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Development of A Blend Poly(ethylene glycol)/Polyethersulfone Membrane for CO₂/N₂ Separation

Lim Shu Yi¹, Zeinab Abbas Jawad^{1*}, Tan Peng Chee²¹School of Engineering and Science, Department of Chemical Engineering, Curtin University Malaysia, CDT 250, Miri 98009, Sarawak, Malaysia²School of Energy and Chemical Engineering, Xiamen University Malaysia, Jalan Sunsuria, Bandar Sunsuria, 43900 Sepang, Selangor Darul Ehsan, Malaysia.

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ABSTRACT

The emissions of carbon dioxide (CO₂) largely contribute to the issue of global warming. Recently, the polymer blend membrane has received attention as an attractive approach to gas separation due to its enhanced gas separation properties by combining the advantages of the different polymers. In this study, the formation of a blend polyethersulfone (PES) and polyethylene glycol (PEG) membrane for CO₂/Nitrogen (N₂) separation was investigated by first studying the effect of casting thickness from 150 µm to 800 µm. Based on the results, the blend membrane casted at 300 µm (M4) showed the best gas separation performance. The CO₂ and N₂ permeances for M4 were 11225.35 ± 5.24 GPU and 9582.99 ± 6.62 GPU, respectively and the CO₂/N₂ selectivity was 1.17. This research was further extended to study the effect of polymer concentration from 10 wt % to 30 wt % casted at 300 µm. The best gas separation performance of the blend membrane was reported at a PES:PEG ratio of 1:1 (M8), where the CO₂/N₂ selectivity was enhanced to 1.45. With the enhanced CO₂ separation performance of the blend membrane, the application of the membrane is a break through in the industrial world as it is capable of mitigating the effects of global warming.

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1. Introduction

Carbon dioxide (CO₂) is one of the greenhouse gases (GHGs) produced largely due to human activities. The amount of CO₂ in the atmosphere has increased from 341 ppm to 410 ppm for the last 40 years [Lindsey 2018]. The emission of CO₂ increased by 1.7 % in the year 2018, which was up to 33.1 Gt of CO₂ [IEA 2019]. Carbon capture and storage (CCS) is gaining the attention of researchers due to its potential to control the emission of GHGs [Benson and Orr 2011]. A full cycle of CCS includes the capture of CO₂, transportation and proper storage of CO₂ [Songolzadeh et al. 2014]. One of the CCS is the post-combustion separation, which is a process where the CO₂ is removed from the flue gas after the process of combustion of fossil fuels [Wang et al. 2017]. Membrane gas separation is one of the post combustion separations that is gaining the attention of researchers for industrial application [Sani et al. 2015].

Polymer blending is one of the membrane modification techniques where the polymeric membrane is being improved to enhance the gas separation performance. It is a technique where two or more polymers are blended together to form a new membrane. This could combine the advantages of the polymers such as mechanical strength and affinity towards CO₂ molecules, resulting in a better gas separation performance [Mannan et al. 2013]. One of the examples of polymer used for CO₂/N₂ separation is polyethylene glycol (PEG) due to its intrinsic gas permeability, as well

as its solubility and diffusivity [Liu et al. 2016]. The ether functional group in PEG tends to separate the CO₂ better in a gas mixture [Chen et al. 2011]. Polyethersulfone (PES) is another polymer that has been used as a commercial polymer for gas separation due to its outstanding chemical and mechanical properties. Besides, the ether-oxygen bond in the PES monomer provides an additional binding mode for CO₂ [Kilic et al. 2007]. Membranes whose CO₂ permeance was at least 1000 GPU had shown the ability to achieve a high CO₂ removal efficiency [Zhai 2019]. Typically, an amine absorption-based process was used to benchmark the membrane-based process to produce a membrane that is highly permeable and selective of CO₂ [Roussanaly et al. 2018]. For example, a cement plant with amine absorption-based that captured 0.62 million ton CO₂ per year was used as the benchmarking reference for the development of a membrane system [Lindqvist et al. 2014].

Up to date, the effect of casting thickness on CO₂/N₂ separation of blend membrane comprising of PEG and PES has not been studied. Besides, the study on the different ratios of PES and PEG to obtain the best performance of CO₂/N₂ separation has not been reviewed. The sorption behavior of CO₂ was affected by the presence of the functional groups as the interactions amongst CO₂ and the functional groups can alter the results of the gas permeance [Carreon et al. 2017]. The increment of casting thickness for the membrane had led to a lower blending

* Corresponding Author: : zeinab.aj@curtin.edu.my

effectiveness of PEG and PES, which caused a reduction in the CO₂ permeance [Prince et al. 2016]. Furthermore, as the PEG concentration increased, the alkanes (-CH₂) group and the hydroxyl (-OH) group increased. Increment in both alkanes (-CH₂) group and hydroxyl (-OH) group could lead to an increase in CO₂ captured [Mushtaq et al. 2013]. Therefore, the main target of this present work is to fabricate a highly compatible blend membrane with a high CO₂/N₂ separation performance by blending PES and PEG. Thus, in order to achieve the target, it is necessary to study the effect of casting thickness and the effect of polymer concentration in the PES/PEG blend membrane towards CO₂/N₂ separation.

2. Experimental

2.1 Materials

The polyethersulfone (PES) and polyethylene glycol (PEG) with molecular weight of 700 g/gmol and 2000 g/gmol, respectively were purchased from Sigma-Aldrich, Malaysia. The dimethylformamide (DMF) (ACS reagent $\geq 97\%$ purity) as a solvent was obtained from Sigma-Aldrich, Malaysia. The acetone (ACS reagent $\geq 99.99\%$ purity) was acquired from Merck, Malaysia whilst the purified CO₂ and N₂ cylinders were supplied by Eastern Oxygen Industries Sdn. Bhd., Malaysia.

2.2 Membrane Preparation

A PES/PEG blend membrane with different casting thickness and polymer concentration was prepared by the wet-phase inversion method. The casting solution was prepared by mixing PES/PEG at a ratio of 1:3 (10 wt% PES and 30wt % PEG) with 60 wt% of DMF in a duran bottle. The mixing was done by stirring the casting solution continuously for 4 hours at 60°C. The casting solution was placed in an ultrasonic degasser and sonicated for 25 minutes at 25°C in order to remove the gas bubbles [Akbarian et al. 2018]. The membrane was casted using an automatic film applicator situated in a fume chamber at room temperatures. The membrane film formed was then immediately immersed into the distilled water bath for 24 hours. Lastly, the membrane was placed in an oven at 60°C for the drying process for 24 hours. The dried membrane was kept in a zip lock bag before use [Amirilargani and Mohammadi 2009b].

2.3 Effect of Casting Thickness

In order to study the effect of casting thickness on the membrane gas separation performance, the membrane was prepared at different casting thickness ranging from 150 μm to 800 μm , as tabulated in Table 1.

Table 1: Blend PES/PEG Membrane at Different Casting Thickness

Sample Description	PES (Weight %)	PEG (Weight %)	DMF (Weight %)	Thickness (μm)
M1	10	30	60	150
M2	10	30	60	200
M3	10	30	60	250
M4	10	30	60	300
M5	10	30	60	500
M6	10	30	60	700
M7	10	30	60	800

2.4 Effect of Polymer Concentration

The blend membrane was then fabricated with the optimized casting thickness of 300 μm and polymer concentration was manipulated, as tabulated in Table 2.

Table 2: Blend PES/PEG Membrane at Different Polymer Concentration

Sample Description	PES (Weight %)	PEG (Weight %)	DMF (Weight %)	Thickness (μm)
M8	20	20	60	300
M9	25	15	60	300
M10	30	10	60	300

2.5 Membrane Performance

The membrane was tested with single gas permeation test with both purified CO₂ and N₂ based on the previously published work [Jawad et al. 2015]. The permeation test was conducted under room temperature. Both purified CO₂ and N₂ gases with a kinetic diameter of 3.3 Å and 3.64 Å, respectively were used. Before conducting the test, the system was purged with N₂ gas for 15 minutes to remove the excess air and impurities. The synthesized blended membrane was cut into a disc-shape and placed on the porous stainless-steel disc, which was covered and tightened with rubber O-rings. The disc was locked securely with bolts and nuts to prevent leakage. A flow rate of 100 mL/min of N₂ was allowed to flow through the membrane. The flow rate of the retentate and permeate was obtained by using the bubble flow meter filled with soap water. A leakage test was done by using soapy water. The bolts and nuts were opened and locked again until there was no leakage.

In this study, single gas permeation test was conducted rather than binary gas permeation test. This is due to the behavior of the gases permeances in both single gas permeation test and binary gas permeation test were similar at low temperatures [Simplicio et al. 2014]. Besides, both permeation tests showed similar gases permeances trends when the permeate pressure was altered, whereas the feed pressure and temperature were kept constant [Mushardt et al. 2016].

2.6 Membrane Characterization

2.6.1 Scanning Microscope Electron (SEM)

The scanning electron microscope (SEM) is an instrument that has been used for the inspection of the microstructure morphology of the membrane surface and its cross-section [Zhou et al. 2007]. The Scanning Electron Microscope (Hitachi TM3000, Tokyo, Japan) was used to characterize the morphology and cross-section of the synthesized blended membrane. The membrane was first kept in the cryogenic freezer for 24 hours and cut into small pieces before the test was conducted. To examine the cross-sections of the blended membrane, the cracked samples were first layered with platinum sputtering.

2.6.2 Attenuated Total Reflectance Fourier Transform Infrared Spectroscopy (ATR-FTIR)

The Attenuated Total Reflectance Fourier Transform Infrared Spectroscopy (ATR-FTIR) is one of the sampling methods that most often used. The Thermo Scientific Fourier Transform Infrared Spectrometer (NICOLET iS10, USA) is used to characterize the existence of the functional groups in the synthesized blended membrane. The test was done from a wavelength range from 400 to 4000 cm⁻¹.

3. Result and Discussion

3.1 Effect of Casting Thickness

3.1.1 Scanning Electron Microscope (SEM)

From Figure 1 (a, c, e, g, i, k, m), it was observed that the membranes had a porous surface with a pore size ranging from 1.5 μm to 3.2 μm . The size of the pores increased as the membrane casting thickness increased, which led to a lower gas permeance. This was because the deposition speed of the polymer becomes slower at a higher casting thickness, resulting in the higher involvement of membrane layers in the formation of the membrane. The amount of vapor, which diffused from the atmosphere into the polymer matrix was high and caused the increment in pore size. In contrast, a thinner membrane having a smaller pore size had a more compact aggregation of the polymer matrix [Ahmad et al. 2007]. Kuo and Hong [2005] observed that there was a relationship between corresponding membrane casting thickness and the characterization of the membrane such as the average size of the pore [Kuo and Hong 2005].

Besides, from Figure 1 (b, d, f, h, j, l, n), the membranes were having a finger-like structure and sponge-like structure at the bottommost surface. Furthermore, the final membrane thickness decreased as compared to the initial casting thickness. The change in the final membrane thickness was due to the solvent (DMF) used in preparing the blend membrane. The DMF underwent ion exchange process with distilled water and it was removed in the process, thus, causing the final membrane thickness to decrease from its initial casting thickness [Silva et al. 2017]. Moreover, the SEM showed that the final thickness of the membrane increased from 69.51 $\pm$ 1.79 μm to 384.03 $\pm$ 1.76 μm when the initial casting thickness increased from 150 μm to 800 μm . Once the membrane film was placed in the distilled water bath, ion exchange process took place immediately, resulting in an increase in the final thickness. This was due to the formation

Figure 1: SEM surface and cross-section of blend membrane at PES/PEG ratio of 1:3 at different casting thickness which are (a, b) 150 μm (M1), (c, d) 200 μm (M2), (e, f) 250 μm (M3), (g, h) 300 μm (M4)

Figure 1: (i, j) 500 μm (M5), (k, l) 700 μm (M6), and (m, n) 800 μm (M7).

of the polymer precipitated solid film, which led to the decrement in the final thickness and resulted in a higher polymer concentration in the membrane film [Amirilargani and Mohammadi 2009a]. Simultaneously, miscibility between the DMF and the distilled water caused the ion exchange process to take place on the top and bottom layers of the membrane film and hence, caused the formation of nuclei of the polymer-poor phase [Guillen et al. 2013]. These nuclei continued to grow until solidification of the membrane occurred. According to Kim and Lee [1998], if the system was an instantaneous demixing system, the membrane solidified quickly once the membrane film was immersed into the distilled water bath and this could prevent the precipitation process [Kim and Lee 1998]. Further, this resulted in the increment of the surface porosity and the final membrane thickness because when the membrane thickness

increases and the polymer content is constant, the increment of the total volume of the polymer content increases [Amirilargani and Mohammadi 2009a].

3.1.2 Attenuated Total Reflectance Fourier Transform Infrared Spectroscopy (ATR-FTIR) Analysis

The structural characteristic of the blend membrane with different thickness was studied by ATR-FTIR analysis. The ATR-FTIR spectra of all blend membranes are shown in Figure 2. Based on Figure 2, the O-H stretching bond was observed at 3632.90 cm⁻¹. Besides, the aromatic benzene ring of =C-H and -C-H stretching bond was represented by the strong absorption peaks observed at 3093.39 cm⁻¹ and 2866.30 cm⁻¹,

Figure 2: ATR-FTIR analysis of blend membrane at PES/PEG ratio of 1:3 at different casting thickness which are (M1) 150 μm , (M2) 200 μm , (M3) 250 μm , (M4) 300 μm , (M5) 500 μm , (M6) 700 μm , and (M7) 800 μm .

respectively [Alenazi et al. 2018]. The peaks at 1484.98 cm^{-1} represented the presence of C=C stretching bond whereas the peaks at 1238.13 cm^{-1} represented the ether C-O stretching bond [Prince et al. 2016]. The presence of PES was confirmed with the O=S=O stretching bond observed at the peak 1149.42 cm^{-1} [Glagovich 2019]. The purity of the blend membrane was proven due to the presence of the elementary and significant peaks in the spectrum [Kim and Park 2011]. By introducing PEG to PES, the absorption band of the C-H stretching bond indicated the good compatibility between PEG and PES. The presence of ether C-O stretching bond, which linked both polymers had resulted in the effective blend of PEG and PES. The presence of the functional groups had an influence on the sorption behavior of CO_2 . The interactions between CO_2 and the functional groups increased the solubility of the polymers and hence, resulted in the increase of the gas permeance [Carreon et al. 2017].

3.1.3 Gas Permeation Test

3.1.3.1 Separation performance towards CO_2

As observed in Figure 3, the CO_2 permeance increased from $13010.83 \pm 7.04\text{ GPU}$ to $13442.19 \pm 12.98\text{ GPU}$ when the membrane casting thickness changed from 150 μm (M1) to 200 μm (M2). This was because more pores were formed in M1 as compared to M2. According to Akbarian et al. [2018], the presence of pores on the surface of the membrane were undesirable as they had poor gas separation performance. Thus, this explained the higher gas permeance in M2 compared to M1 [Akbarian et al. 2018].

Besides, the CO_2 permeance was highest for M2 as it had smaller pore sizes ($1.65 \pm 0.33\text{ }\mu\text{m}$). This is shown in Figure 1. The gas permeance decreased when the membrane casting thickness was further increased.

The CO₂ permeance for M3, M4, M5, M6 and M7 were 13026.04 ± 9.98 GPU, 11225.35 ± 5.24 GPU, 8539.82 ± 4.29 GPU, 7612.89 ± 3.99 GPU and 7028.98 ± 3.41 GPU, respectively. Based on the ATR-FTIR analysis, the lower absorption peak of the ether C-O stretching bond had led to the reduction in CO₂ permeance due to the lower blending effectiveness of PEG and PES [Prince et al. 2016].

3.1.3.2 Separation performance towards N₂

The N₂ permeance of the blend membrane with different casting thickness is shown in Figure 3. As observed, the N₂ permeance increased from 12085.08 ± 6.07 GPU to 12774.39 ± 6.78 GPU when the membrane casting thickness changed from 150 μm (M1) to 200 μm (M2). The increment of N₂ permeance was due to the higher porosity of M1, as shown in Figure 3, which provided more free volume, resulting in higher N₂ permeance.

Moreover, the N₂ permeance showed a decreasing behavior when the casting thickness was further increased from 200 μm to 800 μm . The N₂ permeance of M3, M4, M5, M6, and M7 were 11919.12 ± 10.21 GPU, 9582.99 ± 6.62 GPU, 7451.44 ± 3.83 GPU, 6922.11 ± 2.82 GPU and 6490.19 ± 2.90 GPU, respectively. This was due to the increment in the final thickness of the membrane. It caused increment in the pore diffusion resistance, resulting in decrement in the gas permeance [Shen and Lua 2010]. In addition, Alsari et al. [2007], reported that the overall membrane density decreases when the thickness increases, which leads to the decrement of the gas permeance [Alsari et al. 2007].

3.1.3.3 Separation performance towards CO₂/N₂ selectivity

Figure 3 presents the relationship between CO₂ and N₂ permeance and CO₂/N₂ selectivity with different casting thickness. It was observed that the CO₂ showed a higher permeance compared to N₂. This was due to the smaller kinetic diameter (3.3 Å) of CO₂ whereas N₂ had a larger kinetic diameter (3.64 Å), which allowed more CO₂ to diffuse through the membrane [Duke et al. 2006].

According to Figure 3, M4 had the highest CO₂/N₂ selectivity of 1.17 as compared to the others because it had the lowest membrane porosity, as observed in Figure 1. The increase of casting thickness from M1 to M2 led to a decrease in the CO₂/N₂ selectivity from 1.07 to 1.05 due to the larger amount of N₂ passing through the membrane. This was explained by the SEM surface morphology, where M2 had a slightly larger pore size compared to M1, thus, allowing more N₂ to diffuse through the membrane [Shen and Lua 2010]. The increase in casting thickness from M2 to M4 resulted in an increase in CO₂/N₂ selectivity. This was because CO₂ had a higher permeance as compared to N₂. The larger kinetic diameter of N₂ leads to a slower diffusivity and caused lower N₂ permeance [Ahmad et al. 2007].

The CO₂/N₂ selectivity decreased when the casting thickness was further increased from M4 to M7. This was explained by the SEM analysis. As observed in Figure 1, the size of the finger-like structure increased as the initial casting thickness increased. As a result, this improved the pore

interconnectivity and allowed more N₂ to diffuse through the membrane. The CO₂ permeance was not affected due to the lower kinetic diameter, resulting in a smaller difference between the CO₂ and N₂ permeance and hence, resulting in lower selectivity [Amirilargani and Mohammadi 2009a].

However, based on Figure 3, the CO₂/N₂ selectivity changed slightly when the casting thickness was changed. This result was in line with the findings by Firpo et al. [2015], where the increment of membrane thickness resulted in the decrement of the permeance of the gases, which resulted in an insignificant change in the selectivity [Firpo et al. 2015].

3.2 Effect of Polymer Concentration

3.2.1 Scanning Electron Microscope (SEM) Analysis

It was observed from Figure 4 that M8 and M9 had a defect-free surface. The formation of a defect-free surface membrane was due to the compatible blend between the two polymers [Firpo et al. 2015]. This prevented the formation of molecular size defects on the membrane surface [Akbarian et al. 2018]. However, M10 had a higher porosity with a smaller pore size compared to M4 due to the decrement in the PEG concentration. The smaller pore size was due to the effectiveness of the solvent for dispersing PEG in PES [Abd-Allah et al. 2013].

Furthermore, the size of the canals increased as PES concentration increased and that the structure of the canals changed from channel-like to finger-like, as observed in Figure 4 (b, d, f) [Khorsand-Ghayeni et al.

Figure 3: CO₂ and N₂ permeance (GPU) and CO₂/N₂ Selectivity of blend membrane with different casting thickness of 150 μm (M1), 200 μm (M2), 250 μm (M3), 300 μm (M4), 500 μm (M5), 700 μm (M6), and 800 μm (M7).

Figure 4: SEM surface and cross-section of blend membrane at different PES:PEG ratio where (a, b) 1:3 (M4)

Figure 4: (c, d) 1:1 (M8), (e,f) 5:3 (M9), and (g,h) 3:1 (M10) with casting thickness of 300 μm .

2016]. This was due to the decrement in PEG concentration, which reduced the hydrophilicity of the casting solution. The PEG, which has a rapid outflow rate, allowed the formation of the porous interconnecting channels that were free of macrovoids [Abd-Allah et al. 2013].

3.2.2 Attenuated Total Reflectance Fourier Transform Infrared Spectroscopy (ATR-FTIR) Analysis

Figure 5 shows the ATR-FTIR spectra of blend membrane with different

polymer concentrations. The ATR-FTIR analysis showed the strong absorption peaks at 3629.53 cm^{-1} , 3094.84 cm^{-1} and 2867.27 cm^{-1} , which were assigned to the O-H stretching bond and the aromatic ring of the =C-H and -C-H stretching bond, respectively [Alenazi et al. 2018]. Besides, the C=C stretching bond and C-O stretching bond were also detected at peaks 1484.98 cm^{-1} and 1238.61 cm^{-1} , respectively. The O=S=O stretching bond was also observed at the peak 1149.42 cm^{-1} [Glagovich 2019].

Figure 5: ATR-FTIR analysis of blend membrane at different PES:PEG ratio which are (M4) 1:3, (M8) 1:1, (M9) 5:3, and (M10) 3:1 with casting thickness of 300 μm .

3.2.3 Gas Permeation Test

3.2.3.1 Separation performance towards CO₂

As observed in Figure 6, the permeance of CO₂ decreased by increasing the concentration of PES. When the concentration of PES increased from 10 wt% (M4) to 20 wt% (M8), the CO₂ permeance reduced from 11225.35 ± 5.24 GPU to $1376.87.35 \pm 0.47$ GPU. The increase in the PES concentration produced a defect-free dense surface (Figure 4 c), which caused a reduction in the CO₂ permeance. Furthermore, when the concentration of PES was increased to 30 wt%, the CO₂ permeance decreased insignificantly.

The absorption behavior of CO₂ was affected by the presence of the functional groups as the interactions amongst CO₂ and the functional groups can alter the results of the gas permeance [Carreon et al. 2017]. It was observed that the absorption peaks of -C-H bond for M8, M9, and M10 were slightly lower than M4. The decrement was due to the decrease in the alkanes (-CH₂) group in PEG when the PEG concentration decreased. Moreover, the O-H bond had the highest absorption peaks for M4 when compared to the others. The higher PEG concentration in M4 led to an increase in the hydroxyl (-OH) group, which formed the linkage between PES and PEG. The reduction of the hydroxyl (-OH) group minimized the capture of CO₂ [Mushtaq et al. 2013]. This proved that the hydroxyl (-OH) group in PEG interacted with the PES matrix [Akbarian et al. 2018].

3.2.3.2 Separation performance towards N₂

The effect of polymer concentration on the performance of N₂ permeance is shown in Figure 6. The permeance of N₂ decreased when the PES concentration increased. The significant drop of the N₂ permeance from 9582.99 ± 6.62 GPU to 945.41 ± 0.31 GPU was due to the increase in the PES concentration from 10 wt% (M4) to 20 wt% (M8). This was explained through the SEM analysis. As seen from Figure 4 c, M8 had a dense surface whereas M4 had a porous surface (Figure 4 a). This was because the porous surface on M4 allowed more gases to pass through freely. On the other hand, M8, which had a dense surface prohibits the movement of gas at lower pressure [Hadi et al. 2016]. As the PES concentration was further increased from 20 wt% (M8) to 30 wt% (M10), the N₂ permeance increased. The formation of pores in M10 provided sites for N₂ permeation, which led to higher N₂ permeance in M10 as compared to M8 [Ghadimi et al. 2014].

Figure 6: CO₂ and N₂ permeance (GPU) and CO₂/N₂ Selectivity of blend membrane at different PES:PEG ratio of 1:3 (M4), 1:1 (M8), 5:3 (M9), and 3:1 (M10) with casting thickness of 300 µm.

3.2.3.3 Separation performance towards CO₂/N₂ selectivity

Figure 6 presents the difference between the CO₂ and N₂ permeance and the CO₂/N₂ selectivity with different polymer concentrations. It was observed that M4, M8, and M9 had higher CO₂ permeance as compared to N₂. However, M8 provided the best separation performance with CO₂/N₂ selectivity of 1.45, whereas the CO₂/N₂ selectivity of M4 and M9

were only 1.17 and 1.22, respectively. Based on SEM, these membranes have different surface morphology, whereby M4 had a porous surface and M8 and M9 had a dense surface. Hadi et al. [2016] stated that the membrane with a dense surface produced a better separation performance compared to a porous surface [Hadi et al. 2016]. The dense membrane showed better selectivity as there was lesser free volume in the membrane compared to a porous membrane [Sridhar et al. 2014]. Besides, M8 had better selectivity compared to M9 due to its smaller canal size, which prohibited the movement of N₂ to diffuse through the membrane due to the larger kinetic diameter [Amirilargani and Mohammadi 2009a].

Nevertheless, M10 had a higher N₂ permeance (1141.40 ± 0.36 GPU) as compared to the CO₂ permeance (1027.58 ± 0.39 GPU) and CO₂/N₂ selectivity (0.90). In other words, M10 was more selective to N₂ than CO₂. This was because the reduction in the PEG concentration minimized the ability of the membrane to capture CO₂ due to the reduction of the alkanes (-CH₂) group and hydroxyl (-OH) group, as shown in Figure 5. Besides, the higher porosity and larger size of the finger-like structure of M10 gave a larger free volume that allowed a higher N₂ permeation, which affected the CO₂/N₂ selectivity.

4. Conclusion

In this research project, it was proven that the casting thickness and the polymer concentration of the blend membrane affected the physical structure, CO₂ and N₂ permeance and CO₂/N₂ selectivity of the membrane. The optimum casting thickness for PES/PEG blend membrane was 300 µm (M4), which exhibited the highest CO₂/N₂ selectivity of 1.17 and the permeances for CO₂ and N₂ were 11225.35 ± 5.24 GPU and 9582.99 ± 6.62 GPU, respectively. This research was further extended to study the effect of polymer concentration of the blend membrane at 300 µm. As a result, the blend membrane with a PES:PEG ratio of 1:1 (M8) gave the best separation performance with CO₂/N₂ selectivity of 1.45 and the permeances for CO₂ and N₂ were $1376.87.35 \pm 0.47$ GPU and 945.41 ± 0.31 GPU, respectively.

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