Article

J. Mex. Chem. Soc. **2011**, *55(1),* 42-50

ISSN 1870-249X

Air Dehydration by Permeation Through Dimethylpolysiloxane/polysulfone Membrane

Shui Wai Lin* and Salvador Valera Lamas

Centro de Graduados e Investigación en Química del Instituto Tecnológico de Tijuana
Blvd. Industrial y Av. ITR Tijuana, S/N, Mesa Otay, C.P. 22500, Tijuana, B C., México
e-mail: SL388@AOL.COM

Received June 14, 2010; accepted December 10, 2010

Abstract. The present work focuses on design, fabrication and evaluation of an air-dehydration membrane system that is capable of producing dry air with a Dew Point of –50ºC at a rate of 310 cm^3/s using compressed wet-air (90 psig, 23ºC) as feed to a membrane system of dimethylpolysiloxane thin-film supported by microporous polysulfone substrate (PDMS/PS). The dehydrator element comprises of a flat sheet PDMS/PS membrane fixed to a cylindrical tubular support, the latter is fitted inside an appropriated chamber. The air-dehydration process is achieved by means of selective permeation of $H_2O(g)$ over N_2 and O_2 gases, the major components of the wet- air, through PDMS/PS membrane.
Keywords: gas separation, permselective membranes, dimethylpolysiloxane, dry air.

Resumen. El presente trabajo se centra en el diseño, fabricación y evaluación de un dispositivo capaz de producir aire seco, con punto de rocío de –50ºC a razón de 310 cm^3/s, alimentando aire comprimido (90 psig, 23ºC) a un sistema de membranas compuestas por una película delgada de polidimetilsiloxano, soportada sobre una membrana microporosa de polisulfona (PDMS/PS). El módulo deshidratador consiste de una membrana de PDMS/PS en forma de película plana fijada a un soporte cilíndrico, dentro de una cámara apropiada para la separación de gases. El proceso de deshidratación de aire se consigue por medio de la permeabilidad selectiva del $H_2O_{(g)}$ en N_2 y O_2, los cuales son los principales componentes gaseosos del aire que viaja a través de la membrana de PDMS/PS.
Palabras clave: Separación de gases, membranas permioselectivas, polidimetilsiloxano, aire seco.

Introduction

The presence of water vapor in the air can be a serious problem in some manufacturing processes, especially in storage facilities; wet environment may enhance hydrolysis, powder agglomeration, seed germination, mold grow and other undesired effects in chemical, pharmaceutical and food product processing. Another example of importance of humidity control in air is to maintain the normal performance of sophisticate electronic equipments which can be affected by water vapor condensation on electronic circuits; this would cause the corrosion of the metallic joints. Dry air itself is a dehydrating agent that can be used to dry wet delicate clothes to avoid heating step. Conventional way to produce dry air consists of passing wet air through hydroscopic agent like glycol, silica gel, molecular sieves, calcium chloride, phosphorus pentoxide or concentrated sulfuric acid. This method has disadvantages like drying agent being carried-over in the dry air stream; also it requires a regeneration step to remove the water from the drying agent, this make the dehydration process costly and time consuming. Other method of dehydration of air is to compress and freeze the wet air to condense water vapor (cryogenic method); the advantage of this method over previous technique lies in great amount of air can be treated in a continuous process, however this method consumes high energy and is difficult to reach total removal of the water vapor from the feed wet air.

Gas separation by polymeric membranes started at commercial level in 1980 when the company named Permea launched Prism® [1], a hydrogen separation membrane system. Initially the main market for gas separation using permselective membranes was on O_2/N_2 separation, for that purpose, Polydimethylsiloxane (PDMS) membrane was used, since permeability of oxygen through this polymer is twice fast as nitrogen [2]. Works of air dehydration by polymeric membranes had been reported in literatures [3] and in patents [4-7], where membranes were used in the form of hollow fibers packed in a cylindrical tube; hollow fibers bunch were fixed to the ends of the membrane housing by epoxy resin. Normally in this arrangement, particles carried over by the feed gas tend to plug the membrane surface, since hollow fibers are permanently attached and sealed to the body of the device; its restoration is impractically expensive. Also the mixing of the gas flow through the hollow fiber system is very poor; this would greatly hinder the efficiency of the gas separation process. Moreover, due to high density package, portion of product (dry air) is needed to swap permeated stream and keep low levels of water concentration in permeate side of the membrane.

The arrangement designed this work consists of a flat sheet permselective membrane attached to a rigid cylindrical support, all of this placed inside a cylindrical body in such a way that membrane can easily removed, either to clean, to repair or to change it.

Gas Separation through Permselective Membranes

Gas separation through porous-free polymeric membrane has been described by dissolution-diffusion mechanism [8] that comprises following steps:

1. Under applied high pressure gas is being absorbed at the membrane surface.

2. Gas diffusion across membrane is facilitated by concentration gradient of gas itself; this generates a net flow toward low concentration side.
3. Gas desorption to low-pressure side of membrane (opposite side of the feed gas).

Step (1) is facilitated by the permeating gas and by the polymeric primary structure compatibility; this is, by gas solubility in polymeric membrane. Step (2) is helped by polymeric structures with high degree of motion in their chain segments; this motion causes intermolecular cavities that carry permeating gas. Step (3) can be mainly affected by low pressure of permeating gas in permeation zone. First and second steps involve phenomenological coefficients; solubility coefficient S (cm^3 of gas/cm^3 of membrane · cm of Hg) and diffusion coefficient D (cm^2/s); product of them defines the permeability constant P as expressed below,

$$P = SD \tag{1}$$

Units of P are: $cm^3 \cdot cm/cm^2 \cdot s \cdot$ cm of Hg.

The flow rate per unit area, J ($cm^3/s \cdot cm^2$), of the permeating gas when unit pressure difference Δp (cm of Hg) and unit thickness *l* (cm) are considered, is shown in Equation (2).

$$J = P\frac{\Delta p}{l} \tag{2}$$

$$J = P \text{ if } \Delta p = 1 \text{ and } l = 1$$

Equation 2 represents the result from the combination of Henry's Law and Fick's First Law. Table 1 shows the permeability of N_2 (g), O_2(g) and H_2O(g) through the dimethylpolysiloxane membrane.

The ability of a membrane to separate two different gases (A and B) is determined by the selectivity $\alpha_{A/B}$, the permeability ratio of two gases,

$$\alpha_{A/B} = \frac{P_A}{P_B} \tag{3}$$

According to the permeability of main air components shown in table 1, the selectivity of O_2/N_2 by PDMS membrane equals to 2.017, however, additional reference reported a selectivity of 2.2 [11].

Since air can be approximately considered as a mixture of O_2 (20.95 % in volume) and N_2 (78.09 % in volume), therefore the permeability of air (P_{air}) through PDMS thin film can be calculated as the following,

Table 1. Permeability constant of main air components in dimethylpolysiloxane films (25ºC).

Gas	Permeability Constant (× 10^9) (cm^3(STP))(cm)/(cm^2)(s) (cm of Hg)*	Ref.
N_2	30	[9]
O_2	60.5	[9]
H_2O	1550-5180	[10]

* A factor of 7.5×10^{-4} must be used to convert values to (cm^3(STP))(cm)/(cm^2)(s) (Pa).

$$\begin{aligned} P_{air} &= X_{O2}\, P_{O2} + X_{N2}\, P_{N2} = \\ &= (0.2095)(60.5 \times 10^{-9}) + (0.7809)(30 \times 10^{-9}) = \\ &= 36.1 \times 10^{-9}\ cm^3\ (STP) \cdot cm/cm^2 \cdot s \cdot cm\ of\ Hg \end{aligned}$$

The selectivity of PDMS membrane to water over air can be calculated using mean value of water permeability range showed in table 1 and air permeability calculated above:

$$\alpha_{\text{water/air}} = \frac{P_{\text{water}}}{P_{\text{air}}} = \frac{3365 \times 10^{-9}}{36.1 \times 10^{-9}} = 93.2$$

Selectivity of 93.2 guarantees water separation from air by PDMS membrane. For practical industrial application, gas separation selectivity greater than 20 is required [12].

Membrane nature

According to Equation 2, in order to remove water vapor efficiently from air, PDMS film must be as thin as possible, however high applied pressure is required for gas separation via membrane process; a very thin membrane results mechanically unstable and can be broken. To solve this problem a polysulfone (PS) microporous membrane, casted on a non-woven polyester fabric, can be used as PDMS support. Figure 1 shows chemical structure of PDMS and PS while Figure 2 illustrates a cross-sectional structure of a typical PDMS/PS membrane;

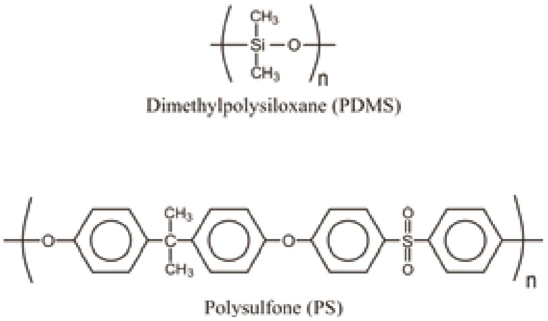

Fig. 1. Chemical structure of dimethylpolysiloxane and polysulfone.

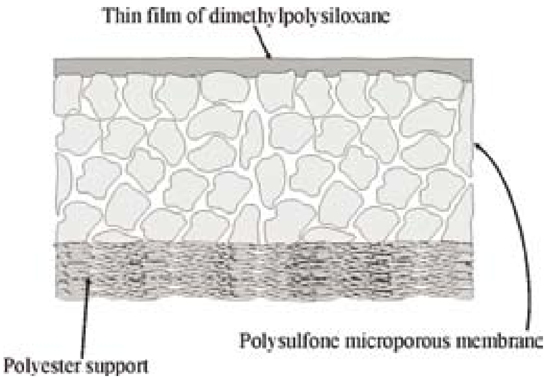

Fig. 2. Sketch of dimethylpolysiloxane-microporous polysulfone compound membrane.

works on scanning electron microscopies of this kind of composite membranes can be found in some references [13-14].

PDMS film on PS support is formed by solution deposition method [15]; PS membrane is immersed in petroleum ether-PDMS solution. Once solvent is removed by evaporation, PDMS thin film remains on PS membrane surface provided that the porous size of PS membrane is small enough to prevent the excessive penetration of PDMS/solvent into the porous support. In case of PS porous support having large pore size, PDMS/solvent can diffuses deep into the support's inner structure and even reaching to the back side of the porous substrate; this will result an undesirable thickness for fast gas separation (Figure 3b). Even though PS membrane used in this work corresponds to the kind shown in Figure 3b, in order to achieve a thinner PDMS film deposition, dammed PS membrane was used in this work; liquid water inside the PS membrane pores prevents PDMS/solvent penetration (Figure 3c).

Results and discussion

Polysulfone membranes porosity

Porosity of polysulfone membrane is expressed in term of A-value which assumes the value as indicated below,

$$\text{“A value”} = \frac{\text{Mass flow of permeated distilled water (g/s)}}{\text{Permeation area (cm}^2\text{)} \times \text{Pressure (atm)}}$$

Table 2 shows "A values" of four PS membranes prepared from different PS wt % polymer solutions; Figure 4 shows relationship between porosity and casting solution concentration.

PS membrane prepared from 21% casting solution ("A value" = 5.7×10^{-4} g/cm^2 · atm) was chosen as the porous support for the PDMS film coating. PS membranes with higher porosity (those prepared from 17 and 19 wt-% PS casting solutions) were rejected because experimental works indicated that it was impossible to coat a thin PDMS film on their surfaces; the PDMS solution diffused deep into the PS porous substrate. PS membrane of low porosity ("A value" = 1.1×10^{-4} g/cm^2 · atm) was considered not enough pore to get a fast permeated flow PDMS/PS membrane.

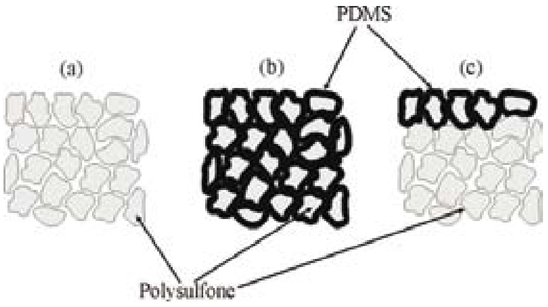

Fig. 3. Models to show polysulfone covered with PDMS: a) Polysulfone alone. b) Polysulfone totally covered by PDMS. c) Polysulfone covered superficially by PDMS.

Table 2. "A value" of PS membranes prepared from different wt-% of PS in membrane casting solutions.

PS conc. (% in weight)	"A value" × 10^{-5} (g/s · cm^2 · atm)
17	280
19	132
21	57
24	11

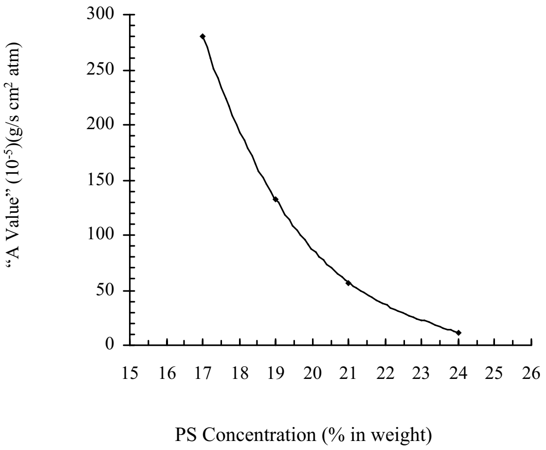

Fig. 4. "A value" of PS membrane as function of polymeric casting solution concentration.

Selectivity O_2/N_2 and apparent thickness

Through permeation tests using pure O_2 and N_2 gases as deed, it shows that there was a DPMS thin-film, coated on PS porous membrane, which is capable for gas separation. Results of permeation tests (Table 3) show the experimental selectivity for each PDMS/PS membrane element. The experimental selectivity of the PDMS/PS membrane agrees with the selectivity calculated from Equation 3 (Table 1). The thickness of the PDMS thin-film coated on PS porous substrate as shown in Table 3 was calculated from Equation 4; the latter is derived from Equation 2.

$$l = \frac{P \Delta p A}{F} \tag{4}$$

Table 3. Results of O_2 and N_2 permeation test of elements 1 to 6; T = 29.1ºC, p = 80 psig.

Element	Permeate volumetric flow, (cm^3/s)		α	Apparent thickness (Å)
	O_2	N_2		
No. 1	97.4	47.9	2.04	14,414
No. 2	105.0	52.0	2.02	13,288
No. 3	96.2	48.5	1.98	14,021
No. 4	112.2	55.1	2.04	12,821
No. 5	111.4	53.4	2.09	12,873
No. 6	106.1	51.8	2.05	12,797

Where:

l = Membrane thickness (cm)
P = Nitrogen permeability =
= 30×10^{-9} cm$^3 \cdot$ cm / cm$^2 \cdot$ s $\cdot$ cm of Hg =
= 15.51 cm$^3 \cdot$ Å / cm$^2 \cdot$ s $\cdot$ psig
Δp = Pressure applied during permeation test (cm of Hg)
A = Membrane area (cm^2)
F = Permeate volumetric flow (cm^3/s)

Substitution of nitrogen permeability in Equation 4 leads to

$$l = 15.51\left(\frac{\Delta pA}{F}\right) \tag{5}$$

where Δp is expressed in psig, F in cm^3/s and l result in Angstroms which is considered an apparent thickness since holes or imperfections in PDMS film can be present, in such case, the apparent thickness will be lower than the absolute thickness.

Air dehydration Test

Table 4 summarizes the conditions and test results of air-dehydration tests using six PDMS/PS membrane elements connected in series. According the experimental results, it demonstrates that air-dehydration with six PDMS/PS membrane elements system can produce dry air of dew point −50ºC at a rate of 310 cm^3/s that corresponds to a yield of 48.8% of wet-air feed operating at 23ºC and at 90 psig.

Water Mass Balance

Efficiency of PDMS membrane in air-dehydration was determined from dew point readings (Table 4). In order to calculate water content in permeated, residual and feed flows, data of water mass in saturated air as function of temperature were used [16]. For each 6ºC interval, the plot of water content in the water saturated air versus temperature, as shown in Figure 5, yields a non-linear line. In some cases it is an exponential function or as a polynomial function. Table 5 shows such functions that were used to calculate by interpolation from the water content from dew point readings.

Table 4. Results of air dehydration test using elements 1, 2, 3, 4, 5 and 6 in series, operating at 23ºC and 90 psig.

Element	Volumetric flow (cm^3/s)			Dew point (ºC)		
	A*	R	P	A	R	P
No. 1	635	583	52	−9.5	−12.8	11.5
No. 2	583	527	56	−12.8	−17.5	7.0
No. 3	527	477	50	−17.5	−21.8	0.6
No. 4	477	420	57	−21.8	−29.0	−4.5
No. 5	420	365	55	−29.0	−37.2	−10.1
No. 6	365	310	55	−37.2	−50.0	−18.1

A = Fed, R = Residual, P = Permeated.
* Calculated from sum of permeated and residual.

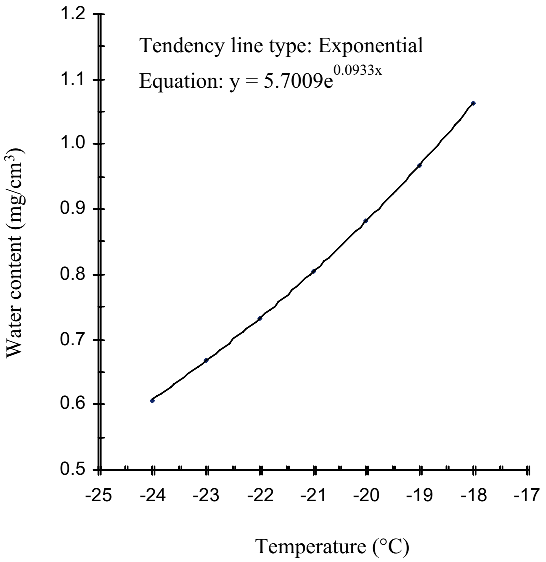

Fig. 5. Water mass in saturated air for temperature interval from −25ºC to −18ºC.

Product of water content in the wet-air and the volumetric flow defines the water mass flow; Table 6 shows the results of water mass balance in the air dehydration tests.

Residence time of the wet-air feed in contact with the PDMS/PS membrane shown in Table 6 was calculated using Equation 6 which is deduced in detail in Appendix.

$$t = \frac{A}{aJ_P}\ln\left(1 + \frac{F_P}{F_R}\right) \tag{6}$$

t = Residence time (s)
A = Cross section area of element (cm^2)
a = Membrane wide (cm)
J_P = Permeate flow density (cm^3/s $\cdot$ cm^2)
F_P = Permeate volumetric flow (cm^3/s)
F_R = Residual volumetric flow (cm^3/s)

Table 5. Equations used to calculate water content from dew point.

Temperature interval	Equation*
−50ºC a −30ºC	$y = 0.0009\,x^2 + 0.0883\,x + 2.1866$
−30ºC a −24ºC	$y = 6.2145\,e^{0.0968x}$
−24ºC a −18ºC	$y = 5.7009\,e^{0.0933x}$
−18ºC a −12ºC	$y = 5.1374\,e^{0.0875x}$
−12ºC a −6ºC	$y = 5.0152\,e^{0.0852x}$
−6ºC a 0ºC	$y = 0.0001\,x^3 + 0.014\,x^2 + 0.3874\,x + 4.8485$
0ºC a 6ºC	$y = 0.0005\,x^3 + 0.0066\,x^2 + 0.3422\,x + 4.8497$
6ºC a 12ºC	$y = 4.9432\,e^{0.0641x}$
12ºC a 18ºC	$y = 5.1462\,e^{0.0607x}$

* y = water content (μg/cm^3), x = Temperature (ºC).

Table 6. Water mass balance in air dehydration test carried out by elements 1, 2, 3, 4, 5 and 6, connected in series, operating at 23ºC and 90 psig.

Element	Water content (μg/cm^3)		Water mass flow (μg/s)			Residence time (s)	% of water removal
	Residual	Permeated	Fed*	Residual	Permeated		
Element 1	1.6762	10.3311	1514.4	977.2	537.2	0.378	33.72
Element 2	1.1110	7.7424	1019.1	585.5	433.6	0.797	60.94
Element 3	0.7458	5.0575	608.6	355.7	252.9	1.259	76.81
Element 4	0.3752	3.4181	352.4	157.6	194.8	1.778	89.04
Element 5	0.1354	2.1211	166.1	49.4	116.7	2.370	96.36
Element 6	0.0000	1.0533	57.9	0.0	57.9	3.059	100.00

* Calculated from mass flow of permeate and residue.

Water removal percentage was calculated from water mass flow in permeate (Q_P) and in residue air (Q_R), according Equation 7 given below.

$$\% \text{ of water removal} = \left(\frac{Q_P}{Q_P + Q_R} \right) \times 100 \qquad (7)$$

Figure 6 shows water removal percentage as function of residence time of air through six elements connected in series. Since at constant applied pressure, the residence time of the feed air and the total membrane area are inter-related; the water removal percentage by the PDMS/PS membrane as function of the membrane area would give us a better understanding on the design of an air-dehydration equipment. Figure 7 reveals such a relationship. Figure 7 proves that six elements connected in series would operate like one PDMS/PS membrane element with a membrane area of 3338 cm^2.

Conclusions

Based on the experimental results of the present research works, the following conclusions can be drawn;

- Polysulfone support membrane, prepared from 21% casting solution, has suitable porosity to form a PDMS thin-film on it, this thin-film is durable enough to be operated at applied pressure of 90 psig.
- Immersion of wet polysulfone membrane in 2.7% PDMS solution (in petroleum ether) produces a composite membrane with O_2/N_2 selectivity slightly lower than value found in the literature, such difference suggests that there is imperfections (holes) in our PDMS film.
- Pores in PDMS polymeric film help the water-air separation process, since portion of feed air that passes through them, without feel membrane selective effect, act like carrier of permeated wet air, accumulated in opposite side of membrane.
- Thickness of PDMS membranes are considered apparent, because Equation 5 is suitable only to dense, uniform polymer film.
- The PDMS/PS membrane system developed in our laboratory is capable of generating 310 cm^3/s of dry air with a dew point of –50ºC at 23ºC and 90 psig applied pres-

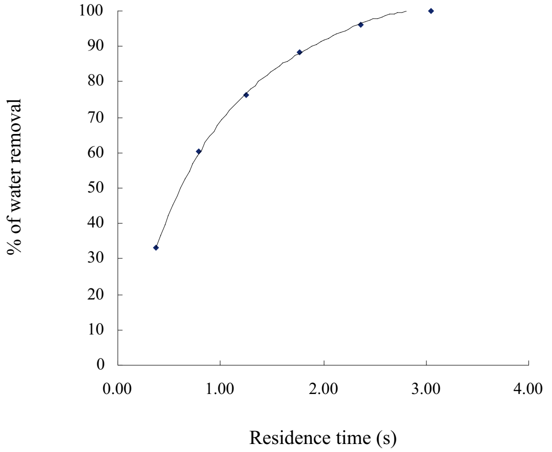

Fig. 6. Water removal percentage as function of residence time through six elements series operating at 23ºC and 90 psi.

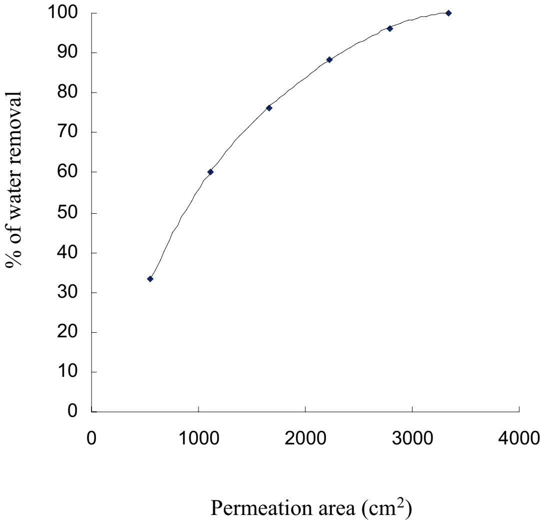

Fig. 7. Water removal percentage as function of permeation area of six elements series operating at 23ºC and 90 psi.

sure, the yield of dry-air, produced by our design, was determined to be 48.8% of the feed wet-air.

Experimental

Materials, Equipments and Methods

Materials

Polysulfone P3500 was purchased from Solvay Polymers, U.S.A. 1-methyl-2-pyrrolidinone was supplied by Aldrich Chemicals, U.S.A., non woven polyester fabric Hollytex 3329 was purchased from Ahlstrom, U.S.A. Methylvinylpolysiloxane RTV615A and Dimethylhidropolysiloxane/Methylvinylpolysiloxane RTV615B were supplied by General Electric, U.S.A. Petroleum ether (b.p. 40-70ºC) was provided by Productos

Químicos Monterrey S.A.), oxygen and nitrogen gases of 99.99% in purity were supplied by INFRA S.A.

Equipments

Microporous polysulfone membranes and PDMS membranes were fabricated using equipments constructed in our laboratory (Figure 8 and Figure 9). Calibrated Flow Meter (Gilmont Accucal flowmeter) was used to measure volumetric flow of gases. Dew points and temperature of feed gases were measured by a Thermohygrometer (Oakton WD-35612).

Methods

1. Microporous polysulfone membrane preparation

Microporous polysulfone membrane was prepared via Phase Inversion Method which had been described in detail by previous investigators[17]. Membrane casting polymer solution, consisting of 21 wt-% in PS and 79 wt-% in 1-Methyl-2-pyrrolidinone (NMP), was prepared by adding 186 g of PS (P3500) into a glass bottle containing 414 g of NMP, immediately the mixture was shaken vigorously to prevent polymer agglutination. The glass bottle was tumbled under heat lamp (~50 ^{0}C) until a homogeneous solution was reached, the polymer solution was then degassed under vacuum until no gas bubble appeared in the polymer solution. After the polymer solution was cooled to room temperature, the polymer solution was ready for membrane fabrication using the membrane casting machine shown in Figure 8. A brief description of the membrane casting procedure is given below.

The gap of the membrane casting knife was adjusted at 0.15 cm. above the polyester fabric (35.6 cm wide), the membrane casting speed was set at 10 cm/s with a d.c. gear motor control. After the driving motor was started, immediately the polymer solution was poured steadily into the trough of the feed chamber under nitrogen atmosphere, as the fabric move forward, the polymer solution was doctored onto the fabric surface, coagulation of polymer solution occurred as the polymer solution reached the water bath. Fresh de-ionized water (20 cm^3/s) was used to continuously flush against the freshly formed PS microporous membrane. For the purpose of having relatively similar porosity of the casted PS membrane, 10 m of the PS membrane was fabricated at a single run for this work. The PS membrane was rinsed three times with de-ionized water, then it was immersed in a plenty of de-ionizeed water and was kept in the refrigeration. By changing the polymer (PS) content in the membrane casting solution and following the same membrane fabrication procedure, another three different porosity polysulfone membranes were made. Porosity of the PS membranes were determined by measuring the permeate-flow of distilled water at an applied cross-flow filtration pressure of 32 psig (2.208 × 10^5 Pa) and using PS membrane of 20 cm^2 in size.

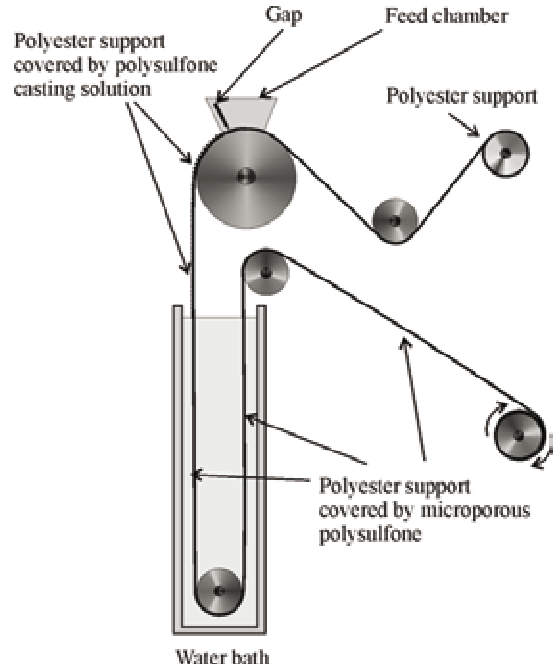

Fig. 8. Equipment used in microporous polysulfone membrane manufacturing.

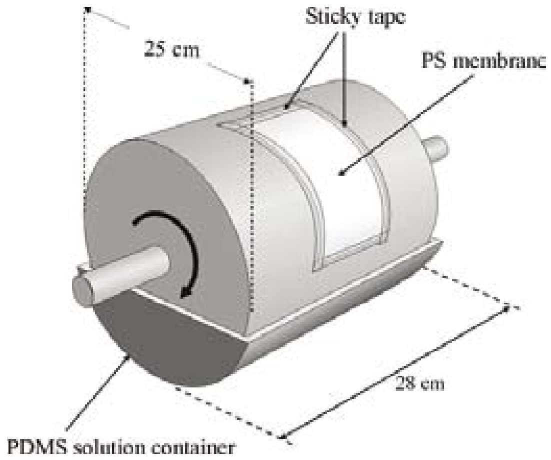

Fig. 9. Equipment used for preparation of PDMS/PS membrane by immersion method.

2. Preparation of Dimethylpolysiloxane Polymer(PDMS) Solution

PDMS solution was made mixing in a polyethylene container 3.213 g of methylvinylpolysiloxane (RTV615A, General Electric) with 0.357 g of cross-linking agent (dimethylhidropolysiloxane and methylvinylpolysiloxane; RTV615B, General Electric), afterward mix was heated at 60ºC for 4 minutes and finally 128.7 g of petroleum ether (bp 40-70ºC) was added, getting a 2.7 % solution of PDMS.

3. Dimethylpolysiloxane (PDMS) membrane preparation

A wet 12 cm by 72 cm polysulfone membrane, fabricated from a 21 wt-% PS polymer solution, was attached to a aluminum roller of 26 cm in diameter (Figure 9), the water droplets on the membrane surface were carefully removed by tissue paper, the immersion of PS membrane surface in PDMS solution (at 27ºC) was done by the rotation of the aluminum roller (linear speed = 2.44 cm/s), after the PDMS/PS membrane left the immersion bath, the membrane sheet was heated at 110ºC for 20 minutes, then cooled to room temperature; second immersion was carried out under the same conditions as the first one. Finally, membrane was heated at 120ºC for 1 hour in order to complete the polymer cross-linking reaction.

Portion of PDMS/PS membrane, 9.3 cm wide and 69 cm long, was attached to the PVC pipe (3.4 cm external diameter) as shown in Figure 10. The air dehydrating element (Figure 11) was then installed inside a permeation chamber. Following the same fabrication procedure, five more elements were made; their dimensions are listed in Table 7. Selectivity O_2/N_2 of each element was determined by permeation tests of pure O_2 and N_2 gases at constant applied pressure of 80 psig (5.52×10^5 Pa), volumetric flows of permeate gas was measured with a calibrated flow meter (Gilmont Accucal flowmeter).

4. Air dehydration test

Six air-dehydration PDMS/PS membrane elements were connected in series as shown in Figure 12.

The procedures of testing the air-dehydration of these membrane elements are given below.

A Gilmont Accucal Flowmeter was used to measure the volumetric flows, and a thermohygrometer (Oakton WD-35612) was used to measure the temperatures and the Dew Points. Compressed air was fed to bottom inlet of Element No.1, residue air coming out from this element was used to feed the bottom inlet of Element No.2 ; following the same sequence, Elements 3, 4, 5 and 6 were connected. During air dehydration test a constant applied pressure of 90 psig (6.21×10^5 Pa) was applied by a compressor, taking measurements of pressure at the feed zone (valves A and C closed, valve B opened) and at residue zone (closed valves A and B and opened valve C). Pressure in feed zone and pressure in residue zone were equal, which indicated that no pressure drop occurred from Element No.1 to No.6 and all of them operated at the same pressure.

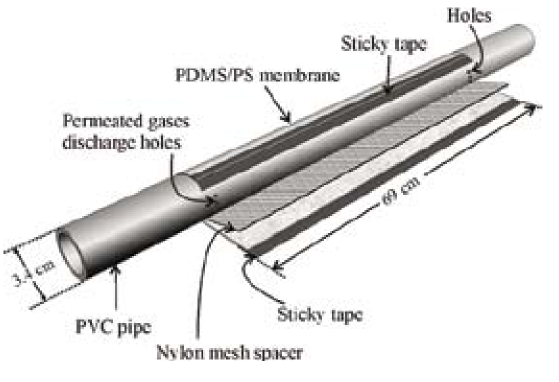

Fig. 10. PDMS/PS membrana partially installed on PVC pipe.

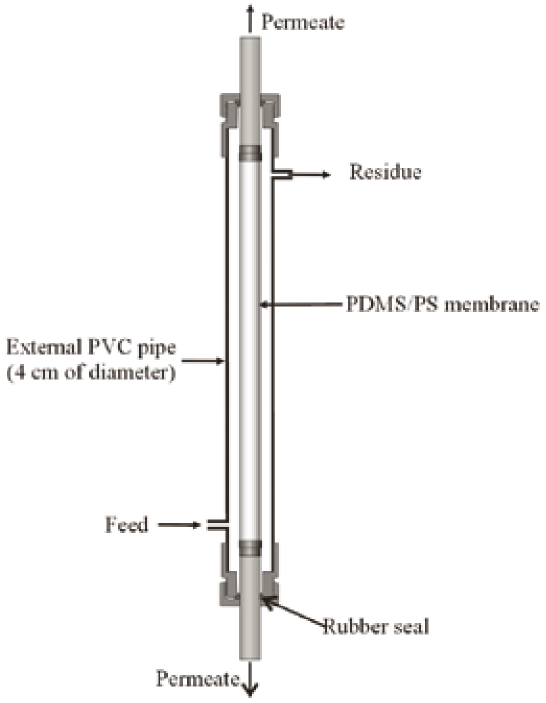

Fig. 11. Whole element used to air dehydration test.

Table 7. Dimensions of PDMS/PS membranes installed in elements named 1, 2, 3, 4, 5 and 6.

Element	Wide (cm)	Long (cm)	Area (cm^2)
Element 1	8.50	65.4	556
Element 2	8.43	66.0	557
Element 3	8.30	66.0	548
Element 4	8.62	66.0	569
Element 5	8.40	66.0	554
Element 6	8.40	66.0	554

Tests were also done at a constant volumetric flow, equally shared, through valves I and J (valves D, E, F, G and H closed). Once the system reached a steady state, volumetric flow and dew point of permeates from Elements No.1 to No.6 were measured, also the volumetric flow and the dew point of the residue air were measured by placing the measurement devices in outlets of valves I and J. In order to measure dew point of residue from Element No.5, valve I was closed while valve H

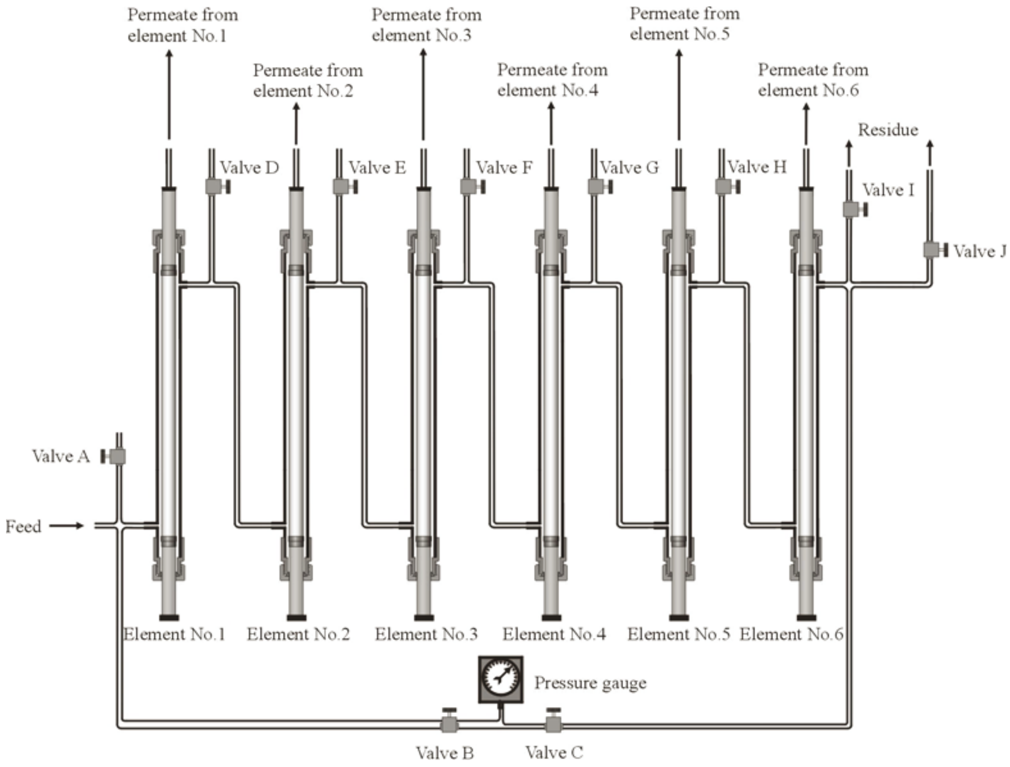

Fig. 12. Arrangement of six elements connected in series for air dehydration test.

was opened until volumetric flow from this valve reach same value as in valve J, thus, flow through element No.5 was not modified by valve H opening. Dew points of residue air from Elements No.4 to No.1 was determined by following the same procedure used for Element No.5. Dew point of feed-air was measured before and after air dehydration tests by placing instruments in valve A outlet.

Appendix

Equation for calculus of residence time

Residence time (t) of a gas flowing in a permeation chamber like shown in figure A1, is related to linear flow velocity (v) according to the following equation;

$$v(x)=\frac{dx}{dt};\quad dt=\frac{dx}{v(x)} \tag{A1}$$

Where x stands for distance traveled inside chamber. v is related to the volumetric flow (F) according to Equation (A2) shown below,

$$v(x)=\frac{F(x)}{A} \tag{A2}$$

where A corresponds to the cross sectional area of the permeation chamber which is perpendicular to the direction of the gas flow and depends on the diameter of the pipe that forms the permeation device; such area is expressed by the following equation,

$$A=\frac{\pi}{4}(D_2^2-D_1^2) \tag{A3}$$

While gas flows in parallel direction to the membrane surface, a portion of it (dF_P) permeates in perpendicular direction across the PDMS/PS membrane, the amount of feed air permeates across the membrane is proportionally to the membrane

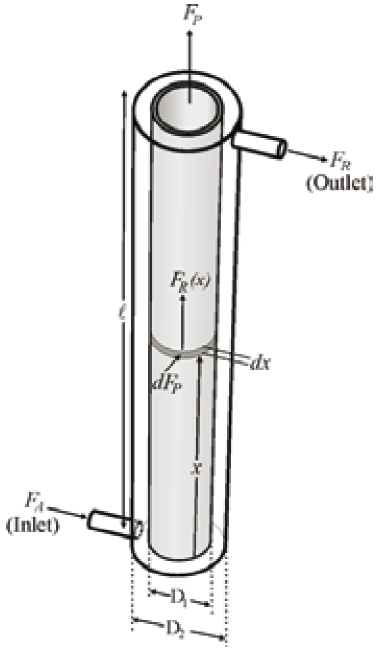

Fig. A1. Gas permeation chamber.

surface. Considering differential portion (dx) of the membrane (Figure A1), permeated volumetric flow (F_P) can be defined by Equation A4 given below,

$$dF_P = K\,a\,dx \tag{A4}$$

where a is the membrane width and K is a proportionality constant. Integrating the previous equation from 0 to x, a new equation for permeated volumetric flow is obtained as a function of distance x as given in Equation A5.

$$F_P(x) = K\,a\,x \tag{A5}$$

K is determined by substituting l (membrane length) in place of x and the total permeated volumetric flow (F_P) in place of $F_P(x)$ in Equation A5: $K=F_P/al = F_P/A_P = J_P$. Here, A_P is the total permeation area of the membrane and J_P is the permeated volumetric flow density which is assumed to be constant along the membrane surface. Substitution of J_P in Equation A5 leads to Equation A6:

$$F_P(\mathrm{x}) = J_P\,ax \tag{A6}$$

On other hand, the feed volumetric flow (F_A) equal to the sum of the residual volumetric flow (F_R) and the permeate volumetric flow (F_P):

$$F_A = F_R(x) + F_P(x) \tag{A7}$$

$$v(x) = \frac{F_A - J_P\,a\,x}{A}$$

Residual volumetric flow in term of distance is obtained by substiting Equation A6 into Equation A7 to give Equation 8 shown below,

$$F_R(x) = F_A - J_P\,a\,x \tag{A8}$$

Now, linear velocity of gas inside the chamber can be written as a function of x if Equation A8 is used in Equation A2:

(A9)

Combination of equations A9 and A1 generates a differential equation for residence time in terms of x:

$$dt = \frac{A\,dx}{F_A - J_P ax} \tag{A10}$$

Residence time is obtained by integration of equation A10 from 0 to x:

$$t(x) = \frac{A}{J_P\,a}\ln\left(\frac{F_A}{F_A - J_P\,a\,x}\right) \tag{A11}$$

Finally, the equation for the total residence time is obtained by substituting membrane length l in place of x; this would yield Equation A12 listed below,

$$t = \frac{A}{J_P\,a}\ln\left(l + \frac{F_P}{F_R}\right) \tag{A12}$$

References

1. Baker, R.W. *Ind. Eng. Chem. Res.* **2002**, *41,* 1393-1411.
2. Kimura, S.G.; Browall, W.R. *J. Membr. Sci.* **1986**, *29,* 69-77.
3. Liu, L.; Chen, Y.; Li, S.; Deng, M. *Sep. Sci. Tech.* **2001**, *36,* 3701-3720.
4. Rice, A.W.; Murphy, M. K. *U.S. Patent* 4,783,201 **1988**.
5. Murphy, M. K.; Rice, A.W.; Freeman J.J. *U.S. Patent* 4,793,830 **1988**.
6. Prasad R. *U.S. Patent* 4,931,070 **1990**.
7. Friesen, D.T.; Ray, R.J.; Newbold, D.D. *U.S. Patent 5*,002,590 **1991**.
8. Rogers, C.E. *Permselective Membranes*, Marcel Decker Inc. **1971**.
9. Osada Y.; Nakagawa T. *Membrane Science and Technology*, Marcel Decker Inc. N.Y. **1992**.
10. Shin-Etsu Chemical Co. *Characteristic properties of silicone rubber compound, (Gas permeability)*, http://www.yjmaterials.com/download_files/rubber_e.pdf accessed in December 2008.
11. Fried, J.R. *Polymer Science and Technology 2nd. Ed.* Prentice Hall, N.J. **2003**.
12. Matsumoto K.; Ishii K.; Kuroda T. *Polymer Journal*, **1991**, *23,* 491-499.
13. Yamasaki, A.; Tyagi R.K.; Fouda A.E.; Matsuura, T.; Jonasson, K. *J. Membr. Sci.* **1997**, *123*, 89-94.
14. Wang, D.; Li, K.; Teo, W.K. *J. Membr. Sci.* **1996**, *115*, 85-108.
15. Henis, J.M.; Tripodi, M.K. *Sep. Sci. Tech.* **1980**, *15*, 1059-1068.
16. Dean, J.A. *Lange's Handbook of Chemistry 13th. Ed.* McGraw-Hill, **1985**.
17. Kesting, R.E. *Synthetic Polymeric Membranes,* Wiley, N.Y. **1985**.