PVDF-ALUMINA AND PVDF-BENTONITE HOLLOW FIBER MEMBRANE FOR CO_2 ABSORPTION VIA MEMBRANE CONTACTOR

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SUPERVISOR'S DECLARATION

We hereby declare that We have checked this thesis and in our opinion, this thesis is adequate in terms of scope and quality for the award of the degree of Master of Science in Chemical Engineering.

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I hereby declare that the work in this thesis is based on my original work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously or concurrently submitted for any other degree at Universiti Malaysia Pahang or any other institutions.

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ABSTRACT

PVDF hollow fiber membrane contactor system was improved by the addition of alumina and bentonite in terms of membrane structure and wetting resistance. Polyvinylidene fluoride (PVDF) polymer was modified by varying different concentration of alumina and bentonite (1 wt%, 3wt% and 5 wt%). Polymer dope solution (18 wt%) with various concentration of (alumina and bentonite) had been prepared and the hollow fiber membrane was fabricated using wet spinning process. CO_2 absorption was conducted using 1 M and 2 M of Monoethanolamine (MEA) as liquid absorbent. The hollow fiber membranes were characterized by using contact angle measurement, gas permeation test and tensile strength test to investigate the mechanical properties and membrane structure. Scanning electron microscope (SEM) and atomic force microscope (AFM) were used to investigate the membrane morphology and surface roughness of the membrane. The introduction of alumina and bentonite to polymer dope solution had improved the PVDF hollow fiber membrane characteristic, including membrane hydrophobicity and CO_2 absorption flux. The formation of sponge-like structure and finger-like structure in the membrane was developed by ranging different concentration of alumina and bentonite. Increasing the alumina and bentonite concentration in PVDF dope solution produced more sponge-like structure. The membrane with more sponge-like structure produced high hydrophobic membrane, reasonable mechanical strength, good gas permeability, high surface porosity, small in mean pore size and high absorption flux. The membranes surface roughness analyzed via atomic force microscope (AFM) showed that the mean surface roughness of the outer membrane was lower than inner membrane as the concentration of alumina and bentonite increased. PA5 and PB5 hollow fiber membranes possessed the highest contact angle values of 97.39° and 95.79°. PA5 and PB5 hollow fiber membrane showed the highest absorption flux in 1 M MEA of 3.89×10^{-2} mol/m^2.s and 4.08×10^{-2} mol/m^2.s at flow rate 200 ml/min, respectively. The CO_2 absorption was repeated by using 2 M MEA as absorbent. The absorption flux of PA5 and PB5 hollow fiber membrane had increased up to 6.12×10^{-2} mol/m^2.s and 6.35×10^{-2} mol/m^2.s, respectively. The long-term absorption test was conducted with PA5 and PB5 hollow fiber membranes in 2 M MEA for 60 hours. From the long-term CO_2 absorption flux, PA5 hollow fiber membrane showed much better performance than PB5 hollow fiber membrane. Therefore, PB5 membrane possessed a more sponge-like structure, high water contact angle, good mechanical strength, great gas permeability, high surface porosity with small mean pore size and demonstrated a higher absorption CO_2 flux is preferred for CO_2 membrane contactor application.

ABSTRAK

Pembasahan membran adalah masalah utama dalam aplikasi penyentuh bermembran untuk penyerapan karbon dioksida. Untuk mengatasi masalah ini, membran serat hidrofobik gabungan komposit telah dibangunkan. Polimer polivinilidena fluorida (PVDF) telah diubahsuai dengan memperkenalkan pelbagai jenis tanah liat organik termasuk alumina dan bentonit (1% berat, 3% berat dan 5% berat) dimasukkan ke dalam larutan polimer untuk menghasilkan membran hidrofobik. Larutan larutan polimer (18 wt%) dengan pelbagai kepekatan tanah liat organik (alumina dan bentonit) telah disediakan dan membran serat berongga dibuat dengan menggunakan proses berputar basah. Penyerapan CO_2 dilakukan menggunakan 1M dan 2M Monoethanolamine (MEA) sebagai cecair penyerap. Membran serat berongga dicirikan menggunakan pengukuran sudut sesentuh, ujian permeasi gas dan ujian kekuatan tarik untuk menyiasat sifat mekanik dan struktur membran. Pengimbasan mikroskop elektron (SEM) dan mikroskop tenaga atom (AFM) digunakan untuk menyiasat morfologi membran dan kekasaran permukaan membran. Pengenalan alumina dan bentonit kepada penyelesaian larutan polimer telah meningkatkan ciri PVDF membran serat berongga termasuk membran hidrofobisiti dan penyerapan CO_2. Pembentukan struktur seperti span dan jejari dalam membran telah dihasilkan oleh kepelbagai kepekatan alumina dan bentonit yang digunakan. Meningkatkan kepekatan alumina dan betonit dalam larutan larutan PVDF menghasilkan lebih banyak struktur span. Membran yang mempunyai lebih banyak struktur span telah menghasilkan membran yang tinggi hidrofobik, kekuatan mekanikal yang bagus, kebolehtelapan gas yang baik, keliangan permukaan yang tinggi, saiz liang yang kecil dan fluks penyerapan yang tinggi. Kekasaran permukaan membran yang dianalisis melalui mikroskop tenaga atom (AFM) menunjukkan bahawa kekasaran permukaan rata dari membran luar adalah lebih rendah daripada membran dalaman kerana kepekatan alumina dan bentonit meningkat. Membran serat berongga bagi PA5 dan PB5 mempunyai nilai sudut sesentuh tertinggi iaitu 97.39° dan 95.79°. Membran serat berongga bagi PA5 dan PB5 menunjukkan fluks penyerapan tertinggi dalam 1M MEA iaitu 3.89×10^{-2} mol / m^2.s dan 4.08×10^{-2} mol / m^2.s pada kadar aliran 200 mL/min. Penyerapan CO_2 diulang dengan menggunakan 2M MEA sebagai penyerap. Fluks penyerapan membran serat berongga bagi PA5 dan PB5 meningkat sehingga 6.12×10^{-2} mol / m^2.s dan 6.35×10^{-2} mol / m^2.s. Ujian penyerapan jangka panjang dilakukan dengan menggunakan membran serat berongga PA5 dan PB5 dalam 2M MEA selama 60 jam. Dari fluks penyerapan CO_2 bagi jangka masa yang panjang, membran serat berongga PA5 menunjukkan prestasi yang lebih baik daripada membran serat berongga PB5. Oleh itu, membran PB5 mempunyai lebih banyak struktur span, sudut sesentuh air yang tinggi, kekuatan mekanikal yang baik, kebolehtelapan gas yang hebat, keliangan permukaan yang tinggi dengan purata saiz liang yang kecil dan menunjukkan penyerapan CO_2 fluks yang lebih tinggi diberikan keutamaan dalam aplikasi penyentuh bermembran khas dalam penyerapan CO_2.

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LIST OF ABBREVATIONS

AFM	-	Atomic Force Microscopy
AMP	-	2-amino-2-methyl-1-propanol
CO_2	-	Carbon Dioxide
DEA	-	Diethanolamine
FAS		1H, 1H, 2H, 2H-perfluorooctyltriethoxysilane
KSar	-	Potassium sarcosinate
KOH	-	Potassium hydroxide
LiCl	-	Lithium chloride
$LiClO_4$		Lithium perchlorate
LEPw	-	Liquid entry pressure of water
MEA	-	Monoethanolamine
MDEA	-	Methyldiethanolamine
MIP	-	Mercury intrusion porosimetry
MMMs	-	Mixed matrix membranes
MMT	-	Montmorillonite
NaOH	-	Sodium hydroxide
NMP	-	N,N-dimethyl pyrolidone
PVDF	-	Polyvinyl fluoride
PE	-	Polyethylene
PEG	-	Polyethylene glycol
PEI	-	Polyetherimide
PP	-	Polypropylene
PTFE	-	Polytetrafluorethylene
PSF	-	Polysulfone
PES	-	Polyether sulfone
PAN	-	Polyacrylonitrile
PCN	-	Polyurethane/clay nanocomposite
SAPO	-	Silicoaluminophosphate
SEM	-	Scanning Electron Microscopy
SMM	-	Surface modified micromolecule
THAM	-	2-amino-2-hydroxymethyl-1,3-propanediol

TEA	-	Triethylamine
TEM	-	Transmission Electron Microscopy
TiO_2	-	Titanium Dioxide

LIST OF SYMBOLS

K_{ov}	-	Overall mass transfer coefficient (m/s)
d_i	-	Fiber internal diameter (m)
d_o	-	Fiber outer diameter (m)
d_{ln}	-	Log mean diameter of the fiber (m)
H	-	Henry's constant (mol/m^3 atm)
E	-	Enhancement factor
S_h	-	Sherwood number
D_L	-	Diffusion coefficient (m^2/s)
L	-	Effective length of the membrane (m)
Sc	-	Schmidt number
K_m	-	Membrane mass transfer coefficient (m/s)
$D_{g,eff}$	-	Effective diffusion coefficient of gas
Re	-	Reynold number
δ	-	Thickness of membrane (m)
τ	-	Tortuosity of the membrane
ε	-	Porosity of the membrane
d_h	-	Hydraulic diameter (m)
L	-	Active length of the membrane (m)
^oC	-	Celcius
J_{CO_2}	-	CO_2 absorption flux (mol/m^2s)
Q_l	-	Liquid flow rate (m^3/s)
A_i	-	Inner surface of the hollow fiber membranes (m^2)

REFERENCES

Abdulhameed, M. A., Othman, M. H. D., Ismail, A. F., Matsuura, T., Harun, Z., Rahman, M. A., & Hubadillah, S. K. (2017). Carbon dioxide capture using a superhydrophobic ceramic hollow fibre membrane for gas-liquid contacting process. *Journal of Cleaner Production*, *140*, 1731–1738. http://doi.org/10.1016/j.jclepro.2016.07.015

Acikyildiz, M., & Gurses, A. (2015). Synthesis of Super Hydrophobic Clay by Solution Intercalation Method from Aqueous Dispersions, *127*(4), 1156–1160. http://doi.org/10.12693/APhysPolA.127.1156

Ahmad, A. L., Ramli, W. K. W., Fernando, W. J. N., & Daud, W. R. W. (2012). Effect of ethanol concentration in water coagulation bath on pore geometry of PVDF membrane for Membrane Gas Absorption application in CO 2 removal. *Separation and Purification Technology*, *88*, 11–18. http://doi.org/10.1016/j.seppur.2011.11.035

Ahmad, N. A., Leo, C. P., Junaidi, M. U. M., & Ahmad, A. L. (2016). PVDF/PBI membrane incorporated with SAPO-34 zeolite for membrane gas absorption. *Journal of the Taiwan Institute of Chemical Engineers*, *63*, 143–150. http://doi.org/10.1016/j.jtice.2016.02.023

Ahmad, N. A., Mohd Noh, A. N., Leo, C. P., & Ahmad, A. L. (2017). CO_2 removal using membrane gas absorption with PVDF membrane incorporated with POSS and SAPO-34 zeolite. *Chemical Engineering Research and Design*, *118*, 238–247. http://doi.org/10.1016/j.cherd.2016.12.019

Amaral, R. A., Habert, A. C., & Borges, C. P. (2016). Performance evaluation of composite and microporous gas–liquid membrane contactors for CO_2 removal from a gas mixture. *Chemical Engineering and Processing: Process Intensification*, *102*, 202–209. http://doi.org/10.1016/j.cep.2016.01.018

Asfand, F., & Bourouis, M. (2015). A review of membrane contactors applied in absorption refrigeration systems. *Renewable and Sustainable Energy Reviews*, *45*, 173–191. http://doi.org/10.1016/j.rser.2015.01.054

Awanis Hashim, N., Liu, Y., & Li, K. (2011). Stability of PVDF hollow fibre membranes in sodium hydroxide aqueous solution. *Chemical Engineering Science*, *66*(8), 1565–1575. http://doi.org/10.1016/j.ces.2010.12.019

Bakeri, G., Ismail, A. F., Shariaty-Niassar, M., & Matsuura, T. (2010). Effect of polymer concentration on the structure and performance of polyetherimide hollow fiber membranes. *Journal of Membrane Science*, *363*(1–2), 103–111. http://doi.org/10.1016/j.memsci.2010.07.018

Bakeri, G., Matsuura, T., & Ismail, A. F. (2011). The effect of phase inversion promoters on the structure and performance of polyetherimide hollow fiber membrane using in gas-liquid contacting process. *Journal of Membrane Science*, *383*(1–2), 159–169. http://doi.org/10.1016/j.memsci.2011.08.048

Bastani, D., Esmaeili, N., & Asadollahi, M. (2013). Polymeric mixed matrix membranes containing zeolites as a filler for gas separation applications: A review. *Journal of Industrial and Engineering Chemistry*, *19*(2), 375–393. http://doi.org/10.1016/j.jiec.2012.09.019

Blath, J., Deubler, N., Hirth, T., & Schiestel, T. (2012). Chemisorption of carbon dioxide in imidazolium based ionic liquids with carboxylic anions. *Chemical Engineering Journal*, *181–182*, 152–158. http://doi.org/10.1016/j.cej.2011.11.042

Boributh, S., Jiraratananon, R., & Li, K. (2013). Analytical solutions for membrane wetting calculations based on log-normal and normal distribution functions for CO_2 absorption by a hollow fiber membrane contactor. *Journal of Membrane Science*, *429*, 459–472. http://doi.org/10.1016/j.memsci.2012.11.074

Bougie, F., Iliuta, I., & Iliuta, M. C. (2014). Absorption of CO_2 by AHPD-Pz aqueous blend in PTFE hollow fiber membrane contactors. *Separation and Purification Technology*, *138*, 84–91. http://doi.org/10.1016/j.seppur.2014.10.006

Chen, S. C., Lin, S. H., Chien, R. Der, Wang, Y. H., & Hsiao, H. C. (2011). Chemical absorption of carbon dioxide with asymmetrically heated polytetrafluoroethylene membranes. *Journal of Environmental Management*, *92*(4), 1083–1090. http://doi.org/10.1016/j.jenvman.2010.08.014

Choi, S. H., Tasselli, F., Jansen, J. C., Barbieri, G., & Drioli, E. (2010). Effect of the preparation conditions on the formation of asymmetric poly(vinylidene fluoride) hollow fibre membranes with a dense skin. *European Polymer Journal*, *46*(8), 1713–1725. http://doi.org/10.1016/j.eurpolymj.2010.06.001

Conway, W., Bruggink, S., Beyad, Y., Luo, W., Melián-Cabrera, I., Puxty, G., & Feron, P. (2015). CO_2 absorption into aqueous amine blended solutions containing monoethanolamine (MEA), N,N-dimethylethanolamine (DMEA), N,N-diethylethanolamine (DEEA) and 2-amino-2-methyl-1-propanol (AMP) for post-combustion capture processes. *Chemical Engineering Science*, *126*, 446–454. http://doi.org/10.1016/j.ces.2014.12.053

Cui, Z., & deMontigny, D. (2017). Experimental study of carbon dioxide absorption into aqueous ammonia with a hollow fiber membrane contactor. *Journal of Membrane Science*, *540*(June), 297–306. http://doi.org/10.1016/j.memsci.2017.06.013

Das, B., Deogam, B., & Mandal, B. (2017). Absorption of CO_2 into novel aqueous bis(3-aminopropyl)amine and enhancement of CO_2 absorption into its blends with N -methyldiethanolamine. *International Journal of Greenhouse Gas Control*, *60*, 172–185. http://doi.org/10.1016/j.ijggc.2017.03.018

Das, R., Sondhi, K., Majumdar, S., & Sarkar, S. (2016). Development of hydrophobic clay–alumina based capillary membrane for desalination of brine by membrane distillation. *Journal of Asian Ceramic Societies*, *4*(3), 243–251. http://doi.org/10.1016/j.jascer.2016.04.004

Dindore, V. Y., Brilman, D. W. F., Feron, P. H. M., & Versteeg, G. F. (2004). CO_2 absorption at elevated pressures using a hollow fiber membrane contactor. *Journal of Membrane Science*, *235*, 99–109. http://doi.org/10.1016/j.memsci.2003.12.029

El-Naas, M. H., Al-Marzouqi, M., Marzouk, S. A., & Abdullatif, N. (2010). Evaluation of the removal of CO_2 using membrane contactors: Membrane wettability. *Journal of Membrane Science*, *350*(1–2), 410–416. http://doi.org/10.1016/j.memsci.2010.01.018

Faiz, R., El-Naas, M. H., & Al-Marzouqi, M. (2011). Significance of gas velocity change during the transport of CO_2 through hollow fiber membrane contactors. *Chemical Engineering Journal*, *168*(2), 593–603. http://doi.org/10.1016/j.cej.2011.01.029

Fashandi, H., Ghodsi, A., Saghafi, R., & Zarrebini, M. (2016). CO_2 absorption using gas-liquid membrane contactors made of highly porous poly(vinyl chloride) hollow fiber membranes. *International Journal of Greenhouse Gas Control*, *52*, 13–23. http://doi.org/10.1016/j.ijggc.2016.06.010

Feng, C. Y., Khulbe, K. C., Matsuura, T., & Ismail, A. F. (2013). Recent progresses in polymeric hollow fiber membrane preparation , characterization and applications. *Separation and Purification Technology*, *111*, 43–71. http://doi.org/10.1016/j.seppur.2013.03.017

Franco, J. A., David, D., Kentish, S. E., Perera, J. M., & Stevens, W. (2012). Polytetrafluoroethylene (PTFE) -Sputtered Polypropylene Membranes for Carbon Dioxide Separation in Membrane Gas Absorption : Hollow Fiber Configuration. *American Chemical Society*, *56*, 1376–1382.

Ghasem, N., Al-Marzouqi, M., & Duidar, A. (2012). Effect of PVDF concentration on the morphology and performance of hollow fiber membrane employed as gas-liquid membrane contactor for CO_2 absorption. *Separation and Purification Technology*, *98*, 174–185. http://doi.org/10.1016/j.seppur.2012.06.036

Ghasem, N., Al-marzouqi, M., & Rahim, N. A. (2012). Effect of polymer extrusion temperature on poly (vinylidene fluoride) hollow fiber membranes : Properties and performance used as gas – liquid membrane contactor for CO_2 absorption. *Separation and Purification Technology*, *99*, 91–103. http://doi.org/10.1016/j.seppur.2012.07.021

Hee, H., Raj, B., Won, I., & Keun, H. (2008). Absorption of SO_2 from flue gas using PVDF hollow fiber membranes in a gas – liquid contactor. *Journal of Membrane Science*, *319*, 29–37. http://doi.org/10.1016/j.memsci.2008.03.023

Hoff, K. A., & Svendsen, H. F. (2014). Membrane contactors for CO_2 absorption - Application, modeling and mass transfer effects. *Chemical Engineering Science, 116,* 331–341. http://doi.org/10.1016/j.ces.2014.05.001

Hou, D., Wang, J., Qu, D., Luan, Z., & Ren, X. (2009). Fabrication and characterization of hydrophobic PVDF hollow fiber membranes for desalination through direct contact membrane distillation. *Separation and Purification Technology*, *69*(1), 78–86. http://doi.org/10.1016/j.seppur.2009.06.026

Hou, D., Wang, J., Sun, X., Ji, Z., & Luan, Z. (2012). Preparation and properties of PVDF composite hollow fiber membranes for desalination through direct contact membrane distillation. *Journal of Membrane Science, 405*, 185–200. http://doi.org/10.1016/j.memsci.2012.03.008

Hu, L., Cheng, J., Li, Y., Liu, J., Zhang, L., Zhou, J., & Cen, K. (2017). Composites of ionic liquid and amine-modified SAPO 34 improve CO_2 separation of CO_2-selective polymer membranes. *Applied Surface Science*, *410*, 249–258. http://doi.org/10.1016/j.apsusc.2017.03.045

Huang, A., Chen, L. H., Chen, C. H., Tsai, H. Y., & Tung, K. L. (2018). Carbon dioxide capture using an omniphobic membrane for a gas-liquid contacting process. *Journal of Membrane Science*, *556*(March), 227–237. http://doi.org/10.1016/j.memsci.2018.03.089

Ismail, A. F., & Kumari, S. N. (2004). Potential effect of potting resin on the performance of hollow fibre membrane modules in a CO_2 / CH_4 gas separation system. *Journal of Membrane Science*, *236*, 183–191. http://doi.org/10.1016/j.memsci.2004.02.023

Jana, A., Bhattacharya, P., Guha, S., Ghosh, S., & Majumdar, S. (2017). Application of a new ceramic hydrophobic membrane for providing CO_2 in algal photobioreactor during cultivation of Arthrospira sp. *Algal Research*, *27*(December 2016), 223–234. http://doi.org/10.1016/j.algal.2017.08.030

Ji, J., Liu, F., Hashim, N. A., Abed, M. R. M., & Li, K. (2015). Poly(vinylidene fluoride) (PVDF) membranes for fluid separation. *Reactive and Functional Polymers*, *86*, 134–153. http://doi.org/10.1016/j.reactfunctpolym.2014.09.023

Jin, J., Rafiq, R., Gill, Y. Q., & Song, M. (2013). Preparation and characterization of high performance of graphene/nylon nanocomposites. *European Polymer Journal*, *49*(9), 2617–2626. http://doi.org/10.1016/j.eurpolymj.2013.06.004

Kang, G. dong, & Cao, Y. ming. (2014). Application and modification of poly(vinylidene fluoride) (PVDF) membranes - A review. *Journal of Membrane Science*, *463*, 145–165. http://doi.org/10.1016/j.memsci.2014.03.055

Khan, A. A., Halder, G. N., & Saha, A. K. (2015). Carbon dioxide capture characteristics from flue gas using aqueous 2-amino-2-methyl-1-propanol (AMP) and monoethanolamine (MEA) solutions in packed bed absorption and regeneration columns. *International Journal of Greenhouse Gas Control*, *32,* 15–23. http://doi.org/10.1016/j.ijggc.2014.10.009

Kim, Y., & Yang, S. (2000). Absorption of carbon dioxide through hollow fiber membranes using various aqueous absorbents. *Separation and Purification Technology*, *21*, 101–109.

Kong, J., & Li, K. (2001). An improved gas permeation method for characterising and predicting the performance of microporous asymmetric hollow fibre membranes used in gas absorption. *Journal of Membrane Science*, *182*(1), 271–281. http://doi.org/10.1016/S0376-7388(00)00573-1

Koonaphapdeelert, S., Wu, Z., & Li, K. (2009). Carbon dioxide stripping in ceramic hollow fibre membrane contactors. *Chemical Engineering Science*, *64*(1), 1–8. http://doi.org/10.1016/J.CES.2008.09.010

Korminouri, F., Rahbari-Sisakht, M., Rana, D., Matsuura, T., & Ismail, A. F. (2014). Study on the effect of air-gap length on properties and performance of surface modified PVDF hollow fiber membrane contactor for carbon dioxide absorption. *Separation and Purification Technology*, *132*, 601–609. http://doi.org/10.1016/j.seppur.2014.06.017

Li, J.-L., & Chen, B.-H. (2005). Review of CO_2 absorption using chemical solvents in hollow fiber membrane contactors. *Separation and Purification Technology*, *41*(2), 109–122. http://doi.org/10.1016/J.SEPPUR.2004.09.008

Li, Y., & Chung, T. S. (2010). Molecular-level mixed matrix membranes comprising Pebax® and POSS for hydrogen purification via preferential CO_2 removal. *International Journal of Hydrogen Energy*, *35*(19), 10560–10568. http://doi.org/10.1016/j.ijhydene.2010.07.124

Li, H. Bin, Shi, W. Y., Zhang, Y. F., Liu, D. Q., & Liu, X. F. (2014). Effects of additives on the morphology and performance of PPTA/PVDF in situ blend UF membrane. *Polymers*, *6*(6), 1846–1861. http://doi.org/10.3390/polym6061846

Liang, Z., Fu, K., Idem, R., & Tontiwachwuthikul, P. (2016). Review on current advances, future challenges and consideration issues for post-combustion CO_2 capture using amine-based absorbents. *Chinese Journal of Chemical Engineering*, *24*(2), 278–288. http://doi.org/10.1016/j.cjche.2015.06.013

Lin, D., Chang, C., Huang, F., & Cheng, L. (2003). Effect of salt additive on the formation of microporous poly (vinylidene fluoride) membranes by phase inversion from LiClO 4 / Water / DMF / PVDF system. *Polymer*, *44*, 413–422.

Lin, D., Chang, C., Lee, C., & Cheng, L. (2006). Preparation and characterization of microporous PVDF / PMMA composite membranes by phase inversion in water / DMSO solutions. *European Polymer Journal*, *42*, 2407–2418. http://doi.org/10.1016/j.eurpolymj.2006.05.008

Lin, Y., Chen, C., Tung, K., Wei, T., & Lu, S. (2013). Mesoporous Fluorocarbon-Modified Silica Aerogel Membranes Enabling Long-Term Continuous CO_2 Capture with Large Absorption Flux Enhancements. *ChemPubSoc Europe*, 437–442. http://doi.org/10.1002/cssc.201200837

Lin, Y. F., Ye, Q., Hsu, S. H., & Chung, T. W. (2016). Reusable fluorocarbon-modified electrospun PDMS/PVDF nanofibrous membranes with excellent CO_2 absorption performance. *Chemical Engineering Journal*, *284*, 888–895. http://doi.org/10.1016/j.cej.2015.09.063

Lin, Y., Xu, Y., Loh, C. H., & Wang, R. (2018). Development of robust fluorinated TiO_2/PVDF composite hollow fiber membrane for CO_2 capture in gas-liquid membrane contactor. *Applied Surface Science*, *436*, 670–681. http://doi.org/10.1016/j.apsusc.2017.11.263

Liu, F., Hashim, N. A., Liu, Y., Abed, M. R. M., & Li, K. (2011). Progress in the production and modification of PVDF membranes. *Journal of Membrane Science, 375*(1–2), 1–27. http://doi.org/10.1016/j.memsci.2011.03.014

Lu, J. G., Lu, Z. Y., Chen, Y., Wang, J. T., Gao, L., Gao, X., & Liu, D. G. (2015). CO_2 absorption into aqueous blends of ionic liquid and amine in a membrane contactor. *Separation and Purification Technology*, *150*, 278–285. http://doi.org/10.1016/j.seppur.2015.07.010

Lu, Wang, Sun, Li, & Liu. (2005). Absorption of CO_2 into Aqueous Solutions of Methyldiethanolamine and Activated Methyldiethanolamine from a Gas Mixture in a Hollow Fiber Contactor. *Industrial & Engineering Chemistry Research*, *44*(24), 9230–9238. http://doi.org/10.1021/ie058023f

Lv, Y., Yu, X., Jia, J., Tu, S., Yan, J., & Dahlquist, E. (2012). Fabrication and characterization of superhydrophobic polypropylene hollow fiber membranes for carbon dioxide absorption. *Applied Energy*, *90*(1), 167–174. http://doi.org/10.1016/j.apenergy.2010.12.038

Lv, Y., Yu, X., Tu, S.-T., Yan, J., & Dahlquist, E. (2010). Wetting of polypropylene hollow fiber membrane contactors. *Journal of Membrane Science*, *362*(1–2), 444–452. http://doi.org/10.1016/j.memsci.2010.06.067

Mansourizadeh, A. (2012). Experimental study of CO_2 absorption/stripping via PVDF hollow fiber membrane contactor. *Chemical Engineering Research and Design*, *90*(4), 555–562. http://doi.org/10.1016/j.cherd.2011.08.017

Mansourizadeh, A., Aslmahdavi, Z., Ismail, A. F., & Matsuura, T. (2014). Blend polyvinylidene fluoride/surface modifying macromolecule hollow fiber membrane contactors for CO_2 absorption. *International Journal of Greenhouse Gas Control*, *26*, 83–92. http://doi.org/10.1016/j.ijggc.2014.04.027

Mansourizadeh, A., & Ismail, A. F. (2010). 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*, *165*(3), 980–988. http://doi.org/10.1016/j.cej.2010.10.034

Mansourizadeh, A., & Ismail, A. F. (2010). 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, 165*(3), 980–988. http://doi.org/10.1016/j.cej.2010.10.034

Mansourizadeh, A., & Ismail, A. F. (2011). 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, 5*(4), 640–648. http://doi.org/10.1016/j.ijggc.2011.03.009

Marzouk, S. A. M., Al-marzouqi, M. H., El-naas, M. H., Abdullatif, N., & Ismail, Z. M. (2010). Removal of carbon dioxide from pressurized CO_2 – CH_4 gas mixture using hollow fiber membrane contactors. *Journal of Membrane Science*, *351*(1–2), 21–27. http://doi.org/10.1016/j.memsci.2010.01.023

Mcdonald, T. M., Lee, W. R., Mason, J. A., Wiers, B. M., Hong, C. S., & Long, R. (2012). Capture of Carbon Dioxide from Air and Flue Gas in the Alkylamine-Appended Metal − Organic Framework mmen-Mg_2(dobpdc). *Journal of the American Chemical Society*, *134*, 7056–7065.

Morihama, A. C. D., & Mierzwa, J. C. (2014). Clay nanoparticles effects on performance and morphology of poly(vinylidene fluoride) membranes. *Brazilian Journal of Chemical Engineering*, *31*(1), 79–93.

Mosadegh-Sedghi, S., Rodrigue, D., Brisson, J., & Iliuta, M. C. (2014). Wetting phenomenon in membrane contactors - Causes and prevention. *Journal of Membrane Science*, *452*, 332–353. http://doi.org/10.1016/j.memsci.2013.09.055

Naim, R., & Ismail, A. F. (2013). Effect of polymer concentration on the structure and performance of PEI hollow fiber membrane contactor for CO_2 stripping. *Journal of Hazardous Materials*, *250–251*(July 2015), 354–361. http://doi.org/10.1016/j.jhazmat.2013.01.083

Naim, R., Ismail, A. F., & Mansourizadeh, A. (2012a). Effect of non-solvent additives on the structure and performance of PVDF hollow fiber membrane contactor for CO_2 stripping. *Journal of Membrane Science*, *423–424*, 503–513. http://doi.org/10.1016/j.memsci.2012.08.052

Naim, R., Ismail, A. F., & Mansourizadeh, A. (2012b). Preparation of microporous PVDF hollow fiber membrane contactors for CO_2 stripping from diethanolamine solution. *Journal of Membrane Science*, *392–393*, 29–37. http://doi.org/10.1016/j.memsci.2011.11.040

Naim, R., Ismail, a. F., & Mansourizadeh, a. (2012c). Preparation of microporous PVDF hollow fiber membrane contactors for CO_2 stripping from diethanolamine solution. *Journal of Membrane Science*, *392–393*, 29–37. http://doi.org/10.1016/j.memsci.2011.11.040

Olajire, A. A. (2013). Valorization of greenhouse carbon dioxide emissions into value-added products by catalytic processes. *Journal of CO_2 Utilization*, *3–4*, 74–92. http://doi.org/10.1016/j.jcou.2013.10.004

Pang, H., Gong, H., Du, M., Shen, Q., & Chen, Z. (2018). Effect of non-solvent additive concentration on CO_2 absorption performance of polyvinylidenefluoride hollow fiber membrane contactor. *Separation and Purification Technology*, *191*(September 2017), 38–47. http://doi.org/10.1016/j.seppur.2017.09.012

Rahbari-sisakht, M., Ismail, A. F., Rana, D., & Matsuura, T. (2012). A novel surface modified polyvinylidene fluoride hollow fiber membrane contactor for CO_2 absorption. *Journal of Membrane Science*, *415–416*, 221–228. http://doi.org/10.1016/j.memsci.2012.05.002

Rahbari-Sisakht, M., Ismail, a. F., Rana, D., & Matsuura, T. (2012). A novel surface modified polyvinylidene fluoride hollow fiber membrane contactor for CO_2 absorption. *Journal of Membrane Science*, *415–416*(November), 221–228. http://doi.org/10.1016/j.memsci.2012.05.002

Rahim, N. A., Ghasem, N., & Al-Marzouqi, M. (2015). 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*, *26*, 108–117. http://doi.org/10.1016/j.jngse.2015.06.010

Rajabzadeh, S., Yoshimoto, S., Teramoto, M., Al-Marzouqi, M., & Matsuyama, H. (2009). CO_2 absorption by using PVDF hollow fiber membrane contactors with various membrane structures. *Separation and Purification Technology*, *69*(2), 210–220. http://doi.org/10.1016/j.seppur.2009.07.021

Rajabzadeh, S., Yoshimoto, S., Teramoto, M., Al-marzouqi, M., Ohmukai, Y., Maruyama, T., & Matsuyama, H. (2013). Effect of membrane structure on gas absorption performance and long-term stability of membrane contactors. *Separation and Purification Technology*, *108*, 65–73. http://doi.org/10.1016/j.seppur.2013.01.049

Ramazani, R., Samsami, A., Jahanmiri, A., Van der Bruggen, B., & Mazinani, S. (2016). Characterization of monoethanolamine + potassium lysinate blend solution as a new chemical absorbent for CO_2 capture. *International Journal of Greenhouse Gas Control*, *51*, 29–35. http://doi.org/10.1016/j.ijggc.2016.05.005

Razmjou, A., Arifin, E., Dong, G., Mansouri, J., & Chen, V. (2012). Superhydrophobic modification of TiO_2 nanocomposite PVDF membranes for applications in membrane distillation. *Journal of Membrane Science*, *415–416*, 850–863. http://doi.org/10.1016/j.memsci.2012.06.004

Rezaei, M., Ismail, A. F., Bakeri, G., Hashemifard, S. A., & Matsuura, T. (2015). Effect of general montmorillonite and Cloisite 15A on structural parameters and performance of mixed matrix membranes contactor for CO 2 absorption. *Chemical Engineering Journal*, *260*, 875–885. http://doi.org/10.1016/j.cej.2014.09.027

Rezaei, M., Ismail, A. F., Hashemifard, S. A., & Matsuura, T. (2014). Preparation and characterization of PVDF-montmorillonite mixed matrix hollow fiber membrane for gas-liquid contacting process. *Chemical Engineering Research and Design*, *92*(11), 2449–2460. http://doi.org/10.1016/j.cherd.2014.02.019

Rongwong, W., Fan, C., Liang, Z., Rui, Z., & Idem, R. O. (2015). Investigation of the effects of operating parameters on the local mass transfer coefficient and membrane wetting in a membrane gas absorption process. *Journal of Membrane Science*, *490*, 236–246. http://doi.org/10.1016/j.memsci.2015.04.071

Rongwong, W., Jiraratananon, R., & Atchariyawut, S. (2009). Experimental study on membrane wetting in gas-liquid membrane contacting process for CO_2 absorption by single and mixed absorbents. *Separation and Purification Technology*, *69*(1), 118–125. http://doi.org/10.1016/j.seppur.2009.07.009

Sharliza, N., Safaai, M., Noor, Z., Hashim, H., & Ujang, Z. (2011). Projection of CO_2 Emissions in Malaysia, (December). http://doi.org/10.1002/ep

Sistla, Y. S., & Khanna, A. (2013). Carbon dioxide absorption studies using amine-functionalized ionic liquids. *Journal of Industrial and Engineering Chemistry*, *20*(4), 2497–2509. http://doi.org/10.1016/j.jiec.2013.10.032

Songolzadeh, M., Soleimani, M., Ravanchi, M. T., & Songolzadeh, R. (2014). Carbon Dioxide Separation from Flue Gases : A Technological Review Emphasizing Reduction in Greenhouse Gas Emissions, *2014*(Figure 1).

Srinivasan, R. (2011). Advances in application of natural clay and its composites in removal of biological, organic, and inorganic contaminants from drinking water. *Advances in Materials Science and Engineering*, *2011*. http://doi.org/10.1155/2011/872531

Sukitpaneenit, P., & Chung, T.-S. (2012). PVDF/Nanosilica Dual-Layer Hollow Fibers with Enhanced Selectivity and Flux as Novel Membranes for Ethanol Recovery. *Industrial & Engineering Chemistry Research*, *51*(2), 978–993. http://doi.org/10.1021/ie202116h

Tan, X., Tan, S. P., Teo, W. K., & Li, K. (2006). Polyvinylidene fluoride (PVDF) hollow fibre membranes for ammonia removal from water. *Journal of Membrane Science*, *271*, 59–68. http://doi.org/10.1016/j.memsci.2005.06.057

Trends, F. (2009). Membrane Applications in Industrial Waste. In *Handbook of Membrane Separation* (pp. 823–825).

Trusov, A., Legkov, S., Van Den Broeke, L. J. P., Goetheer, E., Khotimsky, V., & Volkov, A. (2011). Gas/liquid membrane contactors based on disubstituted polyacetylene for CO_2 absorption liquid regeneration at high pressure and temperature. *Journal of Membrane Science*, *383*(1–2), 241–249. http://doi.org/10.1016/j.memsci.2011.08.058

Wang, L., Zhang, Z., Zhao, B., Zhang, H., Lu, X., & Yang, Q. (2013a). Effect of long-term operation on the performance of polypropylene and polyvinylidene fluoride membrane contactors for CO_2 absorption. *Separation and Purification Technology*, *116*, 300–306. http://doi.org/10.1016/j.seppur.2013.05.051

Wang, L., Zhang, Z., Zhao, B., Zhang, H., Lu, X., & Yang, Q. (2013b). Effect of long-term operation on the performance of polypropylene and polyvinylidene fluoride membrane contactors for CO_2 absorption. *Separation and Purification Technology*, *116*, 300–306. http://doi.org/10.1016/J.SEPPUR.2013.05.051

Wang, Z., Fang, M., Ma, Q., Yu, H., Wei, C. C., & Luo, Z. (2014). Investigation of membrane wetting in different absorbents at elevated temperature for carbon dioxide capture. *Journal of Membrane Science*, *455*, 219–228. http://doi.org/10.1016/j.memsci.2013.12.057

Wongchitphimon, S., Wang, R., Jiraratananon, R., Shi, L., & Loh, C. H. (2011). Effect of polyethylene glycol (PEG) as an additive on the fabrication of polyvinylidene fluoride-co-hexafluropropylene (PVDF-HFP) asymmetric microporous hollow fiber membranes. *Journal of Membrane Science*, *369*(1–2), 329–338. http://doi.org/10.1016/j.memsci.2010.12.008

Wu, X., Zhao, B., Wang, L., Zhang, Z., Zhang, H., Zhao, X., & Guo, X. (2016). Hydrophobic PVDF/graphene hybrid membrane for CO2 absorption in membrane contactor. *Journal of Membrane Science*, *520*, 120–129. http://doi.org/10.1016/j.memsci.2016.07.025

Wu, Y., Liu, Z., Herrera-Alonso, J. M., Marand, E., & Little, J. C. (2016). A new method to predict the effective diffusion coefficient of gases and vapors in polyurethane/clay nanocomposite membranes. *Journal of Membrane Science*, *510*, 201–208. http://doi.org/http://dx.doi.org/10.1016/j.memsci.2016.02.068

Xu, G., Liang, F., Yang, Y., Hu, Y., Zhang, K., & Liu, W. (2014). An improved CO_2 separation and purification system based on cryogenic separation and distillation theory. *Energies*, *7*(5), 3484–3502. http://doi.org/10.3390/en7053484

Yan, S., Fang, M.-X., Zhang, W.-F., Wang, S.-Y., Xu, Z.-K., Luo, Z.-Y., & Cen, K.-F. (2007). Experimental study on the separation of CO_2 from flue gas using hollow fiber membrane contactors without wetting. *Fuel Processing Technology*, *88*(5), 501–511. http://doi.org/10.1016/J.FUPROC.2006.12.007

Yan, S., Fang, M., Zhang, W., Wang, S., & Xu, Z. (2007). Experimental study on the separation of CO_2 from flue gas using hollow fiber membrane contactors without wetting, *88*, 501–511. http://doi.org/10.1016/j.fuproc.2006.12.007

Ye, C., Dang, M., Yao, C., Chen, G., & Yuan, Q. (2013). Process analysis on CO_2 absorption by monoethanolamine solutions in microchannel reactors. *Chemical Engineering Journal*, *225*, 120–127. http://doi.org/10.1016/j.cej.2013.03.053

Yeow, M. L., Liu, Y., & Li, K. (2005). Preparation of porous PVDF hollow fibre membrane via a phase inversion method using lithium perchlorate ($LiClO_4$) as an additive. *Journal of Membrane Science*, *258*, 16–22. http://doi.org/10.1016/j.memsci.2005.01.015

Yu, C. H., Huang, C. H., & Tan, C. S. (2012). A review of CO_2 capture by absorption and adsorption. *Aerosol and Air Quality Research*, *12*(5), 745–769. http://doi.org/10.4209/aaqr.2012.05.0132

Yu, K., Chung, T., & Gryta, M. (2008). Hydrophobic PVDF hollow fiber membranes with narrow pore size distribution and ultra-thin skin for the fresh water production through membrane distillation, *63*, 2587–2594. http://doi.org/10.1016/j.ces.2008.02.020

Zhang, J., Xu, Z., Mai, W., Min, C., Zhou, B., Shan, M., & Qian, X. (2013). Improved hydrophilicity, permeability, antifouling and mechanical performance of PVDF composite ultrafiltration membranes tailored by oxidized low-dimensional carbon nanomaterials. *Journal of Materials Chemistry A*, *1*(9), 3101. http://doi.org/10.1039/c2ta01415g

Zhang, Z. (2016). Comparisons of various absorbent effects on carbon dioxide capture in membrane gas absorption (MGA) process. *Journal of Natural Gas Science and Engineering*, *31*, 589–595. http://doi.org/10.1016/j.jngse.2016.03.052

Zhao, B., Su, Y., & Cui, G. (2016). Post-combustion CO_2 capture with ammonia by vortex flow-based multistage spraying: Process intensification and performance characteristics. *Energy*, *102*, 106–117. http://doi.org/10.1016/j.energy.2016.02.056

Zhao, S., Feron, P. H. M., Deng, L., Favre, E., Chabanon, E., Yan, S., & Qi, H. (2016). Status and progress of membrane contactors in post-combustion carbon capture: A state-of-the-art review of new developments. *Journal of Membrane Science*. http://doi.org/10.1016/j.memsci.2016.03.051

Ziobrowski, Z., Krupiczka, R., & Rotkegel, A. (2016). Carbon dioxide absorption in a packed column using imidazolium based ionic liquids and MEA solution. *International Journal of Greenhouse Gas Control*, *47*, 8–16. http://doi.org/10.1016/j.ijggc.2016.01.018