post-combustion CO_2 capture technologies from coal-fired power

plants. Energy Procedia, 2017, 114: 650–665

10. Nagy E. Basic Equations of Mass Transport Through A Membrane Layer. Amsterdam: Elsevier, 2018, 11–87
11. Khulbe K, Matsuura T. Removal of heavy metals and pollutants by membrane adsorption techniques. Applied Water Science, 2018, 8 (1): 19
12. Luis P, van Gerven T, van der Bruggen B. Recent developments in membrane-based technologies for CO_2 capture. Progress in Energy and Combustion Science, 2012, 38(3): 419–448
13. Hafeez S, Al-Salem S, Constantinou A. Membrane reactors for renewable fuel production and their environmental benefits, in membranes for environmental applications. Vol. 42. Switzerland: Springer, 2020, 383–411
14. Li J L, Chen B H. Review of CO_2 absorption using chemical solvents in hollow fiber membrane contactors. Separation and Purification Technology, 2005, 41(2): 109–122
15. Sun X, Constantinou A, Gavriilidis A. Stripping of acetone from isopropanol solution with membrane and mesh gasliquid contactors. Chemical Engineering and Processing: Process Intensification, 2011, 50(10): 991–997
16. Constantinou A, Ghiotto F, Lam K F, Gavriilidis A. Stripping of acetone from water with microfabricated and membrane gasliquid contactors. Analyst (London), 2014, 139(1): 266–272
17. Ilyas M, Ahmad W, Khan H, Yousaf S, Khan K, Nazir S. Plastic waste as a significant threat to environment—a systematic literature review. Reviews on Environmental Health, 2018, 33 (4): 383–406
18. Favre E. Carbon dioxide recovery from post-combustion processes: can gas permeation membranes compete with absorption? Journal of Membrane Science, 2007, 294(1-2): 50–59
19. Baltus R E, Counce R M, Culbertson B H, Luo H, DePaoli D W, Dai S, Duckworth D C. Examination of the potential of ionic liquids for gas separations. Separation Science and Technology, 2005, 40(1-3): 525–541
20. Yan S P, Fang M X, Zhang W F, Wang S Y, Xu Z K, Luo Z Y, Cen K F. Experimental study on the separation of CO_2 from flue gas using hollow fiber membrane contactors without wetting. Fuel Processing Technology, 2007, 88(5): 501–511
21. Langevin D, Pinoche M, Se E, Me M, Roux R. CO_2 facilitated transport through functionalized cation-exchange membranes. Journal of Membrane Science, 1993, 82(1-2): 51–63
22. Li K, Teo W K. Use of permeation and absorption methods for CO_2 removal in hollow fibre membrane modules. Separation and Purification Technology, 1998, 13(1): 79–88
23. Suzuki H, Tanaka K, Kita H, Okamoto K, Hoshino H, Yoshinaga T, Kusuki Y. Preparation of composite hollow fiber membranes of poly(ethylene oxide)-containing polyimide and their CO_2/N_2 separation properties. Journal of Membrane Science, 1998, 146 (1): 31–37
24. Tokuda Y, Fujisawa E, Okabayashi N, Matsumiya N, Takagi K, Mano H, Haraya K, Sato M. Development of hollow fiber membranes for CO_2 separation. Energy Conversion and Management, 1997, 38: S111–S116
25. Gong Y, Wang Z, Wang S. Experiments and simulation of CO_2 removal by mixed amines in a hollow fiber membrane module. Chemical Engineering and Processing: Process Intensification, 2006, 45(8): 652–660
26. Ismail A F, Yaacob N. Performance of treated and untreated asymmetric polysulfone hollow fiber membrane in series and cascade module configurations for CO_2/CH_4 gas separation system. Journal of Membrane Science, 2006, 275(1-2): 151–165
27. Kapantaidakis G, Koops G, Wessling M, Kaldis S, Sakellaropoulos G. CO_2 plasticization of polyethersulfone/polyimide gas-separation membranes. AIChE Journal. American Institute of Chemical Engineers, 2003, 49(7): 1702–1711
28. Dae-Hwan L, Hyung-Taek K. Simulation study of CO_2 separation process by using hollow fiber membrane. Preprints of Papers-American Chemical Society, Division of Fuel Chemistry, 2004, 49(2): 829–830
29. Lee Y, Noble R D, Yeom B Y, Park Y I, Lee K H. Analysis of CO_2 removal by hollow fiber membrane contactors. Journal of Membrane Science, 2001, 194(1): 57–67
30. Liu L, Chakma A, Feng X. CO_2/N_2 separation by poly(ether block amide) thin film hollow fiber composite membranes. Industrial & Engineering Chemistry Research, 2005, 44(17): 6874–6882
31. Qin J J, Chung T S, Cao C, Vora R. Effect of temperature on intrinsic permeation properties of 6FDA-Durene/1,3-phenylene-diamine (mPDA) copolyimide and fabrication of its hollow fiber membranes for CO_2/CH_4 separation. Journal of Membrane Science, 2005, 250(1-2): 95–103
32. Teramoto M, Kitada S, Ohnishi N, Matsuyama H, Matsumiya N. Separation and concentration of CO_2 by capillary-type facilitated transport membrane module with permeation of carrier solution. Journal of Membrane Science, 2004, 234(1-2): 83–94
33. Wang R, Li D, Liang D. Modeling of CO_2 capture by three typical amine solutions in hollow fiber membrane contactors. Chemical Engineering and Processing: Process Intensification, 2004, 43(7): 849–856
34. Wang R, Zhang H, Feron P, Liang D. Influence of membrane wetting on CO_2 capture in microporous hollow fiber membrane contactors. Separation and Purification Technology, 2005, 46(1-2): 33–40
35. Shim H M, Lee J S, Wang H Y, Choi S H, Kim J H, Kim H T. Modeling and economic analysis of CO_2 separation process with hollow fiber membrane modules. Korean Journal of Chemical Engineering, 2007, 24(3): 537–541
36. Zhang H Y, Wang R, Liang D T, Tay J H. Modeling and experimental study of CO_2 absorption in a hollow fiber membrane contactor. Journal of Membrane Science, 2006, 279(1-2): 301–310
37. Al Marzouqi M, El Naas M H, Marzouk S A, Abdullatif N. Modeling of chemical absorption of CO_2 in membrane contactors. Separation and Purification Technology, 2008, 62(3): 499–506
38. Al Marzouqi M H, El Naas M H, Marzouk S A, Al Zarooni M A, Abdullatif N, Faiz R. Modeling of CO_2 absorption in membrane contactors. Separation and Purification Technology, 2008, 59(3): 286–293
39. El Naas M H, Al Marzouqi M, Marzouk S A, Abdullatif N. Evaluation of the removal of CO_2 using membrane contactors: membrane wettability. Journal of Membrane Science, 2010, 350(1-2): 410–416
40. Faiz R, Al Marzouqi M. Mathematical modeling for the simultaneous absorption of CO_2 and H_2S using MEA in hollow

fiber membrane contactors. Journal of Membrane Science, 2009, 342(1-2): 269–278

41. Ji P, Cao Y, Zhao H, Kang G, Jie X, Liu D, Liu J, Yuan Q. Preparation of hollow fiber poly (*N*,*N*-dimethylaminoethyl methacrylate)-poly(ethylene glycol methyl ether methyl acrylate)/polysulfone composite membranes for CO_2/N_2 separation. Journal of Membrane Science, 2009, 342(1-2): 190–197
42. Keshavarz P, Fathikalajahi J, Ayatollahi S. Analysis of CO_2 separation and simulation of a partially wetted hollow fiber membrane contactor. Journal of Hazardous Materials, 2008, 152 (3): 1237–1247
43. Kumar A, Yuan X, Sahu A K, Dewulf J, Ergas S J, Van Langenhove H. A hollow fiber membrane photo-bioreactor for CO_2 sequestration from combustion gas coupled with wastewater treatment: a process engineering approach. Journal of Chemical Technology and Biotechnology (Oxford, Oxfordshire), 2010, 85 (3): 387–394
44. Lu J G, Ji Y, Zhang H, Chen M D. CO_2 capture using activated amino acid salt solutions in a membrane contactor. Separation Science and Technology, 2010, 45(9): 1240–1251
45. Lu J G, Zheng Y F, Cheng M D. Membrane contactor for CO_2 absorption applying amino-acid salt solutions. Desalination, 2009, 249(2): 498–502
46. Mansourizadeh A, Ismail A F. Effect of LiCl concentration in the polymer dope on the structure and performance of hydrophobic PVDF hollow fiber membranes for CO_2 absorption. Chemical Engineering Journal, 2010, 165(3): 980–988
47. Mansourizadeh A, Ismail A F, Abdullah M, Ng B. Preparation of polyvinylidene fluoride hollow fiber membranes for CO_2 absorption using phase-inversion promoter additives. Journal of Membrane Science, 2010, 355(1-2): 200–207
48. Mansourizadeh A, Ismail A F, Matsuura T. Effect of operating conditions on the physical and chemical CO_2 absorption through the PVDF hollow fiber membrane contactor. Journal of Membrane Science, 2010, 353(1-2): 192–200
49. Marzouk S A, Al-Marzouqi M H, El-Naas M H, Abdullatif N, Ismail Z M. Removal of carbon dioxide from pressurized CO_2CH_4 gas mixture using hollow fiber membrane contactors. Journal of Membrane Science, 2010, 351(1-2): 21–27
50. Sandru M, Kim T J, Hägg M B. High molecular fixed-site-carrier PVAm membrane for CO_2 capture. Desalination, 2009, 240(1-3): 298–300
51. Simons K, Nijmeijer K, Wessling M. Gasliquid membrane contactors for CO_2 removal. Journal of Membrane Science, 2009, 340(1-2): 214–220
52. Yan S, Fang M, Zhang W, Zhong W, Luo Z, Cen K. Comparative analysis of CO_2 separation from flue gas by membrane gas absorption technology and chemical absorption technology in China. Energy Conversion and Management, 2008, 49(11): 3188–3197
53. Zhang H Y, Wang R, Liang D T, Tay J H. Theoretical and experimental studies of membrane wetting in the membrane gasliquid contacting process for CO_2 absorption. Journal of Membrane Science, 2008, 308(1-2): 162–170
54. Boributh S, Assabumrungrat S, Laosiripojana N, Jiraratananon R. Effect of membrane module arrangement of gas-liquid membrane contacting process on CO_2 absorption performance: a modeling study. Journal of Membrane Science, 2011, 372(1-2): 75–86
55. Chen C C, Qiu W, Miller S J, Koros W J. Plasticization-resistant hollow fiber membranes for CO_2/CH_4 separation based on a thermally crosslinkable polyimide. Journal of Membrane Science, 2011, 382(1-2): 212–221
56. Sandru M, Haukebø S H, Hägg M B. Composite hollow fiber membranes for CO_2 capture. Journal of Membrane Science, 2010, 346(1): 172–186
57. Simons K, Nijmeijer K, Mengers H, Brilman W, Wessling M. Highly selective amino acid salt solutions as absorption liquid for CO_2 capture in gas-liquid membrane contactors. ChemSusChem, 2010, 3(8): 939–947
58. Jin H G, Han S H, Lee Y M, Yeo Y K. Modeling and control of CO_2 separation process with hollow fiber membrane modules. Korean Journal of Chemical Engineering, 2011, 28(1): 41–48
59. Khaisri S, deMontigny D, Tontiwachwuthikul P, Jiraratananon R. CO_2 stripping from monoethanolamine using a membrane contactor. Journal of Membrane Science, 2011, 376(1-2): 110–118
60. Boributh S, Rongwong W, Assabumrungrat S, Laosiripojana N, Jiraratananon R. Mathematical modeling and cascade design of hollow fiber membrane contactor for CO_2 absorption by monoethanolamine. Journal of Membrane Science, 2012, 401: 175–189
61. Ghasem N, Al-Marzouqi M, Zhu L. Preparation and properties of polyethersulfone hollow fiber membranes with O-xylene as an additive used in membrane contactors for CO_2 absorption. Separation and Purification Technology, 2012, 92: 1–10
62. Kim D H, Baek I H, Hong S U, Lee H K. Study on immobilized liquid membrane using ionic liquid and PVDF hollow fiber as a support for CO_2/N_2 separation. Journal of Membrane Science, 2011, 372(1-2): 346–354
63. Kumbharkar S, Liu Y, Li K. High performance polybenzimidazole based asymmetric hollow fibre membranes for H_2/CO_2 separation. Journal of Membrane Science, 2011, 375(1-2): 231–240
64. Lee S H, Kim J N, Eom W H, Ko Y D, Hong S U, Back I H. Development of water gas shift/membrane hybrid system for precombustion CO_2 capture in a coal gasification process. Energy Procedia, 2011, 4: 1139–1146
65. Mansourizadeh A, Ismail A F. CO_2 stripping from water through porous PVDF hollow fiber membrane contactor. Desalination, 2011, 273(2-3): 386–390
66. Mansourizadeh A, Ismail A F. Preparation and characterization of porous PVDF hollow fiber membranes for CO_2 absorption: effect of different non-solvent additives in the polymer dope. International Journal of Greenhouse Gas Control, 2011, 5(4): 640–648
67. Nguyen P, Lasseuguette E, Medina Gonzalez Y, Remigy J, Roizard D, Favre E. A dense membrane contactor for intensified CO_2 gas/liquid absorption in post-combustion capture. Journal of Membrane Science, 2011, 377(1-2): 261–272
68. Sohrabi M R, Marjani A, Moradi S, Davallo M, Shirazian S. Mathematical modeling and numerical simulation of CO_2 transport through hollow-fiber membranes. Applied Mathematical Modelling, 2011, 35(1): 174–188
69. Ghasem N, Al Marzouqi M, Rahim N A. Modeling of CO_2 absorption in a membrane contactor considering solvent evaporation. Separation and Purification Technology, 2013, 110: 1–10

70. Hassanlouei R N, Pelalak R, Daraei A. Wettability study in CO_2 capture from flue gas using nano porous membrane contactors. International Journal of Greenhouse Gas Control, 2013, 16: 233–240
71. Hwang H Y, Nam S Y, Koh H C, Ha S Y, Barbieri G, Drioli E. The effect of operating conditions on the performance of hollow fiber membrane modules for CO_2/N_2 separation. Journal of Industrial and Engineering Chemistry, 2012, 18(1): 205–211
72. Lively R P, Dose M E, Xu L, Vaughn J T, Johnson J, Thompson J A, Zhang K, Lydon M E, Lee J S, Liu L, Hu Z, Karvan O, Realff M J, Koros W J. A high-flux polyimide hollow fiber membrane to minimize footprint and energy penalty for CO_2 recovery from flue gas. Journal of Membrane Science, 2012, 423: 302–313
73. Marzouk S A, Al-Marzouqi M H, Teramoto M, Abdullatif N, Ismail Z M. Simultaneous removal of CO_2 and H_2S from pressurized CO_2-H_2S-CH_4 gas mixture using hollow fiber membrane contactors. Separation and Purification Technology, 2012, 86: 88–97
74. Naim R, Ismail A F, Mansourizadeh A. Effect of non-solvent additives on the structure and performance of PVDF hollow fiber membrane contactor for CO_2 stripping. Journal of Membrane Science, 2012, 423: 503–513
75. Naim R, Ismail A F, Mansourizadeh A. Preparation of microporous PVDF hollow fiber membrane contactors for CO_2 stripping from diethanolamine solution. Journal of Membrane Science, 2012, 392: 29–37
76. Rahbari Sisakht M, Ismail A F, Matsuura T. Effect of bore fluid composition on structure and performance of asymmetric polysulfone hollow fiber membrane contactor for CO_2 absorption. Separation and Purification Technology, 2012, 88: 99–106
77. Rahbari Sisakht M, Ismail A F, Rana D, Matsuura T. A novel surface modified polyvinylidene fluoride hollow fiber membrane contactor for CO_2 absorption. Journal of Membrane Science, 2012, 415: 221–228
78. Rahbari Sisakht M, Ismail A F, Rana D, Matsuura T. Effect of novel surface modifying macromolecules on morphology and performance of polysulfone hollow fiber membrane contactor for CO_2 absorption. Separation and Purification Technology, 2012, 99: 61–68
79. Shirazian S, Marjani A, Rezakazemi M. Separation of CO_2 by single and mixed aqueous amine solvents in membrane contactors: fluid flow and mass transfer modeling. Engineering with Computers, 2012, 28(2): 189–198
80. Kim K, Ingole P G, Kim J, Lee H. Separation performance of PEBAX/PEI hollow fiber composite membrane for $SO_2/CO_2/N_2$ mixed gas. Chemical Engineering Journal, 2013, 233: 242–250
81. Mehdipour M, Karami M, Keshavarz P, Ayatollahi S. Analysis of CO_2 separation with aqueous potassium carbonate solution in a hollow fiber membrane contactor. Energy & Fuels, 2013, 27(4): 2185–2193
82. Naim R, Ismail A F. Effect of fiber packing density on physical CO_2 absorption performance in gas-liquid membrane contactor. Separation and Purification Technology, 2013, 115: 152–157
83. Qiao Z, Wang Z, Zhang C, Yuan S, Zhu Y, Wang J, Wang S. PVAm-PIP/PS composite membrane with high performance for CO_2/N_2 separation. AIChE Journal. American Institute of Chemical Engineers, 2013, 59(1): 215–228
84. Rahbari Sisakht M, Ismail A F, Rana D, Matsuura T, Emadzadeh D. Effect of SMM concentration on morphology and performance of surface modified PVDF hollow fiber membrane contactor for CO_2 absorption. Separation and Purification Technology, 2013, 116: 67–72
85. Razavi S M R, Razavi S M J, Miri T, Shirazian S. CFD simulation of CO_2 capture from gas mixtures in nanoporous membranes by solution of 2-amino-2-methyl-1-propanol and piperazine. International Journal of Greenhouse Gas Control, 2013, 15: 142–149
86. Shen J N, Yu C C, Zeng G N, Van der Bruggen B. Preparation of a facilitated transport membrane composed of carboxymethyl chitosan and polyethylenimine for CO_2/N_2 separation. International Journal of Molecular Sciences, 2013, 14(2): 3621–3638
87. Amrei S M H H, Memardoost S, Dehkordi A M. Comprehensive modeling and CFD simulation of absorption of CO_2 and H_2S by MEA solution in hollow fiber membrane reactors. AIChE Journal. American Institute of Chemical Engineers, 2014, 60(2): 657–672
88. Chen H Z, Thong Z, Li P, Chung T S. High performance composite hollow fiber membranes for CO_2/H_2 and CO_2/N_2 separation. International Journal of Hydrogen Energy, 2014, 39(10): 5043–5053
89. Ghasem N, Al Marsouqi M, Rahim N A. Modeling and simulation of membrane contactor employed to strip CO_2 from rich solvents via COMSOL Multiphysics®. In: Proceedings of the COMSOL Conference. Zurich: COMSL, 2014, 1–5
90. He X, Kim T J, Hägg M B. Hybrid fixed-site-carrier membranes for CO_2 removal from high pressure natural gas: membrane optimization and process condition investigation. Journal of Membrane Science, 2014, 470: 266–274
91. Kimball E, Al Azki A, Gomez A, Goetheer E, Booth N, Adams D, Ferre D. Hollow fiber membrane contactors for CO_2 capture: modeling and up-scaling to CO_2 capture for an 800 MWe coal power station. Oil & Gas Science and Technology-Revue d'IFP Energies Nouvelles, 2014, 69(6): 1047–1058
92. Kundu P K, Chakma A, Feng X. Effectiveness of membranes and hybrid membrane processes in comparison with absorption using amines for post-combustion CO_2 capture. International Journal of Greenhouse Gas Control, 2014, 28: 248–256
93. Li S, Wang Z, He W, Zhang C, Wu H, Wang J, Wang S. Effects of minor SO_2 on the transport properties of fixed carrier membranes for CO_2 capture. Industrial & Engineering Chemistry Research, 2014, 53(18): 7758–7767
94. Wang L, Zhang Z, Zhao B, Zhang H, Lu X, Yang Q. Effect of long-term operation on the performance of polypropylene and polyvinylidene fluoride membrane contactors for CO_2 absorption. Separation and Purification Technology, 2013, 116: 300–306
95. Wang Z, Fang M, Pan Y, Yan S, Luo Z. Amine-based absorbents selection for CO_2 membrane vacuum regeneration technology by combined absorption–desorption analysis. Chemical Engineering Science, 2013, 93: 238–249
96. Wang Z, Fang M, Yu H, Wei C C, Luo Z. Experimental and modeling study of trace CO_2 removal in a hollow-fiber membrane contactor, using CO_2-loaded monoethanolamine. Industrial & Engineering Chemistry Research, 2013, 52(50): 18059–18070
97. Yoshimune M, Haraya K. CO_2/CH_4 mixed gas separation using

carbon hollow fiber membranes. Energy Procedia, 2013, 37: 1109–1116

98. Zhao Y, Ho W W. CO_2-selective membranes containing sterically hindered amines for CO_2/H_2 separation. Industrial & Engineering Chemistry Research, 2012, 52(26): 8774–8782
99. Ma C, Koros W J. Effects of hydrocarbon and water impurities on CO_2/CH_4 separation performance of ester-crosslinked hollow fiber membranes. Journal of Membrane Science, 2014, 451: 1–9
100. Makhloufi C, Lasseuguette E, Remigy J C, Belaissaoui B, Roizard D, Favre E. Ammonia based CO_2 capture process using hollow fiber membrane contactors. Journal of Membrane Science, 2014, 455: 236–246
101. Mansourizadeh A, Aslmahdavi Z, Ismail A F, Matsuura T. Blend polyvinylidene fluoride/surface modifying macromolecule hollow fiber membrane contactors for CO_2 absorption. International Journal of Greenhouse Gas Control, 2014, 26: 83–92
102. Mansourizadeh A, Pouranfard A R. Microporous polyvinylidene fluoride hollow fiber membrane contactors for CO_2 stripping: effect of PEG-400 in spinning dope. Chemical Engineering Research & Design, 2014, 92(1): 181–190
103. Masoumi S, Keshavarz P, Rastgoo Z. Theoretical investigation on CO_2 absorption into DEAB solution using hollow fiber membrane contactors. Journal of Natural Gas Science and Engineering, 2014, 18: 23–30
104. Rahbari Sisakht M, Rana D, Matsuura T, Emadzadeh D, Padaki M, Ismail A F. Study on CO_2 stripping from water through novel surface modified PVDF hollow fiber membrane contactor. Chemical Engineering Journal, 2014, 246: 306–310
105. Rahim N A, Ghasem N, Al Marzouqi M. Stripping of CO_2 from different aqueous solvents using PVDF hollow fiber membrane contacting process. Journal of Natural Gas Science and Engineering, 2014, 21: 886–893
106. Rezaei M A, Ismail A F, Hashemifard S A, Bakeri G, Matsuura T. Experimental study on the performance and long-term stability of PVDF/montmorillonite hollow fiber mixed matrix membranes for CO_2 separation process. International Journal of Greenhouse Gas Control, 2014, 26: 147–157
107. Carapellucci R, Giordano L, Vaccarelli M. Study of a natural gas combined cycle with multi-stage membrane systems for CO_2 post-combustion capture. Energy Procedia, 2015, 81: 412–421
108. Farjami M, Moghadassi A, Vatanpour V. Modeling and simulation of CO_2 removal in a polyvinylidene fluoride hollow fiber membrane contactor with computational fluid dynamics. Chemical Engineering and Processing: Process Intensification, 2015, 98: 41–51
109. Goyal N, Suman S, Gupta S. Mathematical modeling of CO_2 separation from gaseous-mixture using a hollow-fiber membrane module: physical mechanism and influence of partial-wetting. Journal of Membrane Science, 2015, 474: 64–82
110. Lee H J, Magnone E, Park J H. Preparation, characterization and laboratory-scale application of modified hydrophobic aluminum oxide hollow fiber membrane for CO_2 capture using H_2O as low-cost absorbent. Journal of Membrane Science, 2015, 494: 143–153
111. Lee S, Choi J W, Lee S H. Separation of greenhouse gases (SF_6, CF_4 and CO_2) in an industrial flue gas using pilot-scale membrane. Separation and Purification Technology, 2015, 148: 15–24
112. Li Y, Li X, Wu H, Xin Q, Wang S, Liu Y, Tian Z, Zhou T, Jiang Z, Tian H, Cao X, Wang B. Anionic surfactant-doped Pebax membrane with optimal free volume characteristics for efficient CO_2 separation. Journal of Membrane Science, 2015, 493: 460–469
113. Lock S S M, Lau K K, Ahmad F, Shariff A. Modeling, simulation and economic analysis of CO_2 capture from natural gas using cocurrent, countercurrent and radial crossflow hollow fiber membrane. International Journal of Greenhouse Gas Control, 2015, 36: 114–134
114. Mulukutla T, Chau J, Singh D, Obuskovic G, Sirkar K K. Novel membrane contactor for CO_2 removal from flue gas by temperature swing absorption. Journal of Membrane Science, 2015, 493: 321–328
115. Rahim N A, Ghasem N, Al Marzouqi M. Absorption of CO_2 from natural gas using different amino acid salt solutions and regeneration using hollow fiber membrane contactors. Journal of Natural Gas Science and Engineering, 2015, 26: 108–117
116. Sadoogh M, Mansourizadeh A, Mohammadinik H. An experimental study on the stability of PVDF hollow fiber membrane contactors for CO_2 absorption with alkanolamine solutions. Royal Society of Chemistry Advances, 2015, 5(105): 86031–86040
117. Vakharia V, Ramasubramanian K, Ho W W. An experimental and modeling study of CO_2-selective membranes for IGCC syngas purification. Journal of Membrane Science, 2015, 488: 56–66
118. Wickramanayake S, Hopkinson D, Myers C, Hong L, Feng J, Seol Y, Plasynski D, Zeh M, Luebke D. Mechanically robust hollow fiber supported ionic liquid membranes for CO_2 separation applications. Journal of Membrane Science, 2014, 470: 52–59
119. Yan S, He Q, Zhao S, Wang Y, Ai P. Biogas upgrading by CO_2 removal with a highly selective natural amino acid salt in gas-liquid membrane contactor. Chemical Engineering and Processing: Process Intensification, 2014, 85: 125–135
120. Zaidiza D A, Billaud J, Belaissaoui B, Rode S, Roizard D, Favre E. Modeling of CO_2 post-combustion capture using membrane contactors, comparison between one- and two-dimensional approaches. Journal of Membrane Science, 2014, 455: 64–74
121. Zhang L, Qu Z Y, Yan Y F, Ju S X, Zhang Z E. Numerical investigation of the effects of polypropylene hollow fibre membrane structure on the performance of CO_2 removal from flue gas. Royal Society of Chemistry Advances, 2015, 5(1): 424–433
122. Zhang X, Seames W S, Tande B M. Recovery of CO_2 from monoethanolamine using a membrane contactor. Separation Science and Technology, 2014, 49(1): 1–11
123. Zhang Y, Wang R. Novel method for incorporating hydrophobic silica nanoparticles on polyetherimide hollow fiber membranes for CO_2 absorption in a gas-liquid membrane contactor. Journal of Membrane Science, 2014, 452: 379–389
124. Zhang Z, Yan Y, Zhang L, Chen Y, Ju S. CFD investigation of CO_2 capture by methyldiethanolamine and 2-(1-piperazinyl)-ethylamine in membranes: Part B. Effect of membrane properties. Journal of Natural Gas Science and Engineering, 2014, 19: 311–316
125. Zhang Z, Yan Y, Zhang L, Ju S. Numerical simulation and analysis of CO_2 removal in a polypropylene hollow fiber membrane

contactor. International Journal of Chemical Engineering, 2014, 2014: 1–7

126. Baghban A, Azar A A. ANFIS modeling of CO_2 separation from natural gas using hollow fiber polymeric membrane. Energy Sources. Part A, Recovery, Utilization, and Environmental Effects, 2018, 40(2): 193–199
127. Dong G, Hou J, Wang J, Zhang Y, Chen V, Liu J. Enhanced CO_2/N_2 separation by porous reduced graphene oxide/Pebax mixed matrix membranes. Journal of Membrane Science, 2016, 520: 860–868
128. Ghadiri M, Marjani A, Shirazian S. Development of a mechanistic model for prediction of CO_2 capture from gas mixtures by amine solutions in porous membranes. Environmental Science and Pollution Research International, 2017, 24(16): 14508–14515
129. Gilassi S, Rahmanian N. CFD modelling of a hollow fibre membrane for CO_2 removal by aqueous amine solutions of MEA, DEA and MDEA. International Journal of Chemical Reactor Engineering, 2016, 14(1): 53–61
130. Hosseini S, Mansourizadeh A. Preparation of porous hydrophobic poly(vinylidene fluoride-co-hexafluoropropylene) hollow fiber membrane contactors for CO_2 stripping. Journal of the Taiwan Institute of Chemical Engineers, 2017, 76: 156–166
131. Jin P, Huang C, Shen Y, Zhan X, Hu X, Wang L, Wang L. Simultaneous separation of H_2S and CO_2 from biogas by gas-liquid membrane contactor using single and mixed absorbents. Energy & Fuels, 2017, 31(10): 11117–11126
132. Jo E S, An X, Ingole P G, Choi W K, Park Y S, Lee H K. CO_2/CH_4 separation using inside coated thin film composite hollow fiber membranes prepared by interfacial polymerization. Chinese Journal of Chemical Engineering, 2017, 25(3): 278–287
133. Jomekian A, Behbahani R M, Mohammadi T, Kargari A. CO_2/CH_4 separation by high performance co-casted ZIF-8/Pebax 1657/PES mixed matrix membrane. Journal of Natural Gas Science and Engineering, 2016, 31: 562–574
134. Kim S J, Park A, Nam S E, Park Y I, Lee P S. Practical designs of membrane contactors and their performances in CO_2/CH_4 separation. Chemical Engineering Science, 2016, 155: 239–247
135. Liao J, Wang Z, Wang M, Gao C, Zhao S, Wang J, Wang S. Adjusting carrier microenvironment in CO_2 separation fixed carrier membrane. Journal of Membrane Science, 2016, 511: 9–19
136. Otani A, Zhang Y, Matsuki T, Kamio E, Matsuyama H, Maginn E J. Molecular design of high CO_2 reactivity and low viscosity ionic liquids for CO_2 separative facilitated transport membranes. Industrial & Engineering Chemistry Research, 2016, 55(10): 2821–2830
137. Rafiq S, Deng L, Hägg M B. Role of facilitated transport membranes and composite membranes for efficient CO_2 capture: a review. ChemBioEng Reviews, 2016, 3(2): 68–85
138. Razavi S M R, Shirazian S, Nazemian M. Numerical simulation of CO_2 separation from gas mixtures in membrane modules: effect of chemical absorbent. Arabian Journal of Chemistry, 2016, 9(1): 62–71
139. Woo K T, Dong G, Lee J, Kim J S, Do Y S, Lee W H, Lee H S, Lee Y M. Ternary mixed-gas separation for flue gas CO_2 capture using high performance thermally rearranged (TR) hollow fiber membranes. Journal of Membrane Science, 2016, 510: 472–480
140. Yan Y, Zhang Z, Zhang L, Wang J, Li J, Ju S. Modeling of CO_2 separation from flue gas by methyldiethanolamine and 2-(1-piperazinyl)-ethylamine in membrane contactors: effect of gas and liquid parameters. Journal of Energy Engineering, 2014, 141(4): 04014034
141. Zaidiza D A, Belaissaoui B, Rode S, Neveux T, Makhloufi C, Castel C, Roizard D, Favre E. Adiabatic modelling of CO_2 capture by amine solvents using membrane contactors. Journal of Membrane Science, 2015, 493: 106–119
142. Zaidiza D A, Wilson S G, Belaissaoui B, Rode S, Castel C, Roizard D, Favre E. Rigorous modelling of adiabatic multicomponent CO_2 post-combustion capture using hollow fibre membrane contactors. Chemical Engineering Science, 2016, 145: 45–58
143. Zhang L, Li J, Zhou L, Liu R, Wang X, Yang L. Fouling of impurities in desulfurized flue gas on hollow fiber membrane absorption for CO_2 capture. Industrial & Engineering Chemistry Research, 2016, 55(29): 8002–8010
144. Zhang L, Qu R, Sha Y, Wang X, Yang L. Membrane gas absorption for CO_2 capture from flue gas containing fine particles and gaseous contaminants. International Journal of Greenhouse Gas Control, 2015, 33: 10–17
145. Zhang L, Wang X, Yu R, Li J, Hu B, Yang L. Hollow fiber membrane separation process in the presence of gaseous and particle impurities for post-combustion CO_2 capture. International Journal of Green Energy, 2017, 14(1): 15–23
146. Kang G, Chan Z P, Saleh S B M, Cao Y. Removal of high concentration CO_2 from natural gas using high pressure membrane contactors. International Journal of Greenhouse Gas Control, 2017, 60: 1–9
147. Kim S H, Kim J K, Yeo J G, Yeo Y K. Comparative feasibility study of CO_2 capture in hollowfiber membrane processes based on process models and heat exchanger analysis. Chemical Engineering Research & Design, 2017, 117: 659–669
148. Lee S, Binns M, Lee J H, Moon J H, Yeo J G, Yeo Y K, Lee Y M, Kim J K. Membrane separation process for CO_2 capture from mixed gases using TR and XTR hollow fiber membranes: process modeling and experiments. Journal of Membrane Science, 2017, 541: 224–234
149. Li H, Ding X, Zhang Y, Liu J. Porous graphene nanosheets functionalized thin film nanocomposite membrane prepared by interfacial polymerization for CO_2/N_2 separation. Journal of Membrane Science, 2017, 543: 58–68
150. Liu B, Zhou R, Bu N, Wang Q, Zhong S, Wang B, Hidetoshi K. Room-temperature ionic liquids modified zeolite SSZ-13 membranes for CO_2/CH_4 separation. Journal of Membrane Science, 2017, 524: 12–19
151. Mirfendereski M, Mohammadi T. Investigation of H_2S and CO_2 removal from gas streams using hollow fiber membrane gas-liquid contactors. Chemical and Biochemical Engineering Quarterly, 2017, 31(2): 139–144
152. Rahmawati Y, Nurkhamidah S. Susianto, Listiyana N I, Putricahyani W. Application of dual membrane contactor for simultaneous CO_2 removal using continues diethanolamine (DEA). In: AIP Conference Proceedings. AIP Publishing, 2017, 100009
153. Rudaini I A, Naim R, Abdullah S, Mokhtar N M, Jaafar J. PVDF-cloisite hollow fiber membrane for CO_2 absorption via membrane

contactor. Jurnal Teknologi, 2017, 79(1-2): 17–23

154. Saidi M. Kinetic study and process model development of CO_2 absorption using hollow fiber membrane contactor with promoted hot potassium carbonate. Journal of Environmental Chemical Engineering, 2017, 5(5): 4415–4430
155. Saidi M. Mathematical modeling of CO_2 absorption into novel reactive DEAB solution in hollow fiber membrane contactors; kinetic and mass transfer investigation. Journal of Membrane Science, 2017, 524: 186–196
156. Usman M, Dai Z, Hillestad M, Deng L. Mathematical modeling and validation of CO_2 mass transfer in a membrane contactor using ionic liquids for pre-combustion CO_2 capture. Chemical Engineering Research & Design, 2017, 123: 377–387
157. Wang F, Kang G, Liu D, Li M, Cao Y. Enhancing CO_2 absorption efficiency using a novel PTFE hollow fiber membrane contactor at elevated pressure. AIChE Journal. American Institute of Chemical Engineers, 2018, 64(6): 2135–2145
158. Zhou F, Tien H N, Xu W L, Chen J T, Liu Q, Hicks E, Fathizadeh M, Li S, Yu M. Ultrathin graphene oxide-based hollow fiber membranes with brush-like CO_2-philic agent for highly efficient CO_2 capture. Nature Communications, 2017, 8(1): 2107
159. Hu L, Cheng J, Li Y, Liu J, Zhou J, Cen K. *In-situ* grafting to improve polarity of polyacrylonitrile hollow fiber-supported polydimethylsiloxane membranes for CO_2 separation. Journal of Colloid and Interface Science, 2018, 510: 12–19
160. Ko D. Development of a dynamic simulation model of a hollow fiber membrane module to sequester CO_2 from coalbed methane. Journal of Membrane Science, 2018, 546: 258–269
161. Pang H, Gong H, Du M, Shen Q, Chen Z. Effect of non-solvent additive concentration on CO_2 absorption performance of polyvinylidenefluoride hollow fiber membrane contactor. Separation and Purification Technology, 2018, 191: 38–47
162. Fazaeli R, Razavi S M R, Najafabadi M S, Torkaman R, Hemmati A. Computational simulation of CO_2 removal from gas mixtures by chemical absorbents in porous membranes. Royal Society of Chemistry Advances, 2015, 5(46): 36787–36797
163. Eslami S, Mousavi S M, Danesh S, Banazadeh H. Modeling and simulation of CO_2 removal from power plant flue gas by PG solution in a hollow fiber membrane contactor. Advances in Engineering Software, 2011, 42(8): 612–620
164. Marti A M, Wickramanayake W, Dahe G, Sekizkardes A, Bank T L, Hopkinson D P, Venna S R. Continuous flow processing of ZIF-8 membranes on polymeric porous hollow fiber supports for CO_2 capture. ACS Applied Materials & Interfaces, 2017, 9(7): 5678–5682
165. Vu D Q, Koros W J, Miller S J. High pressure CO_2/CH_4 separation using carbon molecular sieve hollow fiber membranes. Industrial & Engineering Chemistry Research, 2002, 41(3): 367–380
166. Wang Z, Fang M, Yu H, Ma Q, Luo Z. Modeling of CO_2 stripping in a hollow fiber membrane contactor for CO_2 capture. Energy & Fuels, 2013, 27(11): 6887–6898
167. Lee J H, Lee J, Jo H J, Seong J G, Kim J S, Lee W H, Moon J, Lee D, Oh W J, Yeo J G, Lee Y M. Wet CO_2/N_2 permeation through a crosslinked thermally rearranged poly(benzoxazole-co-imide) (XTR-PBOI) hollow fiber membrane module for CO_2 capture. Journal of Membrane Science, 2017, 539: 412–420
168. Li S, Pyrzynski T J, Klinghoffer N B, Tamale T, Zhong Y, Aderhold J L, Zhou S J, Meyer H S, Ding Y, Bikson B. Scale-up of PEEK hollow fiber membrane contactor for post-combustion CO_2 capture. Journal of Membrane Science, 2017, 527: 92–101
169. Hwang S, Chi W S, Lee S J, Im S H, Kim J H, Kim J. Hollow ZIF-8 nanoparticles improve the permeability of mixed matrix membranes for CO_2/CH_4 gas separation. Journal of Membrane Science, 2015, 480: 11–19
170. Khan A L, Klaysom C, Gahlaut A, Li X, Vankelecom I F. SPEEK and functionalized mesoporous MCM-41 mixed matrix membranes for CO_2 separations. Journal of Materials Chemistry, 2012, 22(37): 20057–20064
171. Khan A L, Klaysom C, Gahlaut A, Vankelecom I F. Polysulfone acrylate membranes containing functionalized mesoporous MCM-41 for CO_2 separation. Journal of Membrane Science, 2013, 436: 145–153
172. Li S, Fan C Q. High-flux SAPO-34 membrane for CO_2/N_2 separation. Industrial & Engineering Chemistry Research, 2010, 49 (9): 4399–4404
173. Li X, Cheng Y, Zhang H, Wang S, Jiang Z, Guo R, Wu H. Efficient CO_2 capture by functionalized graphene oxide nanosheets as fillers to fabricate multi-permselective mixed matrix membranes. ACS Applied Materials & Interfaces, 2015, 7(9): 5528–5537
174. Li X, Jiang Z, Wu Y, Zhang H, Cheng Y, Guo R, Wu H. High-performance composite membranes incorporated with carboxylic acid nanogels for CO_2 separation. Journal of Membrane Science, 2015, 495: 72–80
175. Li X, Ma L, Zhang H, Wang S, Jiang Z, Guo R, Wu H, Cao X, Yang J, Wang B. Synergistic effect of combining carbon nanotubes and graphene oxide in mixed matrix membranes for efficient CO_2 separation. Journal of Membrane Science, 2015, 479: 1–10
176. Lin R, Ge L, Liu S, Rudolph V, Zhu Z. Mixed-matrix membranes with metal-organic framework-decorated CNT fillers for efficient CO_2 separation. ACS Applied Materials & Interfaces, 2015, 7(27): 14750–14757
177. Loloei M, Omidkhah M, Moghadassi A, Amooghin A E. Preparation and characterization of Matrimid® 5218 based binary and ternary mixed matrix membranes for CO_2 separation. International Journal of Greenhouse Gas Control, 2015, 39: 225–235
178. Mahmoudi A, Asghari M, Zargar V. CO_2/CH_4 separation through a novel commercializable three-phase PEBA/PEG/NaX nanocomposite membrane. Journal of Industrial and Engineering Chemistry, 2015, 23: 238–242
179. Moghadassi A, Rajabi Z, Hosseini S, Mohammadi M. Preparation and characterization of polycarbonate-blend-raw/functionalized multi-walled carbon nano tubes mixed matrix membrane for CO_2 separation. Separation Science and Technology, 2013, 48(8): 1261–1271
180. Mohshim D F, Mukhtar H, Man Z. The effect of incorporating ionic liquid into polyethersulfone-SAPO-34 based mixed matrix membrane on CO_2 gas separation performance. Separation and Purification Technology, 2014, 135: 252–258
181. Nafisi V, Hägg M B. Development of dual layer of ZIF-8/PEBAX-2533 mixed matrix membrane for CO_2 capture. Journal of Membrane Science, 2014, 459: 244–255

182. Peydayesh M, Asarehpour S, Mohammadi T, Bakhtiari O. Preparation and characterization of SAPO-34-Matrimid® 5218 mixed matrix membranes for CO_2/CH_4 separation. Chemical Engineering Research & Design, 2013, 91(7): 1335–1342

183. Rodenas T, Van Dalen M, García Pérez E, Serra Crespo P, Zornoza B, Kapteijn F, Gascon J. Visualizing MOF mixed matrix membranes at the nanoscale: towards structure-performance relationships in CO_2/CH_4 separation over NH_2-MIL-53 (Al)@ PI. Advanced Functional Materials, 2014, 24(2): 249–256

184. Rodenas T, Van Dalen M, Serra Crespo P, Kapteijn F, Gascon J. Mixed matrix membranes based on NH_2-functionalized MIL-type MOFs: influence of structural and operational parameters on the CO_2/CH_4 separation performance. Microporous and Mesoporous Materials, 2014, 192: 35–42

185. Roh D K, Kim S J, Chi W S, Kim J K, Kim J H. Dual-functionalized mesoporous TiO_2 hollow nanospheres for improved CO_2 separation membranes. Chemical Communications, 2014, 50 (43): 5717–5720

186. Thompson J A, Vaughn J T, Brunelli N A, Koros W J, Jones C W, Nair S. Mixed-linker zeolitic imidazolate framework mixed-matrix membranes for aggressive CO_2 separation from natural gas. Microporous and Mesoporous Materials, 2014, 192: 43–51

187. Xin Q, Wu H, Jiang Z, Li Y, Wang S, Li Q, Li X, Lu X, Cao X, Yang J. SPEEK/amine-functionalized TiO_2 submicrospheres mixed matrix membranes for CO_2 separation. Journal of Membrane Science, 2014, 467: 23–35

188. Xing R, Ho W W. Crosslinked polyvinylalcohol-polysiloxane/fumed silica mixed matrix membranes containing amines for CO_2/H_2 separation. Journal of Membrane Science, 2011, 367(1-2): 91–102

189. Yilmaz G, Keskin S. Predicting the performance of zeolite imidazolate framework/polymer mixed matrix membranes for CO_2, CH_4 and H_2 separations using molecular simulations. Industrial & Engineering Chemistry Research, 2012, 51(43): 14218–14228

190. Zhang L, Hu Z, Jiang J. Metal-organic framework/polymer mixed-matrix membranes for H_2/CO_2 separation: a fully atomistic simulation study. Journal of Physical Chemistry C, 2012, 116 (36): 19268–19277

191. Zhao D, Ren J, Li H, Hua K, Deng M. Poly(amide-6-*b*-ethylene oxide)/SAPO-34 mixed matrix membrane for CO_2 separation. Journal of Energy Chemistry, 2014, 23(2): 227–234

192. Zhao H Y, Cao Y M, Ding X L, Zhou M Q, Liu J H, Yuan Q. Poly (ethylene oxide) induced cross-linking modification of matrimid membranes for selective separation of CO_2. Journal of Membrane Science, 2008, 320(1-2): 179–184

193. Nasir R, Mukhtar H, Man Z, Shaharun M S, Bakar M A. Development and performance prediction of polyethersulfone-carbon molecular sieve mixed matrix membrane for CO_2/CH_4 separation. Chemical Engineering Transactions, 2015, 45: 1417–1422

194. Rabiee H, Alsadat S M, Soltanieh M, Mousavi S A, Ghadimi A. Gas permeation and sorption properties of poly(amide-12-*b*-ethyleneoxide)(Pebax1074)/SAPO-34 mixed matrix membrane for CO_2/CH_4 and CO_2/N_2 separation. Journal of Industrial and Engineering Chemistry, 2015, 27: 223–239

195. Rezaei M, Ismail A F, Bakeri G, Hashemifard S, Matsuura T. Effect of general montmorillonite and cloisite 15A on structural parameters and performance of mixed matrix membranes contactor for CO_2 absorption. Chemical Engineering Journal, 2015, 260: 875–885

196. Seoane B, Coronas J, Gascon I, Benavides M E, Karvan O, Caro J, Kapteijn F, Gascon J. Metal-organic framework based mixed matrix membranes: a solution for highly efficient CO_2 capture? Chemical Society Reviews, 2015, 44(8): 2421–2454

197. Sorribas S, Comesaña Gándara B, Lozano A E, Zornoza B, Téllez C, Coronas J. Insight into ETS-10 synthesis for the preparation of mixed matrix membranes for CO_2/CH_4 gas separation. Royal Society of Chemistry Advances, 2015, 5(124): 102392–102398

198. Alavi S A, Kargari A, Sanaeepur H, Karimi M. Preparation and characterization of PDMS/zeolite 4A/PAN mixed matrix thin film composite membrane for CO_2/N_2 and CO_2/CH_4 separations. Research on Chemical Intermediates, 2017, 43(5): 2959–2984

199. Amooghin A E, Omidkhah M, Sanaeepur H, Kargari A. Preparation and characterization of Ag^+ ion-exchanged zeolite-Matrimid® 5218 mixed matrix membrane for CO_2/CH_4 separation. Journal of Energy Chemistry, 2016, 25(3): 450–462

200. Dong X, Liu Q, Huang A. Highly permselective MIL-68 (Al)/matrimid mixed matrix membranes for CO_2/CH_4 separation. Journal of Applied Polymer Science, 2016, 133(22): 43485

201. Hosseinzadeh Beiragh H, Omidkhah M, Abedini R, Khosravi T, Pakseresht S. Synthesis and characterization of poly(ether-block-amide) mixed matrix membranes incorporated by nanoporous ZSM-5 particles for CO_2/CH_4 separation. Asia-Pacific Journal of Chemical Engineering, 2016, 11(4): 522–532

202. Kang Z, Peng Y, Qian Y, Yuan D, Addicoat M A, Heine T, Hu Z, Tee L, Guo Z, Zhao D. Mixed matrix membranes (MMMs) comprising exfoliated 2D covalent organic frameworks (COFs) for efficient CO_2 separation. Chemistry of Materials, 2016, 28(5): 1277–1285

203. Kertik A, Khan A L, Vankelecom I F. Mixed matrix membranes prepared from non-dried MOFs for CO_2/CH_4 separations. Royal Society of Chemistry Advances, 2016, 6(115): 114505–114512

204. Kim J, Choi J, Soo Kang Y, Won J. Matrix effect of mixed-matrix membrane containing CO_2-selective MOFs. Journal of Applied Polymer Science, 2016, 133(1): n/a

205. Kim J, Fu Q, Scofield J M, Kentish S E, Qiao G G. Ultra-thin film composite mixed matrix membranes incorporating iron (III)-dopamine nanoparticles for CO_2 separation. Nanoscale, 2016, 8 (15): 8312–8323

206. Kim J, Fu Q, Xie K, Scofield J M, Kentish S E, Qiao G G. CO_2 separation using surface-functionalized SiO_2 nanoparticles incorporated ultra-thin film composite mixed matrix membranes for post-combustion carbon capture. Journal of Membrane Science, 2016, 515: 54–62

207. Kim S J, Chi W S, Jeon H, Kim J H, Patel R. Spontaneously self-assembled dual-layer mixed matrix membranes containing mass-produced mesoporous TiO_2 for CO_2 capture. Journal of Membrane Science, 2016, 508: 62–72

208. Koolivand H, Sharif A, Chehrazi E, Kashani M R, Paran S M R. Mixed-matrix membranes comprising graphene-oxide nanosheets for CO_2/CH_4 separation: a comparison between glassy and rubbery

polymer matrices. Polymer Science, Series A, 2016, 58(5): 801–809

209. Xin Q, Li Z, Li C, Wang S, Jiang Z, Wu H, Zhang Y, Yang J, Cao X. Enhancing the CO_2 separation performance of composite membranes by the incorporation of amino acid-functionalized graphene oxide. Journal of Materials Chemistry. A, Materials for Energy and Sustainability, 2015, 3(12): 6629–6641
210. Brunetti A, Cersosimo M, Kim J S, Dong G, Fontananova E, Lee Y M, Drioli E, Barbieri G. Thermally rearranged mixed matrix membranes for CO_2 separation: an aging study. International Journal of Greenhouse Gas Control, 2017, 61: 16–26
211. Cheng Y, Wang X, Jia C, Wang Y, Zhai L, Wang Q, Zhao D. Ultrathin mixed matrix membranes containing two-dimensional metal-organic framework nanosheets for efficient CO_2/CH_4 separation. Journal of Membrane Science, 2017, 539: 213–223
212. Galaleldin S, Mannan H, Mukhtar H. Development and characterization of polyethersulfone/TiO_2 mixed matrix membranes for CO_2/CH_4 separation. In: AIP Conference Proceedings. Melville, NY: AIP Publishing, 2017, 130017
213. Jusoh N, Yeong Y F, Lau K K, Shariff A M. Transport properties of mixed matrix membranes encompassing zeolitic imidazolate framework 8 (ZIF-8) nanofiller and 6FDA-durene polymer: optimization of process variables for the separation of CO_2 from CH_4. Journal of Cleaner Production, 2017, 149: 80–95
214. Khalilinejad I, Kargari A, Sanaeepur H. Preparation and characterization of (Pebax 1657 + silica nanoparticle)/PVC mixed matrix composite membrane for CO_2/N_2 separation. Chemical Papers, 2017, 71(4): 803–818
215. Khosravi T, Omidkhah M, Kaliaguine S, Rodrigue D. Amine-functionalized CuBTC/poly (ether-*b*-amide-6)(Pebax® MH 1657) mixed matrix membranes for CO_2/CH_4 separation. Canadian Journal of Chemical Engineering, 2017, 95(10): 2024–2033
216. Krea M, Roizard D, Favre E. Copoly (alkyl ether imide) membranes as promising candidates for CO_2 capture applications. Separation and Purification Technology, 2016, 161: 53–60
217. Liu Y, Li X, Qin Y, Guo R, Zhang J. Pebax-polydopamine microsphere mixed-matrix membranes for efficient CO_2 separation. Journal of Applied Polymer Science, 2017, 134(10): 44564
218. Martin Gil V, López A, Hrabanek P, Mallada R, Vankelecom I, Fila V. Study of different titanosilicate (TS-1 and ETS-10) as fillers for mixed matrix membranes for CO_2/CH_4 gas separation applications. Journal of Membrane Science, 2017, 523: 24–35
219. Nematollahi M H, Dehaghani A H S, Abedini R. CO_2/CH_4 separation with poly(4-methyl-1-pentyne) (TPX) based mixed matrix membrane filled with Al_2O_3 nanoparticles. Korean Journal of Chemical Engineering, 2016, 33(2): 657–665
220. Nematollahi M H, Dehaghani A H S, Pirouzfar V, Akhondi E. Mixed matrix membranes comprising PMP polymer with dispersed alumina nanoparticle fillers to separate CO_2/N_2. Macromolecular Research, 2016, 24(9): 782–792
221. Nguyen T H, Gong H, Lee S S, Bae T H. Amine-appended hierarchical Ca—a zeolite for enhancing CO_2/CH_4 selectivity of mixed-matrix membranes. ChemPhysChem, 2016, 17(20): 3165–3169
222. Nordin N A H M, Ismail A F, Misdan N, Nazri N A M. Modified ZIF-8 mixed matrix membrane for CO_2/CH_4 separation. in AIP Conference Proceedings. Melville, NY: AIP Publishing, 2017, 020091
223. Park C H, Lee J H, Jang E, Lee K B, Kim J H. $MgCO_3$-crystal-containing mixed matrix membranes with enhanced CO_2 permselectivity. Chemical Engineering Journal, 2017, 307: 503–512
224. Quan S, Li S W, Xiao Y C, Shao L. CO_2-selective mixed matrix membranes (MMMs) containing graphene oxide (GO) for enhancing sustainable CO_2 capture. International Journal of Greenhouse Gas Control, 2017, 56: 22–29
225. Rahmani M, Kazemi A, Talebnia F. Matrimid mixed matrix membranes for enhanced CO_2/CH_4 separation. Journal of Polymer Engineering, 2016, 36(5): 499–511
226. Sanaeepur H, Kargari A, Nasernejad B, Amooghin A E, Omidkhah M. A novel Co^{2+} exchanged zeolite Y/cellulose acetate mixed matrix membrane for CO_2/N_2 separation. Journal of the Taiwan Institute of Chemical Engineers, 2016, 60: 403–413
227. Sánchez Laínez J, Zornoza B, Friebe S, Caro J, Cao S, Sabetghadam A, Seoane B, Gascon J, Kapteijn F, Le Guillouzer C, Clet G, Daturi M, Téllez C, Coronas J. Influence of ZIF-8 particle size in the performance of polybenzimidazole mixed matrix membranes for pre-combustion CO_2 capture and its validation through interlaboratory test. Journal of Membrane Science, 2016, 515: 45–53
228. Sánchez Laínez J, Zornoza B, Téllez C, Coronas J. On the chemical filler-polymer interaction of nano-and micro-sized ZIF-11 in PBI mixed matrix membranes and their application for H_2/CO_2 separation. Journal of Materials Chemistry. A, Materials for Energy and Sustainability, 2016, 4(37): 14334–14341
229. Shamsabadi A A, Seidi F, Salehi E, Nozari M, Rahimpour A, Soroush M. Efficient CO_2-removal using novel mixed-matrix membranes with modified TiO_2 nanoparticles. Journal of Materials Chemistry. A, Materials for Energy and Sustainability, 2017, 5(8): 4011–4025
230. Shen J, Liu G, Huang K, Li Q, Guan K, Li Y, Jin W. UiO-66-polyether block amide mixed matrix membranes for CO_2 separation. Journal of Membrane Science, 2016, 513: 155–165
231. Shen J, Zhang M, Liu G, Guan K, Jin W. Size effects of graphene oxide on mixed matrix membranes for CO_2 separation. AIChE Journal. American Institute of Chemical Engineers, 2016, 62(8): 2843–2852
232. Shen Y, Wang H, Zhang X, Zhang Y. MoS_2 nanosheets functionalized composite mixed matrix membrane for enhanced CO_2 capture via surface drop-coating method. ACS Applied Materials & Interfaces, 2016, 8(35): 23371–23378
233. Shin H, Chi W S, Bae S, Kim J H, Kim J. High-performance thin PVC-POEM/ZIF-8 mixed matrix membranes on alumina supports for CO_2/CH_4 separation. Journal of Industrial and Engineering Chemistry, 2017, 53: 127–133
234. Sumer Z, Keskin S. Computational screening of MOF-based mixed matrix membranes for CO_2/N_2 Separations. Journal of Nanomaterials, 2016, 2016: 1–12
235. Tseng H H, Chuang H W, Zhuang G L, Lai W H, Wey M Y. Structure-controlled mesoporous SBA-15-derived mixed matrix membranes for H_2 purification and CO_2 capture. International Journal of Hydrogen Energy, 2017, 42(16): 11379–11391
236. Waheed N, Mushtaq A, Tabassum S, Gilani M A, Ilyas A, Ashraf

F, Jamal Y, Bilad M R, Khan A U, Khan A L. Mixed matrix membranes based on polysulfone and rice husk extracted silica for CO_2 separation. Separation and Purification Technology, 2016, 170: 122–129

237. Wang Z, Ren H, Zhang S, Zhang F, Jin J. Polymers of intrinsic microporosity/metal-organic framework hybrid membranes with improved interfacial interaction for high-performance CO_2 separation. Journal of Materials Chemistry. A, Materials for Energy and Sustainability, 2017, 5(22): 10968–10977
238. Xiang L, Pan Y, Zeng G, Jiang J, Chen J, Wang C. Preparation of poly(ether-block-amide)/attapulgite mixed matrix membranes for CO_2/N_2 separation. Journal of Membrane Science, 2016, 500: 66–75
239. Xin Q, Zhang Y, Huo T, Ye H, Ding X, Lin L, Zhang Y, Wu H, Jiang Z. Mixed matrix membranes fabricated by a facile in situ biomimetic mineralization approach for efficient CO_2 separation. Journal of Membrane Science, 2016, 508: 84–93
240. Xin Q, Zhang Y, Shi Y, Ye H, Lin L, Ding X, Zhang Y, Wu H, Jiang Z. Tuning the performance of CO_2 separation membranes by incorporating multifunctional modified silica microspheres into polymer matrix. Journal of Membrane Science, 2016, 514: 73–85
241. Zhang H, Guo R, Hou J, Wei Z, Li X. Mixed-matrix membranes containing carbon nanotubes composite with hydrogel for efficient CO_2 separation. ACS Applied Materials & Interfaces, 2016, 8(42): 29044–29051
242. Zhao D, Ren J, Wang Y, Qiu Y, Li H, Hua K, Li X, Ji J, Deng M. High CO_2 separation performance of Pebax®/CNTs/GTA mixed matrix membranes. Journal of Membrane Science, 2017, 521: 104–113
243. Li Y, Chung T S. Molecular-level mixed matrix membranes comprising Pebax® and POSS for hydrogen purification via preferential CO_2 removal. International Journal of Hydrogen Energy, 2010, 35(19): 10560–10568
244. Ebrahimi S, Mollaiy Berneti S, Asadi H, Peydayesh M, Akhlaghian F, Mohammadi T. PVA/PES-amine-functional graphene oxide mixed matrix membranes for CO_2/CH_4 separation: experimental and modeling. Chemical Engineering Research & Design, 2016, 109: 647–656
245. Xiong L, Gu S, Jensen K O, Yan Y S. Facilitated transport in hydroxide-exchange membranes for post-combustion CO_2 separation. ChemSusChem, 2014, 7(1): 114–116
246. Zhou T, Luo L, Hu S, Wang S, Zhang R, Wu H, Jiang Z, Wang B, Yang J. Janus composite nanoparticle-incorporated mixed matrix membranes for CO_2 separation. Journal of Membrane Science, 2015, 489: 1–10
247. Cui Z, DeMontigny D. Part 7: a review of CO_2 capture using hollow fiber membrane contactors. Carbon Management, 2013, 4 (1): 69–89
248. Ahmad M Z, Navarro M, Lhotka M, Zornoza B, Téllez C, Fila V, Coronas J. Enhancement of CO_2/CH_4 separation performances of 6FDA-based co-polyimides mixed matrix membranes embedded with UiO-66 nanoparticles. Separation and Purification Technology, 2018, 192: 465–474
249. Cao L, Tao K, Huang A, Kong C, Chen L. A highly permeable mixed matrix membrane containing CAU-1-NH_2 for H_2 and CO_2 separation. Chemical Communications, 2013, 49(76): 851–8515
250. Dong L, Sun Y, Zhang C, Han D, Bai Y, Chen M. Efficient CO_2 capture by metallo-supramolecular polymers as fillers to fabricate a polymeric blend membrane. Royal Society of Chemistry Advances, 2015, 5(83): 67658–67661
251. Erucar I, Keskin S. Screening metal-organic framework-based mixed-matrix membranes for CO_2/CH_4 separations. Industrial & Engineering Chemistry Research, 2011, 50(22): 12606–12616
252. Huang A, Chen Y, Liu Q, Wang N, Jiang J, Caro J. Synthesis of highly hydrophobic and permselective metal-organic framework Zn (BDC)(TED) 0.5 membranes for H_2/CO_2 separation. Journal of Membrane Science, 2014, 454: 126–132
253. Li W, Zheng X, Dong Z, Li C, Wang W, Yan Y, Zhang J. Molecular dynamics simulations of CO_2/N_2 separation through two-dimensional graphene oxide membranes. Journal of Physical Chemistry C, 2016, 120(45): 2606–26066
254. Monteiro B, Nabais A R, Almeida Paz F A, Cabrita L, Branco L C, Marrucho I M, Neves L A, Pereira C C. Membranes with a low loading of metal–organic framework-supported ionic liquids for CO_2/N_2 separation in CO_2 capture. Energy Technology (Weinheim), 2017, 5(12): 2158–2162
255. Morris C G, Jacques N M, Godfrey H G, Mitra T, Fritsch D, Lu Z, Murray C A, Potter J, Cobb T M, Yuan F, Tang C C, Yang S, Schröder M. Stepwise observation and quantification and mixed matrix membrane separation of CO_2 within a hydroxy-decorated porous host. Chemical Science (Cambridge), 2017, 8(4): 3239–3248
256. Nordin N A H M, Racha S M, Matsuura T, Misdan N, Sani N A A, Ismail A F, Mustafa A. Facile modification of ZIF-8 mixed matrix membrane for CO_2/CH_4 separation: synthesis and preparation. RSC Advances, 2015, 5(54): 43110–43120
257. Rui Z, James J B, Kasik A, Lin Y. Metal-organic framework membrane process for high purity CO_2 production. AIChE Journal. American Institute of Chemical Engineers, 2016, 62(11): 3836–3841
258. Watanabe T, Keskin S, Nair S, Sholl D S. Computational identification of a metal organic framework for high selectivity membrane-based CO_2/CH_4 separations: Cu (hfipbb)(H_2 hfipbb) 0.5. Physical Chemistry Chemical Physics, 2009, 11(48): 11389–11394
259. Wu D, Maurin G, Yang Q, Serre C, Jobic H, Zhong C. Computational exploration of a Zr-carboxylate based metal-organic framework as a membrane material for CO_2 capture. Journal of Materials Chemistry. A, Materials for Energy and Sustainability, 2014, 2(6): 1657–1661
260. Yin H, Wang J, Xie Z, Yang J, Bai J, Lu J, Zhang Y, Yin D, Lin J Y. A highly permeable and selective amino-functionalized MOF CAU-1 membrane for CO_2-N_2 separation. Chemical Communications, 2014, 50(28): 3699–3701
261. Kelman S, Lin H, Sanders E S, Freeman B D. CO_2/C_2H_6 separation using solubility selective membranes. Journal of Membrane Science, 2007, 305(1-2): 57–68
262. Low B T, Xiao Y, Chung T S, Liu Y. Simultaneous occurrence of chemical grafting, cross-linking, and etching on the surface of polyimide membranes and their impact on H_2/CO_2 separation. Macromolecules, 2008, 41(4): 1297–1309
263. Modigell M, Schumacher M, Teplyakov V V, Zenkevich V B. A

membrane contactor for efficient CO_2 removal in biohydrogen production. Desalination, 2008, 224(1-3): 186–190

264. Yave W, Car A, Wind J, Peinemann K V. Nanometric thin film membranes manufactured on square meter scale: ultra-thin films for CO_2 capture. Nanotechnology, 2010, 21(39): 395301
265. Zhang Y, Wang Z, Wang S. Synthesis and characteristics of novel fixed carrier membrane for CO_2 separation. Chemistry Letters, 2002, 31(4): 430–431
266. Khan A L, Li X, Vankelecom I F. Mixed-gas CO_2/CH_4 and CO_2/N_2 separation with sulfonated PEEK membranes. Journal of Membrane Science, 2011, 372(1-2): 87–96
267. Kim T J, Uddin M W, Sandru M, Hägg M B. The effect of contaminants on the composite membranes for CO_2 separation and challenges in up-scaling of the membranes. Energy Procedia, 2011, 4: 737–744
268. Zhang L, Xiao Y, Chung T S, Jiang J. Mechanistic understanding of CO_2-induced plasticization of a polyimide membrane: a combination of experiment and simulation study. Polymer, 2010, 51(19): 4439–4447
269. Chang J, Kang S W. CO_2 separation through poly(vinylidene fluoride-co-hexafluoropropylene) membrane by selective ion channel formed by tetrafluoroboric acid. Chemical Engineering Journal, 2016, 306: 1189–1192
270. Fu X, Li X, Guo R, Zhang J, Cao X. Block copolymer membranes based on polyetheramine and methyl-containing polyisophthalamides designed for efficient CO_2 separation. High Performance Polymers, 2018, 30(9): 1064–1074
271. Ghadiri M, Marjani A, Shirazian S. Mathematical modeling and simulation of CO_2 stripping from monoethanolamine solution using nano porous membrane contactors. International Journal of Greenhouse Gas Control, 2013, 13: 1–8
272. Kanehashi S, Kishida M, Kidesaki T, Shindo R, Sato S, Miyakoshi T, Nagai K. CO_2 separation properties of a glassy aromatic polyimide composite membranes containing high-content 1-butyl-3-methylimidazolium bis(trifluoromethylsulfonyl) imide ionic liquid. Journal of Membrane Science, 2013, 430: 211–222
273. Kwisnek L, Heinz S, Wiggins J S, Nazarenko S. Multifunctional thiols as additives in UV-cured PEG-diacrylate membranes for CO_2 separation. Journal of Membrane Science, 2011, 369(1-2): 429–436
274. Lee J H, Jung J P, Jang E, Lee K B, Hwang Y J, Min B K, Kim J H. PEDOT-PSS embedded comb copolymer membranes with improved CO_2 capture. Journal of Membrane Science, 2016, 518: 21–30
275. Li Y, Xin Q, Wang S, Tian Z, Wu H, Liu Y, Jiang Z. Trapping bound water within a polymer electrolyte membrane of calcium phosphotungstate for efficient CO_2 capture. Chemical Communications, 2015, 51(10): 1901–1904
276. Lindqvist K, Roussanaly S, Anantharaman R. Multi-stage membrane processes for CO_2 capture from cement industry. Energy Procedia, 2014, 63: 6476–6483
277. Ma Z, Qiao Z, Wang Z, Cao X, He Y, Wang J, Wang S. CO_2 separation enhancement of the membrane by modifying the polymer with a small molecule containing amine and ester groups. Royal Society of Chemistry Advances, 2014, 4(41): 21313–21317
278. Mondal A, Barooah M, Mandal B. Effect of single and blended amine carriers on CO_2 separation from CO_2/N_2 mixtures using crosslinked thin-film poly(vinyl alcohol) composite membrane. International Journal of Greenhouse Gas Control, 2015, 39: 27–28
279. Mondal A, Mandal B. Synthesis and characterization of crosslinked poly(vinyl alcohol)/poly(allylamine)/2-amino-2-hydroxymethyl-1,3-propanediol/polysulfone composite membrane for CO_2/N_2 separation. Journal of Membrane Science, 2013, 446: 383–394
280. Ricci E, Minelli M, De Angelis M G. A multiscale approach to predict the mixed gas separation performance of glassy polymeric membranes for CO_2 capture: the case of CO_2/CH_4 mixture in Matrimid®. Journal of Membrane Science, 2017, 539: 88–100
281. Liu S, Liu G, Wei W, Xiangli F, Jin W. Ceramic supported PDMS and PEGDA composite membranes for CO_2 separation. Chinese Journal of Chemical Engineering, 2013, 21(4): 348–356
282. Sandru M, Kim T J, Capala W, Huijbers M, Hägg M B. Pilot scale testing of polymeric membranes for CO_2 capture from coal fired power plants. Energy Procedia, 2013, 37: 6473–6480
283. Tseng H H, Itta A K, Weng T H, Li Y L. SBA-15/CMS composite membrane for H_2 purification and CO_2 capture: effect of pore size, pore volume, and loading weight on separation performance. Microporous and Mesoporous Materials, 2013, 180: 270–279
284. Wang S, Li X, Wu H, Tian Z, Xin Q, He G, Peng D, Chen S, Yin Y, Jiang Z, Guiver M D. Advances in high permeability polymer-based membrane materials for CO_2 separations. Energy & Environmental Science, 2016, 9(6): 1863–1890
285. Zainab G, Iqbal N, Babar A A, Huang C, Wang X, Yu J, Ding B. Free-standing, spider-web-like polyamide/carbon nanotube composite nanofibrous membrane impregnated with polyethyleneimine for CO_2 capture. Composites Communications, 2017, 6: 41–47
286. Kim K J, Park S H, So W W, Ahn D J, Moon S J. CO_2 separation performances of composite membranes of 6FDA-based polyimides with a polar group. Journal of Membrane Science, 2003, 211(1): 41–49
287. Okabe K, Nakamura M, Mano H, Teramoto M, Yamada K. Separation and recovery of CO_2 by membrane/absorption hybrid method. In: Proceedings of the Eighth Intenational Conference on Greenhouse Gas Control Technologies. Amsterdam: Elsevier, 2006, 409–412
288. Francisco G J, Chakma A, Feng X. Membranes comprising of alkanolamines incorporated into poly(vinyl alcohol) matrix for CO_2/N_2 separation. Journal of Membrane Science, 2007, 303(1-2): 54–63
289. Sridhar S, Suryamurali R, Smitha B, Aminabhavi T. Development of crosslinked poly(ether-block-amide) membrane for CO_2/CH_4 separation. Colloids and Surfaces. A, Physicochemical and Engineering Aspects, 2007, 297(1-3): 267–274
290. Kai T, Kouketsu T, Duan S, Kazama S, Yamada K. Development of commercial-sized dendrimer composite membrane modules for CO_2 removal from flue gas. Separation and Purification Technology, 2008, 63(3): 524–530
291. Kosuri M R, Koros W J. Defect-free asymmetric hollow fiber membranes from Torlon®, a polyamide-imide polymer, for high-pressure CO_2 separations. Journal of Membrane Science, 2008, 320(1-2): 65–72
292. Kosuri M R, Koros W J. Asymmetric hollow fiber membranes for

separation of CO_2 from hydrocarbons and fluorocarbons at high-pressure conditions relevant to C_2F_4 polymerization. Industrial & Engineering Chemistry Research, 2009, 48(23): 10577–10583

293. Safari M, Ghanizadeh A, Montazer Rahmati M M. Optimization of membrane-based CO_2-removal from natural gas using simple models considering both pressure and temperature effects. International Journal of Greenhouse Gas Control, 2009, 3(1): 3–10
294. Xing R, Ho W W. Synthesis and characterization of crosslinked polyvinylalcohol/polyethyleneglycol blend membranes for CO_2/CH_4 separation. Journal of the Taiwan Institute of Chemical Engineers, 2009, 40(6): 654–662
295. Yave W, Car A, Funari S S, Nunes S P, Peinemann K V. CO_2-philic polymer membrane with extremely high separation performance. Macromolecules, 2009, 43(1): 326–333
296. Cong H, Yu B. Aminosilane cross-linked PEG/PEPEG/PPEPG membranes for CO_2/N_2 and CO_2/H_2 separation. Industrial & Engineering Chemistry Research, 2010, 49(19): 9363–9369
297. Park H B, Han S H, Jung C H, Lee Y M, Hill A J. Thermally rearranged (TR) polymer membranes for CO_2 separation. Journal of Membrane Science, 2010, 359(1-2): 11–24
298. Reijerkerk S R, Knoef M H, Nijmeijer K, Wessling M. Poly (ethylene glycol) and poly(dimethyl siloxane): combining their advantages into efficient CO_2 gas separation membranes. Journal of Membrane Science, 2010, 352(1-2): 126–135
299. Yave W, Szymczyk A, Yave N, Roslaniec Z. Design, synthesis, characterization and optimization of PTT-*b*-PEO copolymers: a new membrane material for CO_2 separation. Journal of Membrane Science, 2010, 362(1-2): 407–416
300. Yu X, Wang Z, Wei Z, Yuan S, Zhao J, Wang J, Wang S. Novel tertiary amino containing thin film composite membranes prepared by interfacial polymerization for CO_2 capture. Journal of Membrane Science, 2010, 362(1-2): 265–278
301. Khan A L, Li X, Vankelecom I F. SPEEK/Matrimid blend membranes for CO_2 separation. Journal of Membrane Science, 2011, 380(1-2): 55–62
302. Peters L, Hussain A, Follmann M, Melin T, Hägg M B. CO_2 removal from natural gas by employing amine absorption and membrane technology—a technical and economical analysis. Chemical Engineering Journal, 2011, 172(2-3): 952–960
303. Reijerkerk S R, Jordana R, Nijmeijer K, Wessling M. Highly hydrophilic, rubbery membranes for CO_2 capture and dehydration of flue gas. International Journal of Greenhouse Gas Control, 2011, 5(1): 26–36
304. Reijerkerk S R, Wessling M, Nijmeijer K. Pushing the limits of block copolymer membranes for CO_2 separation. Journal of Membrane Science, 2011, 378(1-2): 479–484
305. Sanaeepur H, Amooghin A E, Moghadassi A, Kargari A. Preparation and characterization of acrylonitrile-butadiene-styrene/poly(vinyl acetate) membrane for CO_2 removal. Separation and Purification Technology, 2011, 80(3): 499–508
306. Spadaccini C M, Mukerjee E V, Letts S A, Maiti A, O'Brien K C. Ultrathin polymer membranes for high throughput CO_2 capture. Energy Procedia, 2011, 4: 731–736
307. Xia J, Liu S, Chung T S. Effect of end groups and grafting on the CO_2 separation performance of poly(ethylene glycol) based membranes. Macromolecules, 2011, 44(19): 7727–7736
308. Ahmad F, Lau K K, Shariff A M, Murshid G. Process simulation and optimal design of membrane separation system for CO_2 capture from natural gas. Computers & Chemical Engineering, 2012, 36: 119–128
309. Bengtson G, Neumann S, Filiz V. Optimization of PIM-membranes for separation of CO_2. Procedia Engineering, 2012, 44: 796–798
310. Han S H, Kwon H J, Kim K Y, Seong J G, Park C H, Kim S, Doherty C M, Thornton A W, Hill A J, Lozano A E, Berchtold K A, Lee Y M. Tuning microcavities in thermally rearranged polymer membranes for CO_2 capture. Physical Chemistry Chemical Physics, 2012, 14(13): 4365–4373
311. Kim S, Lee Y M. Thermally rearranged (TR) polymer membranes with nanoengineered cavities tuned for CO_2 separation, in nanotechnology for sustainable development. New York: Springer, 2012, 265–275
312. Uddin M W, Hägg M B. Natural gas sweetening—the effect on CO_2-CH_4 separation after exposing a facilitated transport membrane to hydrogen sulfide and higher hydrocarbons. Journal of Membrane Science, 2012, 423: 143–149
313. Hu T, Dong G, Li H, Chen V. Improved CO_2 separation performance with additives of PEG and PEG-PDMS copolymer in poly(2,6-dimethyl-1,4-phenylene oxide) membranes. Journal of Membrane Science, 2013, 432: 13–24
314. Kai T, Taniguchi I, Duan S, Chowdhury F A, Saito T, Yamazaki K, Ikeda K, Ohara T, Asano S, Kazama S. Molecular gate membrane: poly(amidoamine) dendrimer/polymer hybrid membrane modules for CO_2 capture. Energy Procedia, 2013, 37: 961–968
315. Kim T J, Vrålstad H, Sandru M, Hägg M B. Separation performance of PVAm composite membrane for CO_2 capture at various pH levels. Journal of Membrane Science, 2013, 428: 218–224
316. Li S, Wang Z, Zhang C, Wang M, Yuan F, Wang J, Wang S. Interfacially polymerized thin film composite membranes containing ethylene oxide groups for CO_2 separation. Journal of Membrane Science, 2013, 436: 121–131
317. Nasir R, Mukhtar H, Man Z, Mohshim D F. Synthesis, characterization and performance study of newly developed amine polymeric membrane (APM) for carbon dioxide (CO_2) removal. World Academy of Science, Engineering and Technology, International Journal of Chemical, Molecular, Nuclear. Materials and Metallurgical Engineering, 2013, 7(9): 670–673
318. Rahman M M, Filiz V, Shishatskiy S, Abetz C, Neumann S, Bolmer S, Khan M M, Abetz V. PEBAX® with PEG functionalized POSS as nanocomposite membranes for CO_2 separation. Journal of Membrane Science, 2013, 437: 286–297
319. Wang M, Wang Z, Li S, Zhang C, Wang J, Wang S. A high performance antioxidative and acid resistant membrane prepared by interfacial polymerization for CO_2 separation from flue gas. Energy & Environmental Science, 2013, 6(2): 539–551
320. Ahmadpour E, Shamsabadi A A, Behbahani R M, Aghajani M, Kargari A. Study of CO_2 separation with PVC/Pebax composite membrane. Journal of Natural Gas Science and Engineering, 2014, 21: 518–523
321. Constantinou A, Barrass S, Gavriilidis A. CO_2 absorption in polytetrafluoroethylene membrane microstructured contactor using

aqueous solutions of amines. Industrial & Engineering Chemistry Research, 2014, 53(22): 9236–9242

322. Hussain A, Nasir H, Ahsan M. Process design analyses of CO_2 capture from natural gas by polymer membrane. Journal of the Chemical Society of Pakistan, 2014, 36(3): 411–421

323. Lin H, He Z, Sun Z, Vu J, Ng A, Mohammed M, Kniep J, Merkel T C, Wu T, Lambrecht R C. CO_2-selective membranes for hydrogen production and CO_2 capture-Part I: Membrane development. Journal of Membrane Science, 2014, 457: 149–161

324. Mondal A, Mandal B. Novel CO_2-selective cross-linked poly(vinyl alcohol)/polyvinylpyrrolidone blend membrane containing amine carrier for CO_2-N_2 separation: synthesis, characterization, and gas permeation study. Industrial & Engineering Chemistry Research, 2014, 53(51): 19736–19746

325. Mondal A, Mandal B. CO_2 separation using thermally stable crosslinked poly(vinyl alcohol) membrane blended with polyvinylpyrrolidone/polyethyleneimine/tetraethylenepentamine. Journal of Membrane Science, 2014, 460: 126–138

326. Nabian N, Ghoreyshi A, Rahimpour A, Shakeri M. Effect of polymer concentration on the structure and performance of polysulfone flat membrane for CO_2 absorption in membrane contactor. Iranian Journal of Chemical Engineering, 2014, 11(2): 79

327. Salih A A, Yi C, Peng H, Yang B, Yin L, Wang W. Interfacially polymerized polyetheramine thin film composite membranes with PDMS inter-layer for CO_2 separation. Journal of Membrane Science, 2014, 472: 110–118

328. Wang L, Li Y, Li S, Ji P, Jiang C. Preparation of composite poly (ether block amide) membrane for CO_2 capture. Journal of Energy Chemistry, 2014, 23(6): 717–725

329. Wang S, Liu Y, Huang S, Wu H, Li Y, Tian Z, Jiang Z. Pebax-PEG-MWCNT hybrid membranes with enhanced CO_2 capture properties. Journal of Membrane Science, 2014, 460: 62–70

330. Scholes C A, Ribeiro C P, Kentish S E, Freeman B D. Thermal rearranged poly(benzoxazole)/polyimide blended membranes for CO_2 separation. Separation and Purification Technology, 2014, 124: 134–140

331. Wang Z, Fang M, Ma Q, Zhao Z, Wang T, Luo Z. Membrane stripping technology for CO_2 desorption from CO_2-rich absorbents with low energy consumption. Energy Procedia, 2014, 63: 765–772

332. Zhou J, Tran M M, Haldeman A T, Jin J, Wagener E H, Husson S M. Perfluorocyclobutyl polymer thin-film composite membranes for CO_2 separations. Journal of Membrane Science, 2014, 450: 478–486

333. Gilassi S, Rahmanian N. Mathematical modelling and numerical simulation of CO_2/CH_4 separation in a polymeric membrane. Applied Mathematical Modelling, 2015, 39(21): 6599–6611

334. Khalilinejad I, Sanaeepur H, Kargari A. Preparation of poly (ether-6-block amide)/PVC thin film composite membrane for CO_2 separation: effect of top layer thickness and operating parameters. Journal of Membrane Science and Research, 2015, 1(3): 124–129

335. Kim S J, Jeon H, Kim D J, Kim J H. High-performance polymer membranes with multi-functional amphiphilic micelles for CO_2 capture. ChemSusChem, 2015, 8(22): 3783–3792

336. Li P, Wang Z, Liu Y, Zhao S, Wang J, Wang S. A synergistic strategy via the combination of multiple functional groups into membranes towards superior CO_2 separation performances. Journal of Membrane Science, 2015, 476: 243–255

337. Li P, Wang Z, Li W, Liu Y, Wang J, Wang S. High-performance multilayer composite membranes with mussel-inspired polydopamine as a versatile molecular bridge for CO_2 separation. ACS Applied Materials & Interfaces, 2015, 7(28): 15481–15493

338. Liao J, Wang Z, Gao C, Wang M, Yan K, Xie X, Zhao S, Wang J, Wang S. A high performance PVAm-HT membrane containing high-speed facilitated transport channels for CO_2 separation. Journal of Materials Chemistry. A, Materials for Energy and Sustainability, 2015, 3(32): 16746–16761

339. Nasir R, Mukhtar H, Man Z, Shaharun M S, Bakar M Z A. Effect of fixed carbon molecular sieve (CMS) loading and various di-ethanolamine (DEA) concentrations on the performance of a mixed matrix membrane for CO_2/CH_4 separation. Royal Society of Chemistry Advances, 2015, 5(75): 60814–60822

340. Park C H, Lee J H, Jung J P, Jung B, Kim J H. A highly selective PEGBEM-g-POEM comb copolymer membrane for CO_2/N_2 separation. Journal of Membrane Science, 2015, 492: 452–460

341. Park S, Lee A S, Do Y S, Hwang S S, Lee Y M, Lee J H, Lee J S. Rational molecular design of PEOlated ladder-structured polysilsesquioxane membranes for high performance CO_2 removal. Chemical Communications, 2015, 51(83): 15308–15311

342. Scofield J M, Gurr P A, Kim J, Fu Q, Halim A, Kentish S E, Qiao G G. High-performance thin film composite membranes with well-defined poly(dimethylsiloxane)–poly(ethylene glycol) copolymer additives for CO_2 separation. Journal of Polymer Science. Part A, Polymer Chemistry, 2015, 53(12): 1500–1511

343. Taniguchi I, Kai T, Duan S, Kazama S, Jinnai H. A compatible crosslinker for enhancement of CO_2 capture of poly(amidoamine) dendrimer-containing polymeric membranes. Journal of Membrane Science, 2015, 475: 175–183

344. Adewole J K, Ahmad A L. Process modeling and optimization studies of high pressure membrane separation of CO_2 from natural gas. Korean Journal of Chemical Engineering, 2016, 33(10): 2998–3010

345. Chen Y, Ho W W. High-molecular-weight polyvinylamine/piperazine glycinate membranes for CO_2 capture from flue gas. Journal of Membrane Science, 2016, 514: 376–384

346. Karamouz F, Maghsoudi H, Yegani R. Synthesis and characterization of high permeable PEBA membranes for CO_2/CH_4 separation. Journal of Natural Gas Science and Engineering, 2016, 35: 980–985

347. Mosleh S, Mozdianfard M, Hemmati M, Khanbabaei G. Synthesis and characterization of rubbery/glassy blend membranes for CO_2/CH_4 gas separation. Journal of Polymer Research, 2016, 23(6): 120

348. Scofield J M, Gurr P A, Kim J, Fu Q, Kentish S E, Qiao G G. Development of novel fluorinated additives for high performance CO_2 separation thin-film composite membranes. Journal of Membrane Science, 2016, 499: 191–200

349. Solimando X, Lherbier C, Babin J, Arnal Herault C, Romero E, Acherar S, Jamart Gregoire B, Barth D, Roizard D, Jonquieres A. Pseudopeptide bioconjugate additives for CO_2 separation membranes. Polymer International, 2016, 65(12): 1464–1473

350. Wu D, Zhao L, Vakharia V K, Salim W, Ho W W. Synthesis and

characterization of nanoporous polyethersulfone membrane as support for composite membrane in CO_2 separation: from lab to pilot scale. Journal of Membrane Science, 2016, 510: 58–71

351. Azizi N, Arzani M, Mahdavi H R, Mohammadi T. Synthesis and characterization of poly(ether-block-amide) copolymers/multi-walled carbon nanotube nanocomposite membranes for CO_2/CH_4 separation. Korean Journal of Chemical Engineering, 2017, 34(9): 2459–2470
352. Azizi N, Mohammadi T, Behbahani R M. Synthesis of a new nanocomposite membrane (PEBAX-1074/PEG-400/TiO_2) in order to separate CO_2 from CH_4. Journal of Natural Gas Science and Engineering, 2017, 37: 39–51
353. Azizi N, Mohammadi T, Behbahani R M. Synthesis of a PEBAX-1074/ZnO nanocomposite membrane with improved CO_2 separation performance. Journal of Energy Chemistry, 2017, 26(3): 454–465
354. Isfahani A P, Sadeghi M, Wakimoto K, Gibbons A H, Bagheri R, Sivaniah E, Ghalei B. Enhancement of CO_2 capture by polyethylene glycol-based polyurethane membranes. Journal of Membrane Science, 2017, 542: 143–149
355. Jung J P, Park C H, Lee J H, Bae Y S, Kim J H. Room-temperature, one-pot process for CO_2 capture membranes based on PEMA-g-PPG graft copolymer. Chemical Engineering Journal, 2017, 313: 1615–1622
356. Prasad B, Mandal B. CO_2 separation performance by chitosan/tetraethylenepentamine/poly(ether sulfone) composite membrane. Journal of Applied Polymer Science, 2017, 134(34): 45206
357. Taniguchi I, Wada N, Kinugasa K, Higa M. CO_2 capture by polymeric membranes composed of hyper-branched polymers with dense poly(oxyethylene) comb and poly(amidoamine). Open Physics, 2017, 15(1): 662–670
358. Tong Z, Ho W W. New sterically hindered polyvinylamine membranes for CO_2 separation and capture. Journal of Membrane Science, 2017, 543: 202–211
359. Himeno S, Tomita T, Suzuki K, Nakayama K, Yajima K, Yoshida S. Synthesis and permeation properties of a DDR-type zeolite membrane for separation of CO_2/CH_4 gaseous mixtures. Industrial & Engineering Chemistry Research, 2007, 46(21): 6989–6997
360. Hudiono Y C, Carlisle T K, Bara J E, Zhang Y, Gin D L, Noble R D. A three-component mixed-matrix membrane with enhanced CO_2 separation properties based on zeolites and ionic liquid materials. Journal of Membrane Science, 2010, 350(1-2): 117–123
361. Junaidi M, Khoo C, Leo C, Ahmad A. The effects of solvents on the modification of SAPO-34 zeolite using 3-aminopropyl trimethoxy silane for the preparation of asymmetric polysulfone mixed matrix membrane in the application of CO_2 separation. Microporous and Mesoporous Materials, 2014, 192: 52–59
362. Kim J, Abouelnasr M, Lin L C, Smit B. Large-scale screening of zeolite structures for CO_2 membrane separations. Journal of the American Chemical Society, 2013, 135(20): 7545–7552
363. Korelskiy D, Grahn M, Ye P, Zhou M, Hedlund J. A study of CO_2/CO separation by sub-micron *b*-oriented MFI membranes. Royal Society of ChemistryAdvances, 2016, 6(70): 65475–65482
364. Kosinov N, Auffret C, Gücüyener C, Szyja B M, Gascon J, Kapteijn F, Hensen E J. High flux high-silica SSZ-13 membrane for CO_2 separation. Journal of Materials Chemistry. A, Materials for Energy and Sustainability, 2014, 2(32): 13083–13092
365. Lai L S, Yeong Y F, Lau K K, Shariff A M. Single and binary CO_2/CH_4 separation of a zeolitic imidazolate framework-8 membrane. Chemical Engineering & Technology, 2017, 40(6): 1031–1042
366. Li X, Remias J E, Neathery J K, Liu K. Liu K. NF/RO faujasite zeolite membrane-ammonia absorption solvent hybrid system for potential post-combustion CO_2 capture application. Journal of Membrane Science, 2011, 366(1-2): 220–228
367. Maghsoudi H, Soltanieh M. Simultaneous separation of H_2S and CO_2 from CH_4 by a high silica CHA-type zeolite membrane. Journal of Membrane Science, 2014, 470: 159–165
368. Mizukami K, Takaba H, Kobayashi Y, Oumi Y, Belosludov R V, Takami S, Kubo M, Miyamoto A. Molecular dynamics calculations of CO_2/N_2 mixture through the NaY type zeolite membrane. Journal of Membrane Science, 2001, 188(1): 21–28
369. Sandström L, Sjöberg E, Hedlund J. Very high flux MFI membrane for CO_2 separation. Journal of Membrane Science, 2011, 380(1-2): 232–240
370. Sun C, Srivastava D J, Grandinetti P J, Dutta P K. Synthesis of chabazite/polymer composite membrane for CO_2/N_2 separation. Microporous and Mesoporous Materials, 2016, 230: 208–216
371. Xiang L, Sheng L, Wang C, Zhang L, Pan Y, Li Y. Amino-functionalized ZIF-7 nanocrystals: improved intrinsic separation ability and interfacial compatibility in mixed-matrix membranes for CO_2/CH_4 separation. Advanced Materials, 2017, 29(32): 1606999
372. Yin X, Chu N, Yang J, Wang J, Li Z. Thin zeolite T/carbon composite membranes supported on the porous alumina tubes for CO_2 separation. International Journal of Greenhouse Gas Control, 2013, 15: 55–64
373. Zhou M, Korelskiy D, Ye P, Grahn M, Hedlund J. A uniformly oriented MFI membrane for improved CO_2 separation. Angewandte Chemie International Edition, 2014, 53(13): 3492–3495
374. Kangas J, Sandström L, Malinen I, Hedlund J, Tanskanen J. Maxwell-Stefan modeling of the separation of H_2 and CO_2 at high pressure in an MFI membrane. Journal of Membrane Science, 2013, 435: 186–206
375. Lee H, Park S C, Roh J S, Moon G H, Shin J E, Kang Y S, Park H B. Metal-organic frameworks grown on a porous planar template with an exceptionally high surface area: promising nanofiller platforms for CO_2 separation. Journal of Materials Chemistry. A, Materials for Energy and Sustainability, 2017, 5(43): 22500–22505
376. An W, Swenson P, Wu L, Waller T, Ku A, Kuznicki S M. Selective separation of hydrogen from C1/C2 hydrocarbons and CO_2 through dense natural zeolite membranes. Journal of Membrane Science, 2011, 369(1-2): 414–419
377. Banihashemi F, Pakizeh M, Ahmadpour A. CO_2 separation using PDMS/ZSM-5 zeolite composite membrane. Separation and Purification Technology, 2011, 79(3): 293–302
378. Chew T L, Ahmad A L, Bhatia S. Ba-SAPO-34 membrane synthesized from microwave heating and its performance for CO_2/CH_4 gas separation. Chemical Engineering Journal, 2011, 171(3): 1053–1059
379. Hao L, Li P, Yang T, Chung T S. Room temperature ionic liquid/ZIF-8 mixed-matrix membranes for natural gas sweetening and post-combustion CO_2 capture. Journal of Membrane Science,

2013, 436: 221–231

380. Kwon W T, Kim S R, Kim E B, Bae S Y, Kim Y. H_2/CO_2 gas separation characteristic of zeolite membrane at high temperature. In: Advanced Materials Research. Zürich, Switzerland: Trans Tech Publications, Ltd., 2007, 267–270
381. Lai L S, Yeong Y F, Lau K K, Shariff A M. Synthesis of zeolitic imidazolate frameworks (ZIF)-8 membrane and its process optimization study in separation of CO_2 from natural gas. Journal of Chemical Technology and Biotechnology (Oxford, Oxfordshire), 2017, 92(2): 420–431
382. Liu Y, Hu E, Khan E A, Lai Z. Synthesis and characterization of ZIF-69 membranes and separation for CO_2/CO mixture. Journal of Membrane Science, 2010, 353(1-2): 36–40
383. Ohta Y, Takaba H, Nakao S I. A combinatorial dynamic Monte Carlo approach to finding a suitable zeolite membrane structure for CO_2/N_2 separation. Microporous and Mesoporous Materials, 2007, 101(1-2): 319–323
384. Song Z, Qiu F, Zaia E W, Wang Z, Kunz M, Guo J, Brady M, Mi B, Urban J J. Dual-channel, molecular-sieving core/shell ZIF@MOF architectures as engineered fillers in hybrid membranes for highly selective CO_2 separation. Nano Letters, 2017, 17(11): 6752–6758
385. Tzialla O, Veziri C, Papatryfon X, Beltsios K, Labropoulos A, Iliev B, Adamova G, Schubert T, Kroon M, Francisco M, Zubeir L F, Romanos G E, Karanikolos G N. Zeolite imidazolate framework-ionic liquid hybrid membranes for highly selective CO_2 separation. Journal of Physical Chemistry C, 2013, 117(36): 18434–18440
386. Ramsay J, Kallus S. Zeolite membranes. In: Membrane Science and Technology. Vol 6. Amsterdam: Elsevier, 2000, 373–395
387. Fan T, Xie W, Ji X, Liu C, Feng X, Lu X. CO_2/N_2 separation using supported ionic liquid membranes with green and cost-effective [Choline][Pro]/PEG200 mixtures. Chinese Journal of Chemical Engineering, 2016, 24(11): 1513–1521
388. Hu L, Cheng J, Li Y, Liu J, Zhang L, Zhou J, Cen K. Composites of ionic liquid and amine-modified SAPO-34 improve CO_2 separation of CO_2-selective polymer membranes. Applied Surface Science, 2017, 410: 249–258
389. Iarikov D, Hacarlioglu P, Oyama S. Supported room temperature ionic liquid membranes for CO_2/CH_4 separation. Chemical Engineering Journal, 2011, 166(1): 401–406
390. Karousos D S, Labropoulos A I, Sapalidis A, Kanellopoulos N K, Iliev B, Schubert T J, Romanos G E. Nanoporous ceramic supported ionic liquid membranes for CO_2 and SO_2 removal from flue gas. Chemical Engineering Journal, 2017, 313: 777–790
391. Karunakaran M, Villalobos L F, Kumar M, Shevate R, Akhtar F H, Peinemann K V. Graphene oxide doped ionic liquid ultrathin composite membranes for efficient CO_2 capture. Journal of Materials Chemistry. A, Materials for Energy and Sustainability, 2017, 5(2): 649–656
392. Li P, Paul D R, Chung T S. High performance membranes based on ionic liquid polymers for CO_2 separation from the flue gas. Green Chemistry, 2012, 14(4): 1052–1063
393. Li P, Pramoda K, Chung T S. CO_2 separation from flue gas using polyvinyl-(room temperature ionic liquid)-room temperature ionic liquid composite membranes. Industrial & Engineering Chemistry Research, 2011, 50(15): 9344–9353
394. Li Y, Rui Z, Xia C, Anderson M, Lin Y. Performance of ionic-conducting ceramic/carbonate composite material as solid oxide fuel cell electrolyte and CO_2 permeation membrane. Catalysis Today, 2009, 148(3-4): 303–309
395. Liu Z, Liu C, Li L, Qin W, Xu A. CO_2 separation by supported ionic liquid membranes and prediction of separation performance. International Journal of Greenhouse Gas Control, 2016, 53: 79–84
396. Lu J G, Ge H, Chen Y, Ren R T, Xu Y, Zhao Y X, Zhao X, Qian H. CO_2 capture using a functional protic ionic liquid by membrane absorption. Journal of the Energy Institute, 2017, 90(6): 933–940
397. Lu J G, Lu C T, Chen Y, Gao L, Zhao X, Zhang H, Xu Z W. CO_2 capture by membrane absorption coupling process: application of ionic liquids. Applied Energy, 2014, 115: 573–581
398. Lu S C, Khan A L, Vankelecom I F. Polysulfone-ionic liquid based membranes for CO_2/N_2 separation with tunable porous surface features. Journal of Membrane Science, 2016, 518: 10–20
399. Mannan H, Mohshim D, Mukhtar H, Murugesan T, Man Z, Bustam M. Synthesis, characterization and CO_2 separation performance of polyether sulfone/[EMIM][Tf2N] ionic liquid-polymeric membranes (ILPMs). Journal of Industrial and Engineering Chemistry, 2017, 54: 98–106
400. Ramli N A, Hashim N A, Aroua M K. Prediction of CO_2/O_2 absorption selectivity using supported ionic liquid membranes (SILMs) for gas-liquid membrane contactor. Chemical Engineering Communications, 2018, 205(3): 295–310
401. Tomé L C, Patinha D J, Freire C S, Rebelo L P N, Marrucho I M. CO_2 separation applying ionic liquid mixtures: the effect of mixing different anions on gas permeation through supported ionic liquid membranes. Royal Society of Chemistry Advances, 2013, 3(30): 12220–12229
402. Ur Rehman R, Rafiq S, Muhammad N, Khan A L, Ur Rehman A, TingTing L, Saeed M, Jamil F, Ghauri M, Gu X. Development of ethanolamine-based ionic liquid membranes for efficient CO_2/CH_4 separation. Journal of Applied Polymer Science, 2017, 134(44): 45395
403. Yoon K W, Kim H, Kang Y S, Kang S W. 1-Butyl-3-methylimidazolium tetrafluoroborate/zinc oxide composite membrane for high CO_2 separation performance. Chemical Engineering Journal, 2017, 320: 50–54
404. Zhang X M, Tu Z H, Li H, Li L, Wu Y T, Hu X B. Supported protic-ionic-liquid membranes with facilitated transport mechanism for the selective separation of CO_2. Journal of Membrane Science, 2017, 527: 60–67
405. Chen H, Kovvali A, Sirkar K. Selective CO_2 Separation from CO_2-N_2 mixtures by immobilized glycine-Na-glycerol membranes. Industrial & Engineering Chemistry Research, 2000, 39(7): 2447–2458
406. Ilyas A, Muhammad N, Gilani M A, Ayub K, Vankelecom I F, Khan A L. Supported protic ionic liquid membrane based on 3-(trimethoxysilyl) propan-1-aminium acetate for the highly selective separation of CO_2. Journal of Membrane Science, 2017, 543: 301–309
407. Ranjbaran F, Kamio E, Matsuyama H. Ion gel membrane with tunable inorganic/organic composite network for CO_2 separation. Industrial & Engineering Chemistry Research, 2017, 56(44): 12763–12772

408. Jindaratsamee P, Shimoyama Y, Ito A. Amine/glycol liquid membranes for CO_2 recovery form air. Journal of Membrane Science, 2011, 385: 171–176
409. Hussain A. Three stage membrane process for CO_2 capture from natural gas. AA, 2017, 50:1
410. Niwa M, Ohya H, Tanaka Y, Yoshikawa N, Matsumoto K, Negishi Y. Separation of gaseous mixtures of CO_2 and CH_4 using a composite microporous glass membrane on ceramic tubing. Journal of Membrane Science, 1988, 39(3): 301–314
411. Saha S, Chakma A. Separation of CO_2 from gas mixtures with liquid membranes. Energy Conversion and Management, 1992, 33 (5-8): 413–420
412. Xu L, Zhang L, Chen H. Study on CO_2 removal in air by hydrogel membranes. Desalination, 2002, 148(1-3): 309–313
413. Jordal K, Bredesen R, Kvamsdal H, Bolland O. Integration of H_2-separating membrane technology in gas turbine processes for CO_2 capture. Energy, 2004, 29(9-10): 1269–1278
414. Li S, Falconer J L, Noble R D. SAPO-34 membranes for CO_2/CH_4 separation. Journal of Membrane Science, 2004, 241(1): 121–135
415. Moon J H, Ahn H, Hyun S H, Lee C H. Separation characteristics of tetrapropylammoniumbromide templating silica/alumina composite membrane in CO_2/N_2, CO_2/H_2 and CH_4/H_2 systems. Korean Journal of Chemical Engineering, 2004, 21(2): 477–487
416. Li S, Alvarado G, Noble R D, Falconer J L. Effects of impurities on CO_2/CH_4 separations through SAPO-34 membranes. Journal of Membrane Science, 2005, 251(1-2): 59–66
417. Li S, Martinek J G, Falconer J L, Noble R D, Gardner T Q. High-pressure CO_2/CH_4 separation using SAPO-34 membranes. Industrial & Engineering Chemistry Research, 2005, 44(9): 3220–3228
418. Jordal K, Bolland O, Möller B F, Torisson T. Optimization with genetic algorithms of a gas turbine cycle with H_2-separating membrane reactor for CO_2 capture. International Journal of Green Energy, 2005, 2(2): 167–180
419. Sakamoto Y, Nagata K, Yogo K, Yamada K. Preparation and CO_2 separation properties of amine-modified mesoporous silica membranes. Microporous and Mesoporous Materials, 2007, 101(1-2): 303–311
420. Xiao S, Feng X, Huang R Y. Trimesoyl chloride crosslinked chitosan membranes for CO_2/N_2 separation and pervaporation dehydration of isopropanol. Journal of Membrane Science, 2007, 306(1-2): 36–46
421. Yegani R, Hirozawa H, Teramoto M, Himei H, Okada O, Takigawa T, Ohmura N, Matsumiya N, Matsuyama H. Selective separation of CO_2 by using novel facilitated transport membrane at elevated temperatures and pressures. Journal of Membrane Science, 2007, 291(1-2): 157–164
422. Paul S, Ghoshal A K, Mandal B. Theoretical studies on separation of CO_2 by single and blended aqueous alkanolamine solvents in flat sheet membrane contactor (FSMC). Chemical Engineering Journal, 2008, 144(3): 352–360
423. Kai T, Kazama S, Fujioka Y. Development of cesium-incorporated carbon membranes for CO_2 separation under humid conditions. Journal of Membrane Science, 2009, 342(1-2): 14–21
424. Nistor C, Shishatskiy S, Popa M, Nunes S P. CO_2 selective membranes based on epoxy silane. Revue Roumaine de Chimie, 2009, 54: 603–610
425. Li S, Carreon M A, Zhang Y, Funke H H, Noble R D, Falconer J L. Scale-up of SAPO-34 membranes for CO_2/CH_4 separation. Journal of Membrane Science, 2010, 352(1-2): 7–13
426. Scholes C A, Smith K H, Kentish S E, Stevens G W. CO_2 capture from pre-combustion processes—strategies for membrane gas separation. International Journal of Greenhouse Gas Control, 2010, 4(5): 739–755
427. Tiscornia I, Kumakiri I, Bredesen R, Téllez C, Coronas J. Microporous titanosilicate ETS-10 membrane for high pressure CO_2 separation. Separation and Purification Technology, 2010, 73 (1): 8–12
428. Favre N, Pierre A C. Synthesis and behaviour of hybrid polymer-silica membranes made by sol gel process with adsorbed carbonic anhydrase enzyme, in the capture of CO_2. Journal of Sol-Gel Science and Technology, 2011, 60(2): 177–188
429. Lotrič A, Sekavčnik M, Kunze C, Spliethoff H. Simulation of water-gas shift membrane reactor for integrated gasification combined cycle plant with CO_2 capture. Chinese Journal of Mechanical Engineering, 2011, 57(12): 911–926
430. Martin F Z, Dijkstra J W, Boon J, Meuldijk J. A membrane reformer with permeate side combustion for CO_2 capture: modeling and design. Energy Procedia, 2011, 4: 707–714
431. Ostwal M, Singh R P, Dec S F, Lusk M T, Way J D. 3-Aminopropyltriethoxysilane functionalized inorganic membranes for high temperature CO_2/N_2 separation. Journal of Membrane Science, 2011, 369(1-2): 139–147
432. Venna S R, Carreon M A. Amino-functionalized SAPO-34 membranes for CO_2/CH_4 and CO_2/N_2 separation. Langmuir, 2011, 27(6): 2888–2894
433. Wade J L, Lee C, West A C, Lackner K S. Composite electrolyte membranes for high temperature CO_2 separation. Journal of Membrane Science, 2011, 369(1-2): 20–29
434. Chabanon E, Roizard D, Favre E. Modelling strategies of membrane contactor processes for CO_2 post-combustion capture: a critical reassessment. Procedia Engineering, 2012, 44: 343–346
435. Lau C H, Paul D R, Chung T S. Molecular design of nanohybrid gas separation membranes for optimal CO_2 separation. Polymer, 2012, 53(2): 454–465
436. Li H, Pieterse J, Dijkstra J, Boon J, Van Den Brink R, Jansen D. Bench-scale WGS membrane reactor for CO_2 capture with co-production of H_2. International Journal of Hydrogen Energy, 2012, 37(5): 4139–4143
437. Madhusoodana C, Patil M, Aminabhavi T. Ceramic supported composite membranes of hydroxy-ethyl-cellulose loaded with AL-MCM-41 for CO_2 separation. Procedia Engineering, 2012, 44: 108–109
438. Modarresi S, Soltanieh M, Mousavi S A, Shabani I. Effect of low-frequency oxygen plasma on polysulfone membranes for CO_2/CH_4 Separation. Journal of Applied Polymer Science, 2012, 124(S1): E199–E204
439. Rongwong W, Boributh S, Assabumrungrat S, Laosiripojana N, Jiraratananon R. Simultaneous absorption of CO_2 and H_2S from biogas by capillary membrane contactor. Journal of Membrane Science, 2012, 392: 38–47
440. Smart S, Vente J, Da Costa J D. High temperature H_2/CO_2 separation using cobalt oxide silica membranes. International

Journal of Hydrogen Energy, 2012, 37(17): 12700–12707

441. Bae T H, Long J R. CO_2/N_2 separations with mixed-matrix membranes containing Mg_2(dobdc) nanocrystals. Energy & Environmental Science, 2013, 6(12): 3565–3569

442. Choi J H, Park M J, Kim J, Ko Y, Lee S H, Baek I. Modelling and analysis of pre-combustion CO_2 capture with membranes. Korean Journal of Chemical Engineering, 2013, 30(6): 1187–1194

443. Koutsonikolas D E, Kaldis S P, Pantoleontos G T, Zaspalis V T, Sakellaropoulos G P. Techno-economic assessment of polymeric, ceramic and metallic membranes integration in an advanced IGCC process for H_2 production and CO_2 capture. Trans, 2013, 35: 715–720

444. Lee C B, Lee S W, Park J S, Lee D W, Hwang K R, Ryi S K, Kim S H. Long-term CO_2 capture tests of Pd-based composite membranes with module configuration. International Journal of Hydrogen Energy, 2013, 38(19): 7896–7903

445. Lin Y F, Chen C H, Tung K L, Wei T Y, Lu S Y, Chang K S. Mesoporous fluorocarbon-modified silica aerogel membranes enabling long-term continuous CO_2 capture with large absorption flux enhancements. ChemSusChem, 2013, 6(3): 437–442

446. Ryi S K, Lee C B, Lee S W, Park J S. Pd-based composite membrane and its high-pressure module for pre-combustion CO_2 capture. Energy, 2013, 51: 237–242

447. Zhang K, Zou Y, Su C, Shao Z, Liu L, Wang S, Liu S. CO_2 and water vapor-tolerant yttria stabilized bismuth oxide (YSB) membranes with external short circuit for oxygen separation with CO_2 capture at intermediate temperatures. Journal of Membrane Science, 2013, 427: 168–175

448. Zhu X, Chai S, Tian C, Fulvio P F, Han K S, Hagaman E W, Veith G M, Mahurin S M, Brown S, Liu H, Dai S. Synthesis of porous, nitrogen-doped adsorption/diffusion carbonaceous membranes for efficient CO_2 separation. Macromolecular Rapid Communications, 2013, 34(5): 452–459

449. Zhao Y, Jung B T, Ansaloni L, Ho W W. Multiwalled carbon nanotube mixed matrix membranes containing amines for high pressure CO_2/H_2 separation. Journal of Membrane Science, 2014, 459: 233–243

450. Deng L, Hägg M B. Carbon nanotube reinforced PVAm/PVA blend FSC nanocomposite membrane for CO_2/CH_4 separation. International Journal of Greenhouse Gas Control, 2014, 26: 127–134

451. Lin Y F, Ko C C, Chen C H, Tung K L, Chang K S, Chung T W. Sol-gel preparation of polymethylsilsesquioxane aerogel membranes for CO_2 absorption fluxes in membrane contactors. Applied Energy, 2014, 129: 25–31

452. Patel R, Kim S J, Roh D K, Kim J H. Synthesis of amphiphilic PCZ-r-PEG nanostructural copolymers and their use in CO_2/N_2 separation membranes. Chemical Engineering Journal, 2014, 254: 46–53

453. Pedram M Z, Omidkhah M, Amooghin A E. Synthesis and characterization of diethanolamine-impregnated cross-linked polyvinylalcohol/glutaraldehyde membranes for CO_2/CH_4 separation. Journal of Industrial and Engineering Chemistry, 2014, 20(1): 74–82

454. Rabiee H, Soltanieh M, Mousavi S A, Ghadimi A. Improvement in CO_2/H_2 separation by fabrication of poly(ether-*b*-amide6)/glycerol triacetate gel membranes. Journal of Membrane Science, 2014, 469: 43–58

455. Ryi S K, Lee S W, Park J W, Oh D K, Park J S, Kim S S. Combined steam and CO_2 reforming of methane using catalytic nickel membrane for gas to liquid (GTL) process. Catalysis Today, 2014, 236: 49–56

456. Scholes C A, Ho M T, Aguiar A A, Wiley D E, Stevens G W, Kentish S E. Membrane gas separation processes for CO_2 capture from cement kiln flue gas. International Journal of Greenhouse Gas Control, 2014, 24: 78–86

457. Shi H. Synthesis of SAPO-34 zeolite membranes with the aid of crystal growth inhibitors for CO_2-CH_4 separation. New Journal of Chemistry, 2014, 38(11): 5276–5278

458. Taniguchi I, Fujikawa S. CO_2 separation with nano-thick polymeric membrane for pre-combustion. Energy Procedia, 2014, 63: 235–242

459. Tseng H H, Chang S H, Wey M Y. A carbon gutter layer-modified α-Al_2O_3 substrate for PPO membrane fabrication and CO_2 separation. Journal of Membrane Science, 2014, 454: 51–61

460. Wu T, Wang B, Lu Z, Zhou R, Chen X. Alumina-supported AlPO-18 membranes for CO_2/CH_4 separation. Journal of Membrane Science, 2014, 471: 338–346

461. Zhang L, Gong Y, Brinkman K S, Wei T, Wang S, Huang K. Flux of silver-carbonate membranes for post-combustion CO_2 capture: the effects of membrane thickness, gas concentration and time. Journal of Membrane Science, 2014, 455: 162–167

462. Zhang L, Gong Y, Yaggie J, Wang S, Romito K, Huang K. Surface modified silver-carbonate mixed conducting membranes for high flux CO_2 separation with enhanced stability. Journal of Membrane Science, 2014, 453: 36–41

463. Azizi M, Mousavi S A. CO_2/H_2 separation using a highly permeable polyurethane membrane: molecular dynamics simulation. Journal of Molecular Structure, 2015, 1100: 401–414

464. Kammakakam I, Nam S, Kim T H. Ionic group-mediated crosslinked polyimide membranes for enhanced CO_2 separation. Royal Society of Chemistry Advances, 2015, 5(86): 69907–69914

465. Konruang S, Sirijarukul S, Wanichapichart P, Yu L, Chittrakarn T. Ultraviolet-ray treatment of polysulfone membranes on the O_2/N_2 and CO_2/CH_4 separation performance. Journal of Applied Polymer Science, 2015, 132(25): 42074

466. Lin Y F, Chang J M, Ye Q, Tung K L. Hydrophobic fluorocarbon-modified silica aerogel tubular membranes with excellent CO_2 recovery ability in membrane contactors. Applied Energy, 2015, 154: 21–25

467. Nabian N, Ghoreyshi A A, Rahimpour A, Shakeri M. Performance evaluation and mass transfer study of CO_2 absorption in flat sheet membrane contactor using novel porous polysulfone membrane. Korean Journal of Chemical Engineering, 2015, 32(11): 2204–2211

468. Nwogu N C, Kajama M N, Osueke G, Gobina E. High performance valuation of CO_2 gas separation ceramic membrane system. In: Ao S I, Gelman L, Hukins D W L, Hunter A, Korsunsky A M, eds. Proceedings of the 2015 World Congress on Engineering (WCE 2015). Hong Kong: Newswood Academic Publishing, 2015, 824–827

469. Qiao Z, Wang Z, Yuan S, Wang J, Wang S. Preparation and

characterization of small molecular amine modified PVAm membranes for CO_2/H_2 separation. Journal of Membrane Science, 2015, 475: 290–302

470. Shin D Y, Hwang K R, Park J S, Park M J. Computational fluid dynamics modeling and analysis of Pd-based membrane module for CO_2 capture from H_2/CO_2 binary gas mixture. Korean Journal of Chemical Engineering, 2015, 32(7): 1414–1421
471. Sun C, Wen B, Bai B. Application of nanoporous graphene membranes in natural gas processing: molecular simulations of CH_4/CO_2, CH_4/H_2S and CH_4/N_2 separation. Chemical Engineering Science, 2015, 138: 616–621
472. Tong J, Zhang L, Fang J, Han M, Huang K. Electrochemical capture of CO_2 from natural gas using a high-temperature ceramic-carbonate membrane. Journal of the Electrochemical Society, 2015, 162(4): E43–E46
473. Wang B, Sun C, Li Y, Zhao L, Ho W W, Dutta P K. Rapid synthesis of faujasite/polyethersulfone composite membrane and application for CO_2/N_2 separation. Microporous and Mesoporous Materials, 2015, 208: 72–82
474. Wang N, Mundstock A, Liu Y, Huang A, Caro J. Amine-modified Mg-MOF-74/CPO-27-Mg membrane with enhanced H_2/CO_2 separation. Chemical Engineering Science, 2015, 124: 27–36
475. Wang S, Tian Z, Feng J, Wu H, Li Y, Liu Y, Li X, Xin Q, Jiang Z. Enhanced CO_2 separation properties by incorporating poly (ethylene glycol)-containing polymeric submicrospheres into polyimide membrane. Journal of Membrane Science, 2015, 473: 310–317
476. Xin Q, Gao Y, Wu X, Li C, Liu T, Shi Y, Li Y, Jiang Z, Wu H, Cao X. Incorporating one-dimensional aminated titania nanotubes into sulfonated poly(ether ether ketone) membrane to construct CO_2-facilitated transport pathways for enhanced CO_2 separation. Journal of Membrane Science, 2015, 488: 13–29
477. Xing W, Peters T, Fontaine M L, Evans A, Henriksen P P, Norby T, Bredesen R. Steam-promoted CO_2 flux in dual-phase CO_2 separation membranes. Journal of Membrane Science, 2015, 482: 115–119
478. Zheng Y, Hu N, Wang H, Bu N, Zhang F, Zhou R. Preparation of steam-stable high-silica CHA (SSZ-13) membranes for CO_2/CH_4 and C_2H_4/C_2H_6 separation. Journal of Membrane Science, 2015, 475: 303–310
479. Zhou R, Wang H, Wang B, Chen X, Li S, Yu M. Defect-patching of zeolite membranes by surface modification using siloxane polymers for CO_2 separation. Industrial & Engineering Chemistry Research, 2015, 54(30): 7516–7523
480. Dai Z, Bai L, Hval K N, Zhang X, Zhang S, Deng L. Pebax®/TSIL blend thin film composite membranes for CO_2 separation. Science China. Chemistry, 2016, 59(5): 538–546
481. Dong G, Zhang Y, Hou J, Shen J, Chen V. Graphene oxide nanosheets based novel facilitated transport membranes for efficient CO_2 capture. Industrial & Engineering Chemistry Research, 2016, 55(18): 5403–5414
482. Dong L, Zhang C, Bai Y, Shi D, Li X, Zhang H, Chen M. High-performance PEBA2533-functional MMT mixed matrix membrane containing high-speed facilitated transport channels for CO_2/N_2 separation. ACS Sustainable Chemistry & Engineering, 2016, 4 (6): 3486–3496
483. Jeon H, Kim D J, Park M S, Ryu D Y, Kim J H. Amphiphilic graft copolymer nanospheres: from colloidal self-assembly to CO_2 capture membranes. ACS Applied Materials & Interfaces, 2016, 8 (14): 9454–9461
484. Karimi S, Korelskiy D, Mortazavi Y, Khodadadi A A, Sardari K, Esmaeili M, Antzutkin O N, Shah F U, Hedlund J. High flux acetate functionalized silica membranes based on *in-situ* co-condensation for CO_2/N_2 separation. Journal of Membrane Science, 2016, 520: 574–582
485. Li W, Zhang Y, Su P, Xu Z, Zhang G, Shen C, Meng Q. Metal-organic framework channelled graphene composite membranes for H_2/CO_2 separation. Journal of Materials Chemistry. A, Materials for Energy and Sustainability, 2016, 4(48): 18747–18752
486. Lin Y F, Kuo J W. Mesoporous bis(trimethoxysilyl) hexane (BTMSH)/tetraethyl orthosilicate (TEOS)-based hybrid silica aerogel membranes for CO_2 capture. Chemical Engineering Journal, 2016, 300: 29–35
487. Moradi M R, Chenar M P, Noie S H. Using PDMS coated TFC-RO membranes for CO_2/N_2 gas separation: experimental study, modeling and optimization. Polymer Testing, 2016, 56: 287–298
488. Mubashir M, Yeong Y F, Lau K K. Ultrasonic-assisted secondary growth of deca-dodecasil 3 rhombohedral (DD3R) membrane and its process optimization studies in CO_2/CH_4 separation using response surface methodology. Journal of Natural Gas Science and Engineering, 2016, 30: 50–63
489. Pohlmann J, Bram M, Wilkner K, Brinkmann T. Pilot scale separation of CO_2 from power plant flue gases by membrane technology. International Journal of Greenhouse Gas Control, 2016, 53: 56–64
490. Qin Y, Lv J, Fu X, Guo R, Li X, Zhang J, Wei Z. High-performance SPEEK/amino acid salt membranes for CO_2 separation. Royal Society of Chemistry Advances, 2016, 6(3): 2252–2258
491. Saedi S, Seidi F, Moradi F, Xiang X. Preparation and characterization of an amino-cellulose (AC) derivative for development of thin-film composite membrane for CO_2/CH_4 separation. Stärke, 2016, 68(7-8): 651–661
492. Saeed M, Deng L. Carbon nanotube enhanced PVA-mimic enzyme membrane for post-combustion CO_2 capture. International Journal of Greenhouse Gas Control, 2016, 53: 254–262
493. Wang Y, Yang Q, Li J, Yang J, Zhong C. Exploration of nanoporous graphene membranes for the separation of N_2 from CO_2: a multi-scale computational study. Physical Chemistry Chemical Physics, 2016, 18(12): 8352–8358
494. Wong K, Goh P, Ismail A F. Thin film nanocomposite: the next generation selective membrane for CO_2 removal. Journal of Materials Chemistry. A, Materials for Energy and Sustainability, 2016, 4(41): 15726–15748
495. Zhang P, Tong J, Jee Y, Huang K. Stabilizing a high-temperature electrochemical silver-carbonate CO_2 capture membrane by atomic layer deposition of a ZrO_2 overcoat. Chemical Communications, 2016, 52(63): 9817–9820
496. Zhong S, Bu N, Zhou R, Jin W, Yu M, Li S. Aluminophosphate-17 and silicoaluminophosphate-17 membranes for CO_2 separations. Journal of Membrane Science, 2016, 520: 507–514
497. Benito J, Sánchez Laínez J, Zornoza B, Martín S, Carta M,

Malpass Evans R, Téllez C, McKeown N B, Coronas J, Gascón I. Ultrathin composite polymeric membranes for CO_2/N_2 separation with minimum thickness and high CO_2 permeance. ChemSusChem, 2017, 10(20): 4014–4017

498. Kgaphola K, Sigalas I, Daramola M O. Synthesis and characterization of nanocomposite SAPO-34/ceramic membrane for post-combustion CO_2 capture. Asia-Pacific Journal of Chemical Engineering, 2017, 12(6): 894–904

499. Khakpay A, Rahmani F, Nouranian S, Scovazzo P. Molecular insights on the CH_4/CO_2 separation in nanoporous graphene and graphene oxide separation platforms: adsorbents versus membranes. Journal of Physical Chemistry C, 2017, 121(22): 12308–12320

500. Kim N U, Park B J, Choi Y, Lee K B, Kim J H. High-performance self-cross-linked PGP-POEM comb copolymer membranes for CO_2 capture. Macromolecules, 2017, 50(22): 8938–8947

501. Kline G K, Weidman J R, Zhang Q, Guo R. Studies of the synergistic effects of crosslink density and crosslink inhomogeneity on crosslinked PEO membranes for CO_2-selective separations. Journal of Membrane Science, 2017, 544: 25–34

502. Mahdavi H R, Azizi N, Mohammadi T. Performance evaluation of a synthesized and characterized Pebax1657/PEG1000/γ-Al_2O_3 membrane for CO_2/CH_4 separation using response surface methodology. Journal of Polymer Research, 2017, 24(5): 67

503. Peng D, Wang S, Tian Z, Wu X, Wu Y, Wu H, Xin Q, Chen J, Cao X, Jiang Z. Facilitated transport membranes by incorporating graphene nanosheets with high zinc ion loading for enhanced CO_2 separation. Journal of Membrane Science, 2017, 522: 351–362

504. Qu Y, Li F, Zhao M. Theoretical design of highly efficient CO_2/N_2 separation membranes based on electric quadrupole distinction. Journal of Physical Chemistry C, 2017, 121(33): 17925–17931

505. Selyanchyn R, Fujikawa S. Membrane thinning for efficient CO_2 capture. Science and Technology of Advanced Materials, 2017, 18 (1): 816–827

506. Shafie S N A, Man Z, Idris A. Development of polycarbonate-silica matrix membrane for CO_2/CH_4 separation. In: AIP Conference Proceedings. Melville, NY: AIP Publishing, 2017, 020129

507. Song C, Liu Q, Ji N, Deng S, Zhao J, Li Y, Kitamura Y. Reducing the energy consumption of membrane-cryogenic hybrid CO_2 capture by process optimization. Energy, 2017, 124: 29–39

508. Taniguchi I, Kinugasa K, Toyoda M, Minezaki K. Effect of amine structure on CO_2 capture by polymeric membranes. Science and Technology of Advanced Materials, 2017, 18(1): 950–958

509. Wang P, Li W, Du C, Zheng X, Sun X, Yan Y, Zhang J. CO_2/N_2 separation via multilayer nanoslit graphene oxide membranes: molecular dynamics simulation study. Computational Materials Science, 2017, 140: 284–289

510. Wang S, Xie Y, He G, Xin Q, Zhang J, Yang L, Li Y, Wu H, Zhang Y, Guiver M D, Jiang Z. Graphene oxide membranes with heterogeneous nanodomains for efficient CO_2 separations. Angewandte Chemie International Edition, 2017, 56(45): 14246–14251

511. Zhang C, Zhang W, Gao H, Bai Y, Sun Y, Chen Y. Synthesis and gas transport properties of poly(ionic liquid) based semi-interpenetrating polymer network membranes for CO_2/N_2 separation. Journal of Membrane Science, 2017, 528: 72–81

512. Zhang Y, Wang H, Zhang Y, Ding X, Liu J. Thin film composite membranes functionalized with montmorillonite and hydrotalcite nanosheets for CO_2/N_2 separation. Separation and Purification Technology, 2017, 189: 128–137

513. Zhao L, Sang P, Guo S, Liu X, Li J, Zhu H, Guo W. Promising monolayer membranes for $CO_2/N_2/CH_4$ separation: graphdiynes modified respectively with hydrogen, fluorine and oxygen atoms. Applied Surface Science, 2017, 405: 455–464

514. Zhu L, Swihart M T, Lin H. Tightening polybenzimidazole (PBI) nanostructure via chemical cross-linking for membrane H_2/CO_2 separation. Journal of Materials Chemistry. A, Materials for Energy and Sustainability, 2017, 5(37): 19914–19923

515. Constantinou A, Barrass S, Gavriilidis A. CO_2 absorption in flat membrane microstructured contactors of different wettability using aqueous solution of NaOH. Green Processing and Synthesis, 2018, 7(6): 471–476

516. Russo G, Prpich G, Anthony E J, Montagnaro F, Jurado N, Di Lorenzo G, Darabkhani H G. Selective-exhaust gas recirculation for CO_2 capture using membrane technology. Journal of Membrane Science, 2018, 549: 649–659

517. Yu L, Kanezashi M, Nagasawa H, Moriyama N, Tsuru T, Ito K. Enhanced CO_2 separation performance for tertiary amine-silica membranes via thermally induced local liberation of CH_3Cl. AIChE Journal. American Institute of Chemical Engineers, 2018, 64(5): 1528–1539

518. Zhang N, Peng D, Wu H, Ren Y, Yang L, Wu X, Wu Y, Qu Z, Jiang Z, Cao X. Significantly enhanced CO_2 capture properties by synergy of zinc ion and sulfonate in Pebax-pitch hybrid membranes. Journal of Membrane Science, 2018, 549: 670–679

519. Hu L, Cheng J, Li Y, Liu J, Zhou J, Cen K. Optimization of coating solution viscosity of hollow fiber-supported polydimethylsiloxane membrane for CO_2/H_2 separation. Journal of Applied Polymer Science, 2018, 135(5): 45765

520. Ovalle Encinia O, Pfeiffer H, Ortiz Landeros J. $Ce_{0.85}Sm_{0.15}O_2$-$Sm_{0.6}Sr_{0.4}Al_{0.3}Fe_{0.7}O_3$ composite for the preparation of dense ceramic-carbonate membranes for CO_2 separation. Journal of Membrane Science, 2018, 547: 11–18

521. Constantinou A, Barrass S, Pronk F, Bril T, Wenn D, Shaw J, Gavriilidis A. CO_2 absorption in a high efficiency silicon nitride mesh contactor. Chemical Engineering Journal, 2012, 207: 766–771

522. Constantinou A, Gavriilidis A. CO_2 absorption in a microstructured mesh reactor. Industrial & Engineering Chemistry Research, 2010, 49(3): 1041–1049

523. Li S, Falconer J L, Noble R D. SAPO-34 membranes for CO_2/CH_4 separations: effect of Si/Al ratio. Microporous and Mesoporous Materials, 2008, 110(2-3): 310–317

524. Duan S, Taniguchi I, Kai T, Kazama S. Development of poly (amidoamine) dendrimer/polyvinyl alcohol hybrid membranes for CO_2 capture at elevated pressures. Energy Procedia, 2013, 37: 924–931

525. Ahmad F, Lau K K, Shariff A M. Modeling and parametric study for CO_2/CH_4 separation using membrane processes. World Academy of Science, Engineering and Technology, 2010, 2010 (4): 387–392

526. Arias A M, Mussati M C, Mores P L, Scenna N J, Caballero J A, Mussati S F. Optimization of multi-stage membrane systems for

CO_2 capture from flue gas. International Journal of Greenhouse Gas Control, 2016, 53: 371–390

527. Couling D J, Prakash K, Green W H. Analysis of membrane and adsorbent processes for warm syngas cleanup in integrated gasification combined-cycle power with CO_2 capture and sequestration. Industrial & Engineering Chemistry Research, 2011, 50 (19): 11313–11336
528. Hasan M F, Baliban R C, Elia J A, Floudas C A. Modeling, simulation, and optimization of postcombustion CO_2 capture for variable feed concentration and flow rate. 1. Chemical absorption and membrane processes. Industrial & Engineering Chemistry Research, 2012, 51(48): 15642–15664
529. Johannessen E, Jordal K. Study of a H_2 separating membrane reactor for methane steam reforming at conditions relevant for power processes with CO_2 capture. Energy Conversion and Management, 2005, 46(7-8): 1059–1071
530. Jusoh N, Lau K K, Shariff A M, Yeong Y. Capture of bulk CO_2 from methane with the presence of heavy hydrocarbon using membrane process. International Journal of Greenhouse Gas Control, 2014, 22: 213–222
531. Jusoh N, Lau K K, Yeong Y F, Shariff A M. Bulk CO_2/CH_4 separation for offshore operating conditions using membrane process. Sains Malaysiana, 2016, 45(11): 1707–1714
532. Lee S H, Kim J N, Eom W H, Ryi S K, Park J S, Baek I H. Development of pilot WGS/multi-layer membrane for CO_2 capture. Chemical Engineering Journal, 2012, 207: 521–525
533. Merkel T C, Wei X, He Z, White L S, Wijmans J, Baker R W. Selective exhaust gas recycle with membranes for CO_2 capture from natural gas combined cycle power plants. Industrial & Engineering Chemistry Research, 2012, 52(3): 1150–1159
534. Nagumo R, Iwata S, Mori H. Simulated process evaluation of synthetic natural gas production based on biomass gasification and potential of CO_2 capture using membrane separation Technology. Journal of the Japan Petroleum Institute, 2013, 56(6): 395–400
535. Piroonlerkgul P, Laosiripojana N, Adesina A, Assabumrungrat S. Performance of biogas-fed solid oxide fuel cell systems integrated with membrane module for CO_2 removal. Chemical Engineering and Processing: Process Intensification, 2009, 48(2): 672–682
536. Rezvani S, Huang Y, McIlveen Wright D, Hewitt N, Mondol J D. Comparative assessment of coal fired IGCC systems with CO_2 capture using physical absorption, membrane reactors and chemical looping. Fuel, 2009, 88(12): 2463–2472
537. Scholes C A, Simioni M, Qader A, Stevens G W, Kentish S E. Membrane gas-solvent contactor trials of CO_2 absorption from syngas. Chemical Engineering Journal, 2012, 195: 188–197
538. Shao P, Dal Cin M M, Guiver M D, Kumar A. Simulation of membrane-based CO_2 capture in a coal-fired power plant. Journal of Membrane Science, 2013, 427: 451–459
539. Shen J, Liu G, Huang K, Jin W, Lee K R, Xu N. Membranes with fast and selective gas-transport channels of laminar graphene oxide for efficient CO_2 capture. Angewandte Chemie, 2015, 127(2): 588–592
540. Skorek Osikowska A, Bartela Ł, Kotowicz J. Thermodynamic and economic evaluation of a CO_2 membrane separation unit integrated into a supercritical coal-fired heat and power plant. Journal of Power Technologies, 2015, 95(3): 201–210
541. Stanislowski J, Holmes M, Snyder A, Tolbert S, Curran T. Advanced CO_2 separation technologies: coal gasification, warm-gas cleanup, and hydrogen separation membranes. Energy Procedia, 2013, 37: 2316–2326
542. Tuinier M, Hamers H, van Sint Annaland M. Techno-economic evaluation of cryogenic CO_2 capture—a comparison with absorption and membrane technology. International Journal of Greenhouse Gas Control, 2011, 5(6): 1559–1565
543. Turi D, Ho M, Ferrari M, Chiesa P, Wiley D, Romano M C. CO_2 capture from natural gas combined cycles by CO_2 selective membranes. International Journal of Greenhouse Gas Control, 2017, 61: 168–183
544. Wang B, Zhu D C, Zhan M C, Liu W, Chen C S. Combustion of coal-derived CO with membrane-supplied oxygen enabling CO_2 capture. AIChE Journal. American Institute of Chemical Engineers, 2007, 53(9): 2481–2484
545. Yang D, Wang Z, Wang J, Wang S. Potential of two-stage membrane system with recycle stream for CO_2 capture from postcombustion gas. Energy & Fuels, 2009, 23(10): 4755–4762
546. Franz J, Scherer V. An evaluation of CO_2 and H_2 selective polymeric membranes for CO_2 separation in IGCC processes. Journal of Membrane Science, 2010, 359(1-2): 173–183
547. Wang Z, Dong S, Li N, Cao X, Sheng M, Xu R, Wang B, Wu H, Ma C, Yuan Y. CO_2-selective membranes: how easy is their moving from laboratory to industrial scale? In: Current Trends and Future Developments on (bio-) membranes. Amsterdam: Elsevier, 2018, 75–102
548. Doran P. Chapter 11-Unit Operations, In: Bioprocess Engineering Principles. 2nd ed. London: Elsevier, 2013, 445–595
549. Cui Z, Muralidhara H. Membrane Technology: A Practical Guide to Membrane Technology and Applications in Food and Bioprocessing. Burlington: Elsevier, 2010, 1–270
550. Yilbas B S. The Laser Cutting Process: Analysis and Applications. Amsterdam: Elsevier, 2017, 5–311
551. Rezzadori K, Penha F M, Proner M C, Zin G, Petrus J C, Di Luccio M. Impact of organic solvents on physicochemical properties of nanofiltration and reverse-osmosis membranes. Chemical Engineering & Technology, 2019, 42(12): 2700–2708
552. Zhang Y T, Dai X G, Xu G H, Zhang L, Zhang H Q, Liu J D, Chen H L. Modeling of CO_2 mass transport across a hollow fiber membrane reactor filled with immobilized enzyme. AIChE Journal. American Institute of Chemical Engineers, 2012, 58(7): 2069–2077
553. Zhang Y T, Zhang L, Chen H L, Zhang H M. Selective separation of low concentration CO_2 using hydrogel immobilized CA enzyme based hollow fiber membrane reactors. Chemical Engineering Science, 2010, 65(10): 3199–3207
554. Singh R. Membrane Technology and Engineering for Water Purification: Application, Systems Design and Operation. Oxford: Butterworth-Heinemann, 2014, 1–300