Renewable and Sustainable Energy Reviews 68 (2017) 659–684

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Process and engineering trends in membrane based carbon capture

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ARTICLE INFO

Keywords:
Membrane carbon capture
Synthesis
Characterization
Modeling and simulation
Contactor design

ABSTRACT

Global warming due to greenhouse gases mostly carbon dioxide has become a serious concern worldwide. Carbon capture using adsorption, absorption, chemical looping combustion, cryogenic and membrane separations has been widely studied to tackle this problem. Significant research efforts have been made in membrane based carbon capture employable in both pre- and post-combustion options as it is a simple, efficient economical and environmentally benign option. In this paper, a comprehensive review has been done on this technology with reference to various aspects viz., synthesis, characterization and performance analysis of various membrane materials, contactors and their design aspects, modeling and simulation studies and membrane wetting phenomenon. The prospects and future challenges of the membrane based carbon capture are also highlighted.

1. Introduction

Carbondioxide (CO_2) being one of the most harmful gases in the world, is an integral part of most of the flue gases from industries. It's rising levels in the atmosphere could be attributed to increasing industrial demands and various natural processes like volcanoes, ocean temperature oscillations, fires, etc [1,2]. Industries play a predominant factor and contributes to nearly 40% of all CO_2 emissions in the world, with reports suggesting that the main contributors being the power and cement industries [3,4]. A study suggests that a 600MW coal fired power plant could generate flue gases at a rate of 500 m^3/s, a significant constituent of which is CO_2 [5]. Concentration in the

Abbreviations: 1D, One Dimensional; 2D, Two Dimensional; 40MCO–60CPO, Mn1.5Co1.5O4-$^{\delta}$–60 wt%Ce0.9Pr0.1O2-$^{\delta}$; 60CGO–40BSCF, Ce0.9Gd0.1O2–δ–40 wt% Ba0.5Sr0.5Co0.8- Fe0.2O3–δ; 6FBPA, Hexafluorobisphenol A; 6FPPy, 2,6-bis(trifluoromethylphenylene)pyridine; 6FPT, 2,5-bis(3-trifluoromethylphenylene)thiophene; AFM, Atomic Force Microscopy; AFRC-AHIE, Aqueous free radical copolymerization followed by acid hydrolysis and ion exchange; AMP, 2-amino-2-methyl-1-proponol; APTS, (3-Aminopropyl) triethoxysilane; ATR, Attenuated total reflectance; BBL, polybenzimidazo-benzoisoquinoline; BET, Brunauer- Emmet- Teller; CaLS, Calcium lignosulfonate; CAP, Continuous Assembly of Polymers; CC, Carbon Capture; CCP, Carbon Capture Project; CCS, Carbon Capture and Sequestration; CLC, Chemical Looping Combustion; CNT, Carbon Nano Tube; DEA, Diethanolamine; DJWSP, Dry jet/wet spinning process; DMAc N NAPDE, Nonlinear Algebraic Partial Differential Equation; NELF, Non-Equilibrium Lattice Fluid;N-Dimethyl acetamide; DMAEMA-AA, dimethylaminoethyl methacrylate- acrylic acid; DME, Dimethyl ether; DNMDAm, 3,3_-Diamino-N-methyldipropylamine; DSC, Differential scanning calorimetry; EDTA, Ethylenediaminetetraacetic acid; EDS, Energy Dispersion Spectrometer; EDXS, Energy dispersive X-ray spectroscopy; EOR, Enhance Oil Recovery; ESEM, Environmental scanning electron microscope; FESEM, Field Emission Scanning Electron Microscopy; FFV, Fractional free volume; FTIR, Fourier Transform Infrared Spectroscopy; FVM, Finite Volume Method; GO, Graphene Oxide; HFPSF, Hexafluoropolysulfone; ICP, Inductive coupled plasma; IEA, International Energy Agency; IR, Infra-Red; KJS, Kruk-Jaronaic-Sayari; Ksar, Potassium sarcosinate; LBLST-SGC, Layer-by layer seeding technique followed by secondary growth crystallization; LEP, Liquid Entry Pressure; LOMOMS, Layering of membrane on mullite support; MDEA, Methyl diethanolamine; MEA, Monoethanolamine; MIP, Mercury Intrusion Porosimetry; MMM, Mixed Matrix Membranes; MS-U, Mass Trasfer based UNIQUAC; MNWT, Multi-walled nanotubes; MWCNT, Multiwall Carbon Nanotubes; NF/RO, Nano filtration/Reverse Osmosis; NMP, N-Methyl-2-pyrrolidone; P (DAD- MACA-co-VAm), Poly (diallyldimethylammonium carbonate-co-vinylamine); PAMAM, Poly(amidoamine); PANI, Polyaniline; PBI, Polybenzimidazole; PBI, Polybenzimidazole; PDMAEMA, poly (N, N-dimethylaminoethyl methacrylate); PDMS, Poly (dimethyl siloxane); PDU, Process development unit; PE, Polyethylene; Pebax, Polyether block amide; PEDOT, Poly(3,4-ethylenedioxythiophene); PEG, Polyethylene glycol; PEGDA, Polyethylene (glycol) Diacrylate; PEGDMA, PEG dimethacrylates; PEGDME, Poly (ethylene glycol) dimethyl ether; PEI, Polyetherimide; PEO, Poly ethylene oxide; PFA, Polyfluoroaniline; PIL, Polymeric Ionic Liquid; PIM, Porous Intrinsic Membrane; PPG, Polypropylene glycol; PSA, Pressure Swing Adsorption; PSf, Polysulfone; PSS, Polystyrene sulfonate; PTFE, Poly(tetrafluoroethylene); PVA, Poly (vinyl alcohol); PVDF, Polyvinylidene fluoride; QSPR, Quantitative Structure Property Relationship; RF, Radio frequency; RO, Reverse Osmosis; RTIL, Room Temperature Ionic Liquid; SCFR, Semi continuous flow reactor; SDA, Structure-directing agent; SEM, Scanning electron microscopy; SILM, Supported Ionic Liquid Membrane; SLM, Supported Liquid Membranes; SMM, Surface Modifying Macromolecules; STEM, Scanning transmission electron microscopy; TAB, 1,3,5-triaminophenoxybenzene; TEM, Transmission electron microscopy; TFC, Thin Film Composite; TFE, Tetrafluoroethylene; TGA, Thermal gravimetric analysis; TMC, trimesoyl chloride; TMF, Tetrahydrofuran; TMHFPC, Tetramethylhexafluorocarbonate; TMMPD, Trimethyl-w-phenylenediamine; TR, Thermally Rearranged; TRIS, 3-[Tris-(trimethylsiloxy)silyl] propyl acrylate; TSA, Temperature Swing Adsorption; TTD, 2,2,4-trifluoro-5-trifluorometoxy-1,3-dioxole; UTFC, Ultra-thin film composite; UV SPEC, Ultra violet spectroscopy; WGS, Water Gas Shift; WGSMR, Water-gas shift membrane reactor XPS, X-ray photoelectron spectroscopy; XRD, X-ray diffractometer; XRF, X-ray fluorescent spectroscopy; ZA, Zinc Acetate; ZC, Zinc Chloride; ZN, Zinc Nitrate

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http://dx.doi.org/10.1016/j.rser.2016.10.025
Received 20 January 2016; Received in revised form 8 October 2016; Accepted 16 October 2016
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Nomenclature

P_A	Permeability
D_A	Diffusivity
S_A	Sorption Coefficient
T	Temperature
Δp	Pressure gradient
η	CO_2 capture ratio
K_{ov}	Overall mass transfer coefficient
u_g	Interstitial gas velocity
A	Specific interfacial area
$C_{CO2,l}$	Concentration of CO_2 in liquid phase
$C_{CO2,g}$	Concentration of CO_2 in gas phase
Q_g	Flow rate of gas phase
K	local mass transfer coefficient
S_{Shell}	Module area without fibers
y_{co2}	Volume fraction of CO_2 in gas phase
P_g	Gas phase pressure
Q_l	Flow rate of liquid phase
$C_{MEA,\ l}$	Concentration of MEA in liquid phase
$u_{z,l}$	Liquid velocity at coordinate z
r	Radial coordinate
D_l	Coefficient of diffusion of CO_2 in liquid phase
D_{MEA}	Diffusion coefficient of MEA in liquid phase
R_{CO2}	Reaction rate of CO_2 with MEA
$u_{z,g}$	Gas velocity at coordinate z
D_{meff}	Effective CO_2 diffusion in membrane
S^{∞}	Infinite dilution solubility coefficient
$\alpha_{CO2/CH4}$	Selectivity of CO_2/CH_4
$\alpha_{CO2/N2}$	Selectivity of CO_2/N_2
β	Pore geometry coefficient
$_{\gamma}$	Liquid surface tension
θ	Contact angle
d_{max}	Maximum pore diameter
P	Permeance
Δp	Pressure difference across membrane;

Unit conversions

1 Barrer	3.348×10^{-19} kmol m/(m^2 s Pa)
1 GPU	10^{-6} cm^3(STP)/cm^2 s (cm Hg))
1 psig/psia	6894.76 Pa
1 atm	101325 Pa

atmosphere was just 280 ppm before the industrial era [6–9] and has reached its all-time high of 400 ppm in 2015 [10]. With no alternative in sight for fossil fuels and the demand for energy only increasing, we could expect this number to reach catastrophic limits soon. Moreover, the associated global temperature increase due to CO_2 emissions is projected to be somewhere between 1.4 to 5.8 °C by the start of the 22nd century [9], unless climate change policies are properly implemented. Thus, this level of rising CO_2 concentration may lead to catastrophic events and ecological imbalance [11].

To reduce the CO_2 emissions, three options available are reducing energy intensity, reducing carbon footprint and improving carbon capture and sequestration (CCS). First one requires an efficient use of energy which could be accomplished by reducing energy penalties in different industries while the second option requires finding alternatives to fossil fuels viz., wind energy, solar energy, tidal energy etc. Third option requires exploration of new methods of CO_2 capture and storage. With no possibility of large scale replacement of fossil fuels with alternate ones in the near future, CCS seems to be the only option for mitigating CO_2 emissions. Storage of CO_2 could be done in deep geological or oceanic sites [12–16], which reduces the chances of anthropogenic CO_2 emissions [17]. Alternatively, the captured CO_2 could also be used in many applications, viz., food and metal industries, EOR, chemical feedstock and solvent extraction [18–22]. Thus CC is the best solution available today to tackle rising CO_2 emissions. The practical application of CC technology in the boundary dam, Saskpower, Canada in 2014, [23], has not only reinforced this but has also led to fostering of research in this field.

CC could be broadly classified as post-, pre- and oxy-fuel combustion types. The process of removal of CO_2 depends on the type of combustion process used. It involves additional infrastructure requirement and energy penalty [24], and hence is an option only in large scale plants where the process could be economically viable. In post combustion method, CO_2 is removed from the flue gases after the fuel combustion. It is hence compatible with the existing power plants and requires only slight modifications. However, the energy penalty involved in this type of capture is large, as the concentration of CO_2 in flue gases is quite low [25–27]. Furthermore, though the concentration of CO_2 in these flue gases, varies owing to factors like fuel and process used, the gas is almost always present with a significant amount of SO_2, NO_2 and other constituents. Thus the energy penalty though varying with the process is always present. In contrast, in the pre-combustion method, the fuel goes through a process which eases the separation of CO_2 later. For example, gasification process is carried out so that fuels like natural gas are directly converted to syn-gas using reforming. Detailed studies are reported on the efficiency and cost analysis of CC in this case [28]. Oxy-fuel combustion uses pure oxygen instead of air, thereby lowers the concentration of NO_x formed. Hence flue gases in this case mainly consist of only water vapour, particulate matter, CO_2 and SO_2 [29]. The major drawback of this method however is the need of separation of O_2 from atmosphere for generating pure oxygen [30]. Also, since reduction of other gases, increases the concentration of SO_2, corrosion becomes a major issue. A recent study by IEA, projected that the proper implementation of CCP would lead to a 14% drop in the man-made greenhouse gas emissions [31].

There are several techniques available for the separation of CO_2 from flue gases, the most prominent ones being absorption, adsorption, CLC, cryogenic distillation and membrane separation.

Absorption involves the use of a liquid sorbent to separate CO_2 from flue gases. Later, the sorbent is recovered by stripping, heating or depressurization. This process has received a lot of attention from researchers and is the most developed technology till date [1,32–34]. Due to the extensive research done on this area, lot of sorbents are readily available today that suit most of the industrial scenarios [35]. The major drawback in absorption technique is the solvent loss due to amine degradation, which in turn produces volatile degrading compounds [36,37]. As an alternative, adsorption could be used as a viable method, where a solid sorbent is used instead for the CO_2 separation. The sorbent selection here is based on high surface area, high selectivity and high regeneration ability. CO_2 is later recovered from the sorbent by changing the temperature (TSA) [38,39] or pressure (PSA) [40–42]. PSA has shown an efficiency of 85% at a commercial scale recovery [43]. The scale of research done in this method is slowly increasing and search for novel sorbents from industrial and agricultural wastes is grabbing worldwide attention [44–47]. CLC is similar to oxy-fuel combustion but it uses an oxygen carrier like metal oxides for transferring oxygen from air to fuel. In the phase I of the CC project (CCP), CLC was reported to be one of the best alternatives for cost reduction [48]. The process involves two stages, i.e., oxidation and reduction. Initially, metal oxide gets reduced during the fuel combustion which is regenerated by oxidation in the presence of air. The main advantage of this method is that it generates a mixture of CO_2 and H_2O from which CO_2 could be easily separated by condensing water. Studies

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