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Gas separation properties of crosslinked and non-crosslinked carboxymethylcellulose (CMC) membranes

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KEYWORDS
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Gas permeability;
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Abstract. In this study, crosslinked and non-crosslinked carboxymethylcellulose (CMC) membranes were prepared with different concentrations of polymer. Then, the permeability of pure CO_2, N_2, and CH_4 was measured through these membranes in dry state to investigate the influence of polymer concentration and applied feed pressure on permeability and permselectivity. The permeability of CO_2 through membranes was higher than the other gases. A comparison of permeabilities revealed that the permeability of N_2, CO_2, and CH_4 increased on an average of 33, 40 and 20 percent, respectivly, by increasing the feed pressure from 6 to 10 bar. Increasing CMC concentration from 1.2 to 3.0 wt%, the permeability of N_2, CO_2, and CH_4 decreased on an average of 25, 12 and 19 percent, respectivly. Also, the CO_2/CH_4 and CO_2/N_2 permselectivities increased 9 and 18 percent, respectivly, with an increment in CMC concentration from 1.2 to 3 wt%. The crosslinked CMC membranes with the same polymer concentrations were also prepared to investigate the effects of crosslinking reaction on permeability and permselectivity. The ATR-FTIR test was applied, and the peak at about 1108 cm^{-1} confirmed the presence of corsslinker groups. The comparision of gas permeation test results for crosslinked and non-crosslinked CMC membranes showed that the gas permeability decreased and its permselectivity increased due to crosslinking reaction. According to Robeson's plots, the prepared CMC membranes would have potential for commercialization.

1. Introduction

The separation and capture of CO_2 from flue gas and natural gas streams is an important process in industry. Also, the removing of CO_2 during steam reforming process of hydrocarbons is very important to produce high purity hydrogen [1]. The most common technology for CO_2 removal is amine absorption [2]. Membrane separation technology is an alternative approach withless energy consumption and lower capital cost [3-5]. In addition, the membrane process does not involve sorbent regeneration and there is no secondary waste product [6]. Moreover, Membrane-based separation processes have simple operating procedures versus amine absorption [7].

Many research activities have been made for preparation of novel membranes from various types of polymers. High CO_2 permeability, good selectivity in favor of CO_2 and mechanical and thermal stabilities of membrane should be concerned in preparation of an efficient membrane. Most of the researches have discussed about improving gas separation properties of membranes by:

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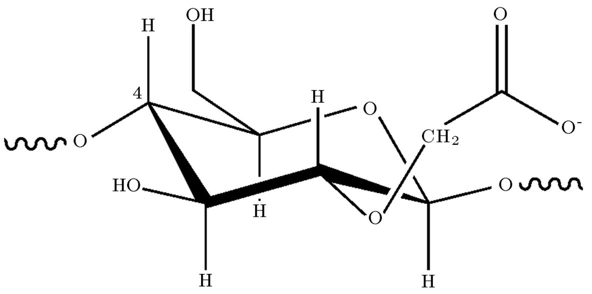

Figure 1. Structural unit of Carboxymethylcellulose (CMC).

(i) Changing chemical composition of materials;

(ii) Effectively controlling of membrane structure by controlling of preparation conditions.

Adding new bulky, electronegative and polar group into the macromolecules is an effective way to improve selectivity of the membrane [8]. Hydrogel compounds, due to their physical-chemical characterizations, have good potential for preparation of the membrane.

Hydrogels are hydrophilic polymer networks with incredibly absorption properties. Production of Soft Contact Lenses (SCLs) [9], food packaging [10], wound dressings [11], drug delivery [12] and humidification or dehumidification of gases are the most common applications of hydrogel materials. Hydrogels, due to their hydrophilic functional groups (see Figure 1), allow the passage of some types of molecules, while rejecting many others. There are many studies on possible use of hydrogel membrane for gas separation processes [13-16]. Feng et al. studied the role of water content in water-swollen hydrogel membranes (e. g. PVA, CMC, Chitosan). According to their investigations, comparing of hydrogel membranes in swell and dry states showed that the gases permeabilities through these membranes in dry state were lower than the swell state [6]. The ability to swell in water is an advantage of hydrogels, despite the poor mechanical properties of swollen hydrogels [16]. Tanaka et al. reported the weak mechanical strength of wet hydrogel membranes against dry ones [17]. Xing and Ho remarked that increasing the crosslinking degree of the membrane slightly decreased the CO_2 permeability [18]. Wijmans explained the importance of operational condition on membrane performance [19]. Many investigations have been made to show the influence of operational conditions, such as applied pressure [20,21]. Based on these reports, increasing pressure difference increases the permeability of membrane. In addition, in manner of capturing CO_2 from flue gas containing acid gases as impurities, water would cause reduction of membrane performance and stability [22].

The aim of this work is to prepare a hydrophilic membrane and then investigate the influence of preparation condition and applied pressure difference on membrane performance in case of CO_2 separation. Carboxymethylcellulose (CMC) is a hydrogel material with excellent hydrophilic property. CMC is a cellulose derivative with carboxymethyl groups bound to some of the hydroxyl groups of the glucose monomers that has high hydrophilic properties and intensive polarity, because of its hydroxyl and carboxylate groups. With respect to the hydrophilic property of CMC, it seems that CMC could be a suitable candidate for separation of gases with high interaction with polar groups, such as CO_2. As mentioned before, these membranes could have very good potential in some applications such as gas sweetening.

Hence, a set of non-crosslinked and crosslinked CMC membranes were prepared at different conditions, and then the permeability of pure CO_2, N_2 and CH_4 was measured through these membranes in dry state. The effects of preparation condition and feed pressure on these membrane performance were discussed.

2. Materials and methods

2.1. Materials

The polysaccharide carboxymethyl cellulose (CMC) with a Degree of Substitution (D.S), 0.52, was purchased from Merck. Distilled water was used as solvent. N_2 and CO_2 gases with 99.99% purity (Roham Gas Corp., Tehran, Iran), and ultra high purity CH_4 (Air Products Co.) were used in permeation experiments. Glutaraldehyde (25 wt.% in H_2O) was purchased from Sigma-Aldrich as crosslinking agent. All of materials were analytical grade.

2.2. Membrane preparation method

The CMC polymer were dissolved in distilled water at ambient temperature. The CMC powder was added into water slowly. The produced solution was decanted into a glass petri dish at room temperature, and dried for one day in a dust-free chamber. The decant process should have been done as quickly as possible to obtain uniform films. Finally, dried film was easily detached from the plate. A set of CMC membranes were prepared from solution mixtures of CMC polymer with different compositions. Table 1 shows the preparation conditions of CMC membrane.

The dry CMC membranes were crosslinked by immersion for 24 hours at room temperature in crosslinking solution (2 wt.% of Glutaraldehyde in water). At the end of crosslinking reaction period, the membranes were taken out of solution and washed out with distilled water.

2.3. Gas permeation test

Nitrogen, methane, and carbon dioxide permeabilities of the prepared membranes were measured using a constant pressure/variable volume method at room temperature.

Table 1. The preparation conditions of CMC membranes.

Sample number	Solvent volume	Amount of CMC (gr)	Polymer concentration	Crosslinking condition
1	50 cc	0.6	1.20%	-
2	50 cc	0.8	1.60%	-
3	50 cc	1.2	2.40%	-
4	50 cc	1.5	3.00%	-
5	50 cc	0.6	1.20%	Immersion in 2 wt% of GA solution
6	50 cc	0.8	1.60%	Immersion in 2 wt% of GA solution
7	50 cc	1.2	2.40%	Immersion in 2 wt% of GA solution
8	50 cc	1.5	3.00%	Immersion in 2 wt% of GA solution

Each gas was fed from high pressure cylinders to a stainless steel membrane cell. The membranes were fastened between cell plates by nuts and bolts. The feed pressure was regulated with 6, 8 and 10 bar, and permeates were collected at atmospheric pressure. The gas permeability of each membrane in their dry state was determined from the following equation [6,8]:

$$P = \frac{ql}{\Delta pA}, \tag{1}$$

where P is the gas permeability in barrer (1 barrer = 10^{-10} cm^3 (STP) cm/cm^2 s cmHg), q is the permeation flowrate (cm^3 (STP)/s), l is the membrane thickness (cm), Δp is the pressure difference between feed and permeate sides (cmHg), and A is the effective membrane area (cm^2).

The ideal gas selectivity, $\alpha_{A,B}$ (permselectivity), of pair gases A and B was calculated by the following equation:

$$\alpha_{A,B} = \frac{P_A}{P_B}, \tag{2}$$

where P_A and P_B are the gas permeabilities of A and B gases, respectively.

Reproducibility and repeatability of the data were checked randomly in some occasions, and a maximum variability of 17% demonstrated a fair level of reproducibility and repeatability in the experimentation.

2.4. ATR-FTIR test method

The ATR-FTIR spectra were obtained on a Fourier Transform Infrared spectrometer (EQUINOX 55, Bruker, Germany). The Attenuated Total Reflectance accessory (ATR) was mounted into the sample compartment. The internal reflection crystal, made of zinc selenide (ZnSe), had a 45° angle of incidence to the IR beam. Spectra were acquired at a resolution of 2 cm^{-1}, and the measurement range was 4000-700 cm^{-1}. All experiments were performed in triplicate at ambient temperature, 25 ± 2° C.

3. Results and discussion

Permeability of non-crosslinked CMC membranes with respect to N_2, CH_4 and CO_2 gases were studied at different feed pressures, and the results are summarized in Table 2. According to these results, carbon dioxide and nitrogen have the highest and lowest permeabilities, respectively. These results can be discussed by the condensability and kinetic diameter of the applied gases. Table 3 shows the condensability and kinetic diameter of N_2, CH_4 and CO_2. According to Table 3, Carbon dioxide has the highest permeability due to its low kinetic diameter and high condensability. The permeability of CH_4 is always higher than that of N_2, in spite of its bigger molecular size. The reason of this

Table 2. Gas permeability of CMC membranes at different feed pressures.

	Permeability (Barrer)								
	Feed pressure = 6 bar			Feed pressure = 8 bar			Feed pressure = 10 bar		
CMC concentration	N_2	CH_4	CO_2	N_2	CH_4	CO_2	N_2	CH_4	CO_2
1.20%	1041	2947	8901	1225	3211	10660	1402	3424	12294
1.60%	979	2687	8706	1112	3091	10370	1244	3224	11994
2.40%	826	2442	8254	996	2888	10098	1105	2976	11606
3.00%	776	2290	7809	899	2597	9124	1055	2832	11130

Table 3. Physical properties of penetrants [8].

Gas	Kinetic diameter (Å)	Condensability (K)
Carbon dioxide	3.3	195
Methane	3.8	149
Nitrogen	3.64	71

matter should be the higher condensability of CH_4 in comparison with N_2.

The gas permeability depends on some physico-chemical factors of membrane structure, such as the presence of electronegative and polar groups in the polymer backbone and bulky or polar side-groups linked to the main chain of the polymer [7,14,16,23,24]. In case of CMC membranes, the presence of polar carboxyl groups bounded to some hydroxyl groups of glucose monomers (shown in Figure 1) enhances the solubility of CO_2 due to the increased interaction between this gas and the polymer. This fact helps CO_2 molecules to have higher permeability through CMC membranes.

Figures 2, 3 and 4 show the effect of feed pressure on the N_2, CH_4 and CO_2 permeabilities, respectively. Increasing feed pressure can increase the amount of gas molecules on the membrane surface. This phenomenon leads to more gas molecules available to interact with polar groups of CMC polymer chain. Based on these figures, the permeability of all three gases were increased by increasing the feed pressure. The permeability of methane evidently changes with feed pressure, because of its high condensability and consequently high solubility.

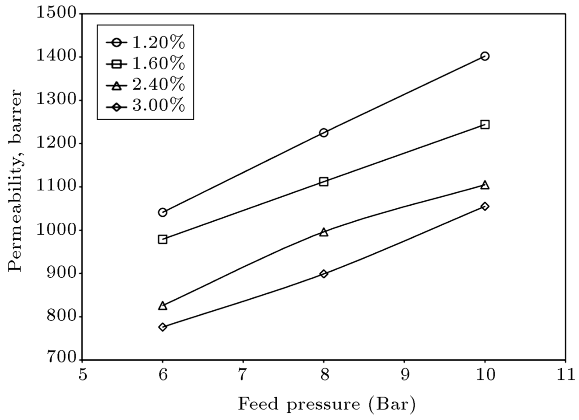

Figure 2. Permeability of pure nitrogen gas through non-crosslinked CMC membranes.

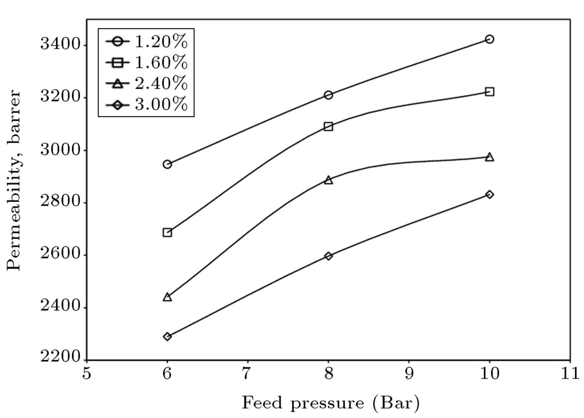

Figure 3. Permeability of pure methane gas through non-crosslinked CMC membranes.

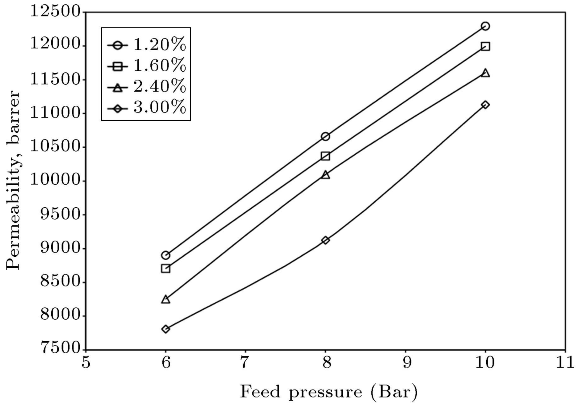

Figure 4. Permeability of pure carbon dioxide gas through non-crosslinked CMC membranes.

According to solid lines in Figure 5, a comparison of gas permeabilities through membranes prepared at different concentrations revealed that the permeability of each gas decreased as polymer concentration increased. With respect to the direct relationship of gas permeation and membrane free volume [15,24], indirectly, it can be concluded that an increment in concentration of CMC polymer decreases the free volumes in membrane, and the membrane with more free volumes shows higher diffusivity. As the amount of polar groups at membrane surface does not change with polymer concentration, the solubility of gases is relativly constant, and hence the difference in gas

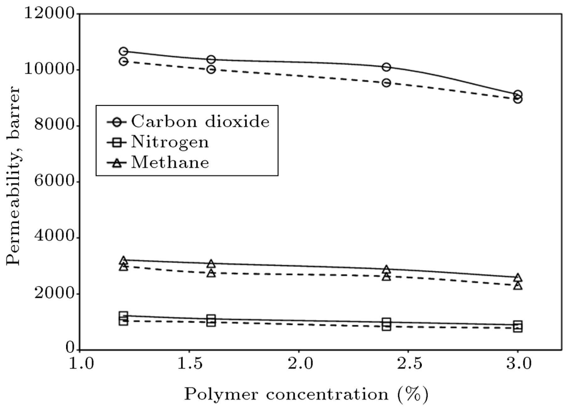

Figure 5. Gas permeability of crosslinked (dashed lines) and non-crosslinked (solid lines) CMC membranes at 8 bar feed pressure.

permeability of membranes should be related to the diffusivity effects.

Considering the small difference of N_2 and CH_4 permeabilities, it can be concluded that the diffusivity effect is small due to high kinetic diameters of these gases. But, the considerable difference of CO_2 permeability at different concentrations of polymer reveales that the polymer concentation and consequently free volumes of membrane have important effect on CO_2 diffusivity, because of its low kinetic diameter.

The results of gas permeability through membranes with different CMC concentrations for other feed pressures (6 bar and 10 bar) are similar to that of the 8 bar.

The permselectivity values of CO_2/CH_4 and CO_2/N_2 of non-crosslinked CMC membranes at 6, 8 and 10 bar feed pressure are reported in Figure 6. These data show that permselectivity of the CO_2/N_2 and CO_2/CH_4 increased considerably by increasing the CMC concentration. As mentioned before, by increasing the CMC concentration, the diffusivity of CO_2 increased more than the other gases.

The effect of feed pressure on CO_2/N_2 and CH_4/N_2 permselectivity of CMC membranes is shown in Figure 7. The CH_4/N_2 permselectivity is approximately constant with an increament in the feed pressure in the range of 6 to 10 bar. However, the CO_2/N_2 permselectivity increased from 8.80 to 9.65 in this range of feed pressure. These observations was made up from this fact that the pressure had no significant effect on the permeability of N_2 and CH_4, while the permeability of CO_2 increased with pressure, as shown in Figure 4.

There are numerous hydroxyl groups on the chain of CMC polymer that has the potential to react with glutaraldehyde (GA) to form crosslinked membrane. The products of crosslinking reaction have complex structures and are considered to form interpenetrated-interconnected networks [25].

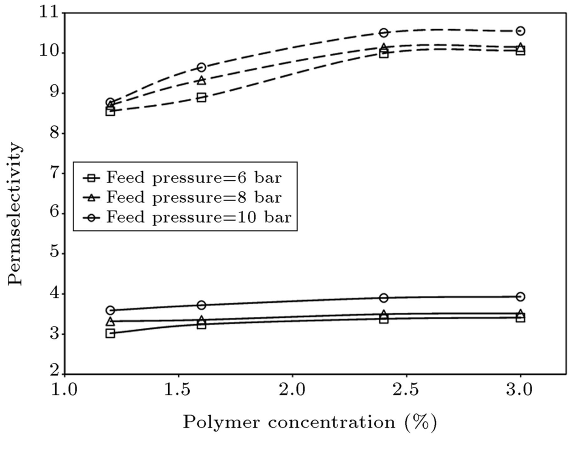

Figure 6. CO_2/N_2 (dashed lines) and CO_2/CH_4 (solid lines) permselectivities of non-crosslinked CMC membranes at different feed pressures.

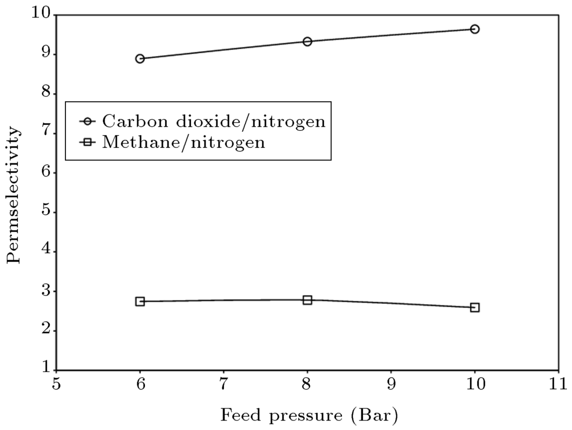

Figure 7. CO_2/N_2 and CH_4/N_2 permselectivity of non-crosslinked CMC membrane with 1.6% polymer concentration.

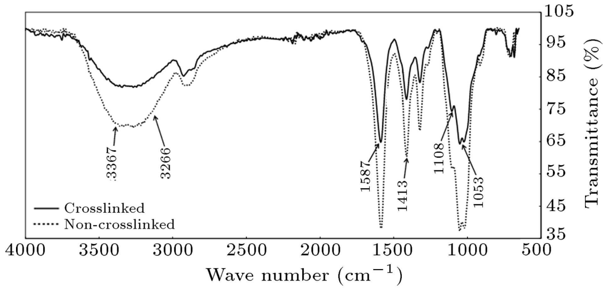

Figure 8. ATR-FTIR spectural data of crosslinked and non-crosslinked CMC membranes with 2.4% polymer concentration.

The ATR-FTIR spectral data of crosslinked and non-crosslinked CMC membranes with 2.4% polymer concentration are shown in Figure 8 to confirm the crosslinking reaction. The ATR-FTIR spectrum of both crosslinked and non-crosslinked membranes showed bands at about 3367 and 3266 cm^{-1}, because of O-H groups. Also, there were bands at about 1587, 1413 and 1053 cm^{-1} due to asymmetric and symmetric stretching of the carboxylate groups, and stretching vibrations of C-O-C groups, respectively.

There are numerous hydroxyl groups available on the macromolecular chains of CMC that may react with glutaraldehyde. These hydroxyl groups may give either semiacetal or acetal type rings, but the semiacetals are less stable than the acetals [25]. As shown in Figure 8, the peak at about 1108 cm^{-1} in crosslinked CMC membrane indicates that the C-O groups are inserted to polymer chains due to reaction between hydroxyl groups available on CMC chains and glutaraldehyde. Figure 9 shows this reaction mechanism.

The effect of crosslinking reaction has not been clearly determined, yet. However, a majority of literature reports suggest that crosslinking reduces gas permeability [15,16,19], and this should be considered as a result of formation of interpenetrated-interconnected

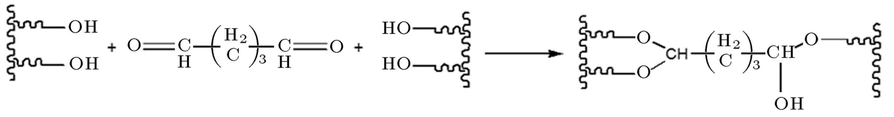

Figure 9. Crosslinking reaction of carboxymethylcellulose (CMC) with glutaraldehyde (GA).

networks. The formation of these interpenetrated-interconnected networks resulted in decreasing the pore size of membrane, and subsequently, the gas permeation is reduced.

The effect of crosslinking reaction on gas permeation of CMC membranes was shown in Figure 5. Also, formation of C-O-C groups in polymer chains intensify polarity of network, and the solubility of CO_2 increased due to enhanced interaction between CO_2 and crosslinked CMC membrane. Consequently, the CO_2/N_2 and CO_2/CH_4 permselectivities increased as shown in Figure 10.

Figures 11 and 12 show CO_2/CH_4 and CO_2/N_2 permselectivities versus permeability of CO_2 for 8 bar feed pressure, respectively. According to Figures 11 and 12, the data for all samples were placed below the Robeson's upper bound. The Robeson's plots show the maximum obtained permselectivities versus permeabilities of commercial membranes for different pair gasses [26]. Therefore, according to proximity of data samples to the upper bound of Robeson's plots, the prepared CMC membranes would be a potential candidate for comercial use.

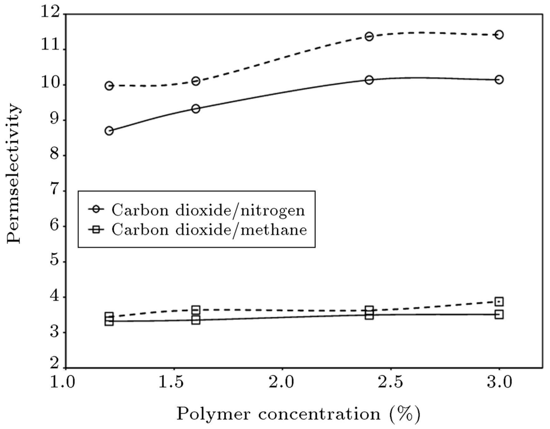

Figure 10. CO_2/N_2 and CO_2/CH_4 permselectivity of crosslinked (dashed lines) and non-crosslinked (solid lines) CMC membranes at 8 bar feed pressure.

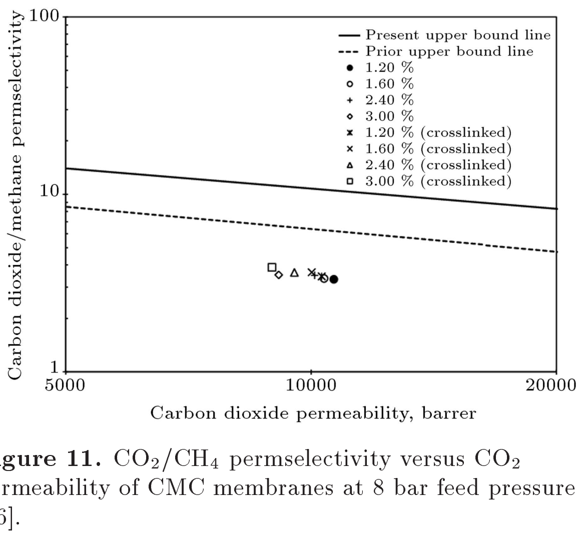

Figure 11. CO_2/CH_4 permselectivity versus CO_2 permeability of CMC membranes at 8 bar feed pressure [26].

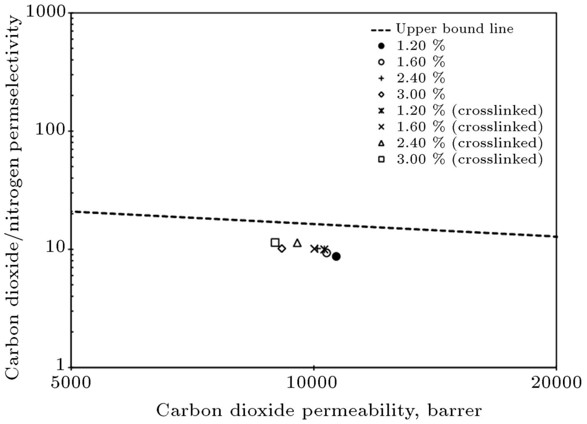

Figure 12. CO_2/N_2 permselectivity versus CO_2 permeability of CMC membranes at 8 bar feed pressure [26].

4. Conclusions

A set of membranes were prepared based on carboxymethylcellulose (CMC) and in a variety of polymer concentrations (1.2%, 1.6%, 2.4% and 3.0%). In addition, the crosslinked CMC membranes with the same polymer concentrations were made to investigate the effect of crosslinking. The occurance of crosslinking reaction was determined by ATR-FTIR test.

The permeability of CO_2, N_2 and CH_4 through each membrane was messured at 6, 8 and 10 bar of feed pressure. The permeability of CO_2 through each membrane was evidently higher than the permeabilities of other gases. Also, permeability of gases were increased with the feed pressure. The permeability of CO_2 increased more than the other gases with increasing the pressure. In other hand, gas permeability decreased as CMC concentration inceased.

The permselectivity of the CO_2/N_2 and CO_2/CH_4 increased considerably by increasing the CMC concentration. By comparing CO_2/N_2 and CH_4/N_2 permselectivity of CMC membranes, it was concluded that the pressure had no significant effect on the permeability of N_2 and CH_4, but the permeability of CO_2 increased with pressure.

The crosslinking reaction reduced the permeability of gases through crosslinked membranes, but enhanced the solubility of CO_2 in membrane. Consequently, the CO_2/N_2 and CO_2/CH_4 permselectivities were increased.

Eventually, according to Robeson's plots, prepared CMC membranes would have potential for commertialization.

References

1. Hu, X., Tang, J., Blasig, A., Shen, Y. and Radosz, M. "JCO_2 permeability, diffusivity and solubility in polyethylene glycol-grafted polyionic membranes and their CO_2 selectivity relative to methane and nitrogen", *Journal of Membrane Science*, **281**, pp. 130-138 (2006).
2. White, C.M., Strazisar, B.R., Granite, E.J., Hoffman, J.S. and Pennline, H.W. "Separation and capture of CO_2 from large stationary sources and sequestration in geological formations-coalbeds and deep saline aquifers", *Journal of the Air & Waste Management Association*, **53**, pp. 645-715 (2003).
3. Koros, W.J., Pinnau, I., Paul, D.R. and Yampol'skii, Y.P., *Polymeric Gas Separation Membranes*, CRC Press, Boca Raton, FL (1994).
4. Kesting, P.E. and Fritzsche, A.K., *Polymeric Gas Separation Membranes*, John Wiley & Sons, New York (1993).
5. Ho, W.S. and Sirkar, K.K., *Membrane Handbook*, Van Nostrand Reinhold, New York (1992).
6. Liu, L., Chakma A. and Feng, X. "Gas permeation through water-swollen hydrogel membranes", *Journal of Membrane Science*, **310**, pp. 66-75 (2008).
7. Wang, L., Cao, Y., Zhou, M., Zhou, S.J. and Yuan, Q. "Novel copolyimide membranes for gas separation", *Journal of Membrane Science*, **305**, pp. 338-346 (2007).
8. Mousavi, S.A., Sadeghi, M., Motamed-Hashemi, M.M.Y., Pourafshari Chenar, M., Roosta-Azad, R. and Sadeghi, M. "Study of gas separation properties of ethylene vinyl acetate (EVA) copolymer membranes prepared via phase inversion method", *Separation & Purification Technology*, **62**, pp. 642-647 (2008).
9. Hoch, G., Chauhan, A. and Radke, C.J. "Permeability and diffusivity for water transport through hydrogel membranes", *Journal of Membrane Science*, **214**, pp. 199-209 (2003).
10. Farris, S., Schaich, K.M., Liu, L.S., Piergiovanni, L. and Yam, K.L. "Development of polyion-complex hydrogels as an alternative approach for the production of bio-based polymers for food packaging applications: a review", *Trends in Food Science & Technology*, **20**, pp. 316-332 (2009).
11. Tamura, H., Furuike, T., Nair, S.V. and Jayakumar, R. "Biomedical applications of chitin hydrogel membranes and scaffolds", *Carbohydrate Polymers*, **84**, pp. 820-824 (2011).
12. Amin, S., Rajabnezhad, S. and Kohli, K. "Hydrogels as potential drug delivery systems: a review", *Scientific Research and Essays*, **3**, pp. 1175-1183 (2009).
13. Car, A., Stropnik, C., Yave, W. and Peinemann, K.V. "PEG modified poly(amide-b-ethylene oxide) membranes for CO_2 separation", *Journal of Membrane Science*, **307**, pp. 88-95 (2008).
14. Kim, M.J., Park, Y.I., Youm, K.H. and Lee, K.H. "Gas permeation through water-swollen polysaccharide/poly(vinyl alcohol) membranes", *Journal of Applied Polymer Science*, **91**, pp. 3225-3232 (2004).
15. Park, Y.I. and Lee, K.H. "Preparation of water-swollen hydrogel membranes for gas separation", *Journal of Applied Polymer Science*, **80**, pp. 1785-1791 (2001).
16. Xu, L., Zhang, L. and Chen, H. "Study on CO_2 removal in air by hydrogel membranes", *Desalination*, **148**, pp. 309-313 (2002).
17. Tanaka, Y., Gong, J.P. and Osada, Y. "Novel hydrogels with excellent mechanical performance", *Progress in Polymer Science*, **30**, pp. 1-9 (2005).
18. Xing, R. and Ho, W.S.W. "Crosslinked polyvinylalcohol-polysiloxane/fumed silica mixed matrix membranes containing amines for CO_2/H_2 separation", *Journal of Membrane Science*, **367**, pp. 91-102 (2011).
19. Wijmans, J.G. "Process PERFORMANCE = membrane properties + operating conditions", *Journal of Membrane Science*, **220**, pp. 1-3 (2003).
20. Shen, S., Kentish, S.E. and Stevens, G.W. "Effects of operational conditions on the removal of phenols from wastewater by a hollow-fiber membrane contactor", *Separation and Purification Technology*, **95**, pp. 80-88 (2012).
21. Gholizadeh, M., Razavi, J. and Mousavi, S.A. "Gas permeability measurement in polyethylene and its copolymer films", *Materials and Design*, **28**, pp. 2528-2532 (2007).
22. Okabe, K., Matsumiya, N. and Mano, H. "Stability of gel-supported facilitated transport membrane for carbon dioxide separation from model flue gas", *Separation and Purification Technology*, **57**, pp. 242-249 (2007).
23. Compañ, V., Andrio, A., López-Alemany, A., Riande, E. and Refojo, M.F. "Oxygen permeability of hydrogel contact lenses with organosilicon moieties", *Biomaterials*, **23**, pp. 2767-2772 (2002).
24. Zafar Khan, F., Shiotsuki, M., Nishio, Y. and Masuda, T. "Synthesis, characterization and gas permeation properties of t-butylcarbamates of cellulose derivatives", *Journal of Membrane Science*, **312**, pp. 207-216 (2008).

25. Buhus, G., Popa, M. and Desbrieres, J. "Hydrogels based on carboxymethylcellulose and gelatin for inclusion and release of chloramphenicol", *Journal of Bioactive and Compatible Polymers*, **24**, pp. 525-545 (2009).
26. Robeson, L.M. "The upper bound revisited", *Journal of Membrane Science*, **320**, pp. 390-400 (2008).

Biographies

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Mohammad Sadegh Amini-Fazl received his BS degree in Chemistry from Tabriz University in 2003 and his MS degree in Polymer Chemistry from Sharif University of Technology, Tehran, Iran, in 2005. Now, he is a PhD student in Polymer Engineering at Iran Polymer and Petrochemical Institute. His research interest is polymer synthesis.