報　　文
화학공학 제13권 제2호
HWAHAK KONGHAK
J of the KOREAN INTS. CHEM. ENGRS.
Vol. 13, No. 2, April 1975

濃縮技術로서의 誘起逆透法의 開發

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(접수 1975.2.19)

Development of the Induced Reverse Osmosis Technique for Concentration

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(Received February 19, 1975)

要　約

本 研究는 적절한 外部溶液을 膜의 低壓側에 접촉시킴으로써 재래적인 逆滲透法 보다 좀더 효율적으로 溶液을 濃縮시킬려는 誘起逆滲透의 개발을 목적으로 管形모듈 流動濃縮工程에서 誘起될 외부용액의 接觸効果에 대한 理論的 推定과 실제적인 誘起 가능성에 대한 實驗的 接近을 시도하였다. 管形 膜支持管의 軸을 따라서 균일하게 膜의 低壓側에 외부용액을 交流式으로 도입하여 접촉시킴은 膜內側 原液을 汚染시킴이 없이 接觸効果를 효율적으로 誘起시키는 方法이었다. 逆滲透法에서 애용되는 非對稱形 多孔性膜은 膜의 構造上接觸効果의 誘起에 不利한 영향을 미치는 것으로 보여졌고 本法의 실제적인 활용에 있어서 최대의 難點은 膜外側流를 위한 가장 적절한 膜支持材의 開發에 있는 것으로 발견되었다.

Abstract

This study attempted an experimental approach to the applicability of the induced reverse osmosis technique in the tubular module concentration unit on the basis of the theoretically predicted contacting effect of an external solution. Keeping a suitable external solution in contact with the feed solution on the low pressure side of the membrane uniformly along the axis of the tubular pressure vessel induced effectively the contacting effect with no evidence of contaminating the feed solution. The asymmetric porous membranes which are appreciated in the reverse osmosis process appeared to be less beneficial in the induced reverse osmosis process. The crux of the technique was found to lie in developing the most suitable backing material for flow outside the membrane.

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Introduction

The development of reverse osmosis separation process as a practical concentration technique has many potential applications. It is promising for the concentration of biological fluids and biochemical solutions where the usual methods such as precipitation, lyophilization, evaporation, and freeze drying are likely to affect the stability, property, and chemical nature of the solution. A more extensive application is likely to be found in the general field of concentration of industrial solutions, waste recovery, and pollution control.

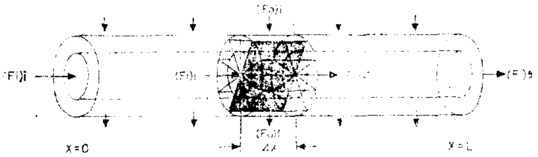
The reverse osmosis concentration of economically valuable aqueous solutions can be greatly facilitated in theory by keeping a suitable external solution in contact with the low pressure side of the membrane. At a given operating pressure, the effective pressure and hence the permeation rate is increased with a consequent increase in the capacity of the membrane for a given level of solute concentration. This technique is obviously a combination of 'osmosis' and 'reverse osmosis' and is called by Sourirajan7) Induced Reverse Osmosis to distinguish it from reverse osmosis which does not involve an external solution.

No experimental data have appeared in the literature using the above technique except for a preliminary study by the present authors.3) This study attempted an experimental approach to the applicability of the technique in the tubular module concentration unit on the basis of the theoretically predicted contacting effect of an external solution.

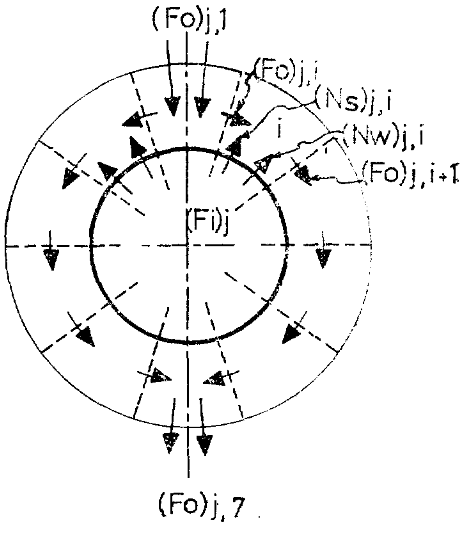
Theoretical

In the light of the underlying principle, the advantage of the induced reverse osmosis technique can be evaluated by calculating the processing capacity of the membrane (volume of feed solution that a unit area of the film surface can handle per unit time) for a given level of solute concentration. However, the contacting effect of an external solution to be induced, in actuality, depends on the specific mode of contact employed. The maximum effect in a tubular flow process may be expected where the external solution is kept in contact with the low pressure side of the membrane at the same flow rate and at the same concentration in its entire length as the feed solution flowing countercurrently in the tubular membrane. In reality, however, the flow rate of an external solution cannot be so great as that of an internal feed solution because of the excessive resistance in the annular gap between the membrane and the wall of its supporting vessel. It also may not be economical to employ an external solution of high concentration unless it is much cheaper than the feed solution. It is, therefore, more practical to consider the experimentally feasible case where a portion of feed solution is introduced as an external solution uniformly into the low pressure side of the membrane along the axis of the tubular vessel and flows out through the short circumferential passage.

The mathematical model set up for the analysis in such a case is depicted in *Fig.* 1. In the model, the tubular module is composed of a series of equ-



(a) Longitudinal view



(b) Circumferential view

Fig. 1. Mathematical model for analyzing the contacting effect of external solution.

al-sized stages, and the contacting area pertaining to each stage is divided into several substages (10 in the *Figure*).

Let F_i and X_i represent, respectively, the molar flow rate and mole fraction of the high pressure side feed solution at a longitudinal position X from the tube entrance. The steady-state total material balance around the j-th stage is written as

$$(F_i)_{j+1}=(F_i)_j-(N_w+N_s)_j \tag{1}$$

and the concentration in the next stage is given by

$$(X_i)_{j+1}=\frac{(F_i)_j(X_i)_j-(N_s)_j}{(F_i)_{j+1}}. \tag{2}$$

Here, $(N_w)_j$ and $(N_s)_j$ represent, respectively, the total rate of permeation of solvent (water) and solute across the membrane to the low pressure side. That is

$$(N_w)_j=2\sum_{i=1}^{6}(N_w)_{j,i}=2\sum_{i=1}^{6}(J_w)_{j,i}(\Delta S)_i \tag{3}$$

$$(N_s)_j=2\sum_{i=1}^{6}(N_s)_{j,i}=2\sum_{i=1}^{6}(J_s)_{j,i}(\Delta S)_i \tag{4}$$

where $(J_w)_{j,i}$ and $(J_s)_{j,i}$ denote, respectively, the molar fluxes of solvent and solute into the i-th substage in the j-th stage. Since the external solution is divided into two parts at the entrance and is collected at the exit, the contacting areas of the first and the last substages are half of the areas of the other substages in between them.

For porous reverse osmosis membranes which have a preferential sorption of water from aqueous feed solutions, the Kimura-Sourirajan[5)] analysis gives rise to the following basic equations for J_w and J_s at a given operating pressure, P, neglecting the concentration polarization effect on the high pressure side of the membrane, and assuming the fluid in each stage to remain at the uniform, constant concentration while the external solution passes out through the substages: i.e., the equations

$$(J_w)_{j,i}=A[P-\pi\{(X_i)_j\}+\pi\{(x_0)_{j,i}\}] \tag{5}$$

$$(J_s)_{j,i}=\left(\frac{D_{sm}}{k\delta}\right)\{(C_i)_j(X_i)_j-(C_0)_{j,i}(X_0)_{j,i}\} \tag{6}$$

In, subscript 0 in the parenthesis denotes the external solution, C is the molar density of the solution, and π the osmotic pressure. A is the pure water permeability constant defined as $A=\frac{\text{PWP}}{M_w\times3600\times P\times S}$ where PWP is the pure water permeability (grams/hour), S, the given area of membrane surface(cm^2), and M_w, the molecular weight of water. At a given operating pressure, A is independent of any solution under consideration. $D_{sm}/k\delta$ is the solute transport parameter in which D_{sm} is the diffusivity of the solute in the membrane phase, k, the distribution constant between the solution phase and the membrane phase, and δ, the effective thickness of the membrane. This parameter plays the role of a mass transfer coefficient with respect to solute transport through the membrane. Hence it is treated as a single quantity for the purpose of analysis. Based on the reverse osmosis data for the Loeb-Sourirajan type porous cellulose acetate membranes and aqueous solutions, there exists a unique relationship between A and $D_{sm}/k\delta$ (independent of feed concentration and feed flow rate) for a given membrane-solution system at a particular operating pressure.

The variation in concentration of the external solution through the substages can be calculated by

$$(X_0)_{j,i+1}=\frac{(F_0)_{j,i}(x_0)_{j,i}+(N_s)_{j,i}(\Delta S)_i}{(F_0)_{j,i+1}}, \tag{7}$$

associated with the material balance around the i-th substage

$$(F_0)_{j,i+1}=(F_0)_{j,i}+(J_w+J_s)_{j,i}(\Delta S)_i \tag{8}$$

The system of equations represented by Eqs. (1) through (8) can be used to obtain numerically the concentration profile along the longitudinal position in a given apparatus, together with the experimental data on the performance of the membrane to be used and on the physical properties of the solutions involved.

Figures 2, 3 and 4 illustrate a set of theoretical concentration curves as a function of the operating pressure for different membrane specifications for the case where the external solution is involved as compared with the case of no external solution involved (or pure water contact). In illustrative calculations, the feed solution was 0.7 molality (3.93 wt. %) sodium chloride aqueous solution flowing at 500 cc/min through 0.5-in-ID CA-NRC-18 type cellulose acetate lined tube, and the external solution was the same solution flowing in contact with the atmospheric pressure side of the membrane at the rate of 100 cc/min per each longitudinal distance of 50 cm. Calculations were performed on a 6-m-long tube (J=1200 in the *Figures*) in 5 mm intervals using IBM 1130 computer. As for the physical property relations for the sodium chloride-water system, the following equations extracted from the literature values[8] were used:

$C(\text{moles/cc})=0.05535-0.784X$

$\pi(\text{atm})=(36.07\times10^3X+0.0954\times10^6X^2)/14.7$

The CA-NRC-18 type C/A membrane specifications were given by the following relationship extracted from the data of Agrawal and Sourirajan[1] obtained for sodium chloride-water system for the pressure range 25 to 1500 psig:

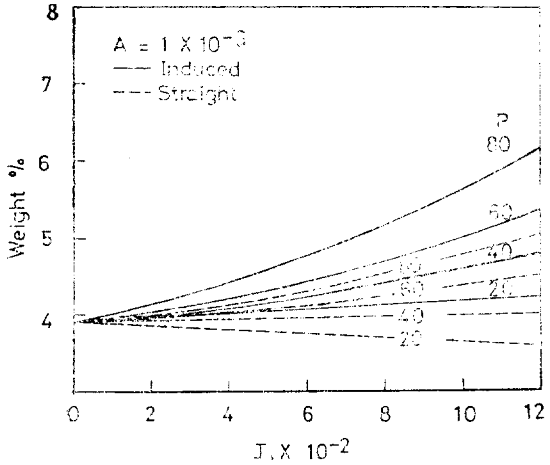


Fig. 2. Theoretical curves of concentration when A is 1×10^{-6}g-mole H_2O/cm^2 sec atm.

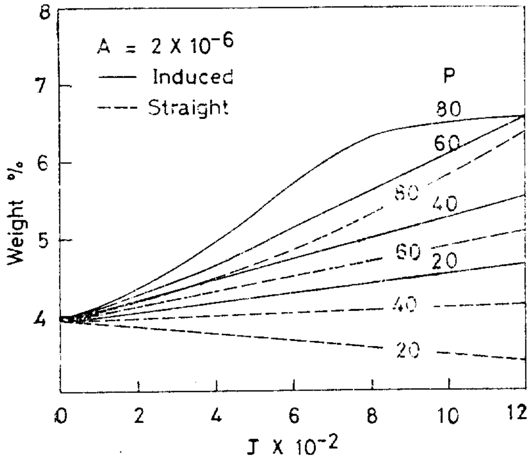


Fig. 3. Theoretical curves of concentration when A is 2×10^{-6}g-mole H_2O/cm^2 sec atm.

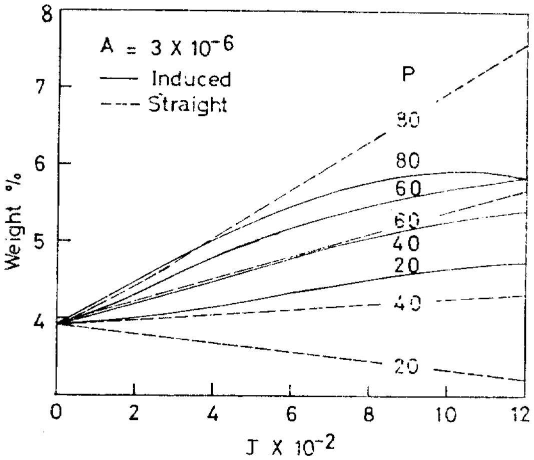


Fig. 4. Theoretical curves of concentration when A is 3×10^{-6}g-mole H_2O/cm^2 sec atm.

$$ln\left(\frac{D_{sm}}{k\delta}\times10^5\right)=3.48\,ln(A\times10^6)+1.34\,lnP-2.6$$

Calculations have been applied to the specific membrane-solution system for the preset operating conditions in a given apparatus, and to the ideal case for convenience where the external solution is perfectly kept in contact with the low pressure side of the membrane and there is no concentration polarization occurring on the high pressure side of the membrane. However, they help in evaluating the expected contacting effect in the induced reverse osmosis technique, and in drawing some guides for the application of the technique. One can see clearly the advantage due to the contacting effect induced. At any particular operating pressure, even lower than the osmotic pressure of the feed solution, it is possible to concentrate the solution effectively. It implies the increase in the processing capacity of the membrane for a given level of concentration. It is noted that the extent of this contacting effect depends on the membrane characteristics. The figures show that among the three values considered, $A=2\times10^{-6}$ g-mole H_2O/cm^2 sec. atm. is the most favorable. It is also noted that the use of an external solution of a given concentration places a limit on the effective longitudinal distance with a given membrane specifications.

The results of illustrative calculations have led to the conclusion that with a proper selection of membrane specifications and a proper variation of concentration of an external solution with the tube length, one can make use of the technique to the advantage for concentration in the once-through tubular flow process.

Experimental

It is the purpose of the experiments to verify experimentally the inducement of the contacting effect of an external solution and to experience the experimental difficulties to be encountered in the tubular flow process for the future application of the technique.

Fabrication of tubular membranes

The membranes used in this study were cast from the solution of Eastman grade E-400-25 cellulose acetate 23.1: formamide 26.9: acetone 50.0 by weight. This is the same solution used by McCutchan *et al.*[4] for use in sea water in the hope that the high acetyl content and long chain length would benefit performance at high operating pressures.

The solutions were made in 100 g quantities in a completely sealed 200 ml flask, and were mixed by shaking violently for at least 24 hours to insure complete and uniform dissolutions. The solution was ready for use, although time was allowed for any bubbles to emerge and escape.

Membranes were cast using an apparatus as described by Loeb.[6] *Figure* 5 shows the apparatus used. The casting tube is a 60-cm-long and 12.7-mm-ID glass tube. The cable is threaded through the casting tube and attached to the casting bob which is made of brass. For casting, the casting tube was charged with casting solution from 250 ml graduated syringe with the casting bob inserted at the bottom of the tube. Because of the very high viscosity of the solution, the tube was clamped stationary and the casting bob was pulled through the tube by the cable. The annular space between the bob and the tube was 0.15 mm which determined the thickness of the wiped solution.

The winch speed was set such that 30 seconds were required for the bob to travel the 60cm of the tube. The tube was then allowed to fall into the immersion water bath located directly beneath the casting tube during 30 seconds. Thus the evaporation time of the entire wiped film was controlled to be 30 seconds before immersion.

The cast films with their glass tubes were immersed for two hours in ice water where solution gels forming the membrane. As the films came out from the immersion water, they were left in their casting tubes and immersed in hot water for 10 minutes at a temperature slightly below the final curing temperature. They were then pulled out of the casting tubes, inserted into the tubular modules and cured in a final step by the flow of hot water at 0.7 atm through the modules as shown in *Fig.* 6. Such a technique of thermal treatment was used for curing the tubular membranes in order to achieve successful subsequent performance of membranes during the course of high-pressure experiments at room temperature. The membranes were kept wet at all times and in general they

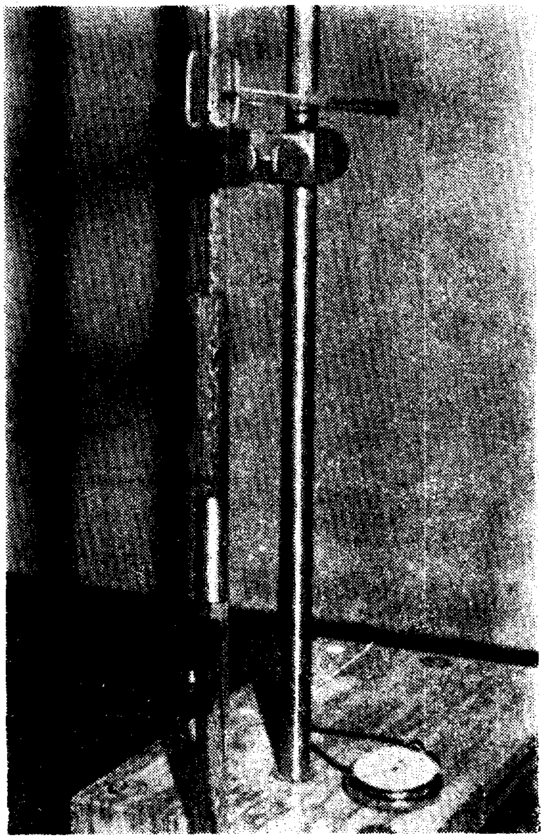


Fig. 5. Tube casting apparatus with winch drive.

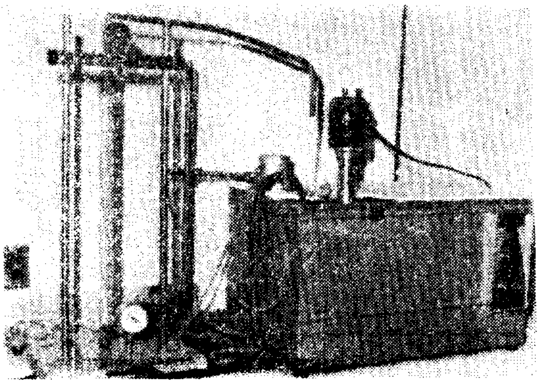


Fig. 6 . Apparatus for shrinking tubular membrane.

were put into service as soon as possible after fabrication.

Equipment

A schematic flow diagram of the complete unit and a photograph showing the tubular concentration assemblies are given in *Figs.* 7 and 8, respectively. The test unit accommodates up to 10 50-cm-long tubular assemblies connected in series by U bend turnarounds.

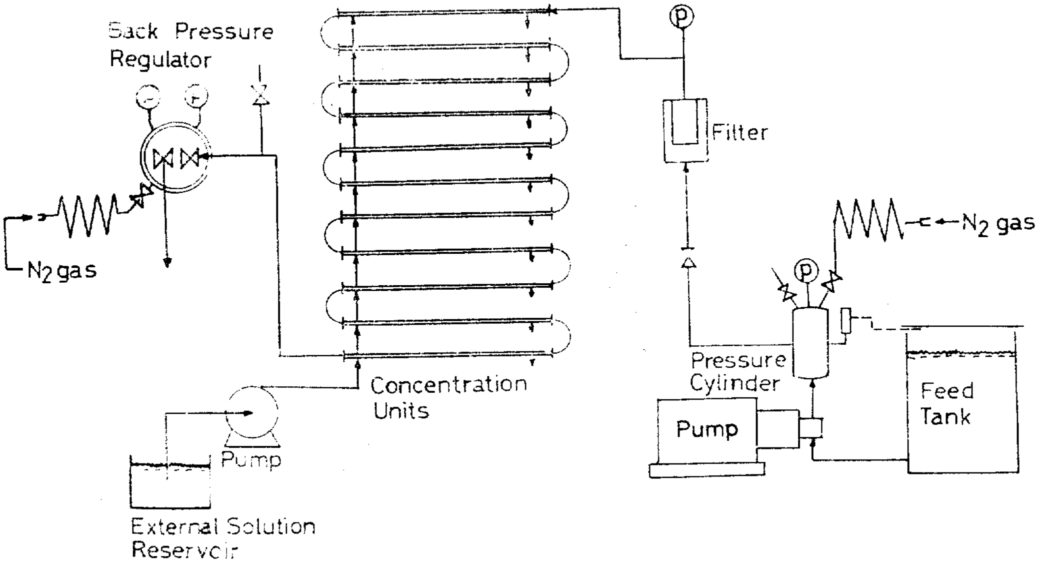


Fig. 7. Flow diagram of reverse osmosis equipment.

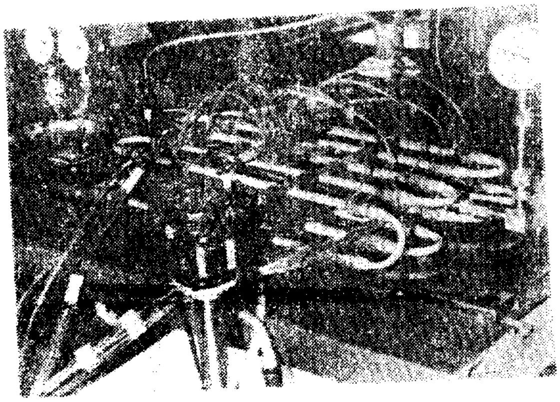


Fig. 8. Photograph of reverse osmosis equipment.

Fig. 9. is a diagram showing the detail of one tubular assembly. The perforated support vessel is a hard-drawn copper tube. Two lines of 1/16-in holes were made in parallel on the two sides of the tube in an interval of 1 cm in a slightly zigzag shape along the axis of the tube. Each line consisted of 45 holes and was enveloped with a cap welded around. An external solution could be introduced uniformly into the low pressure side of the membrane after being first collected in the cap and then flow in two parts through the circumferential short passage provided by the backing layer between the membrane and the tube wall. Since the path for an external solution is reasonably short, the external solution could be

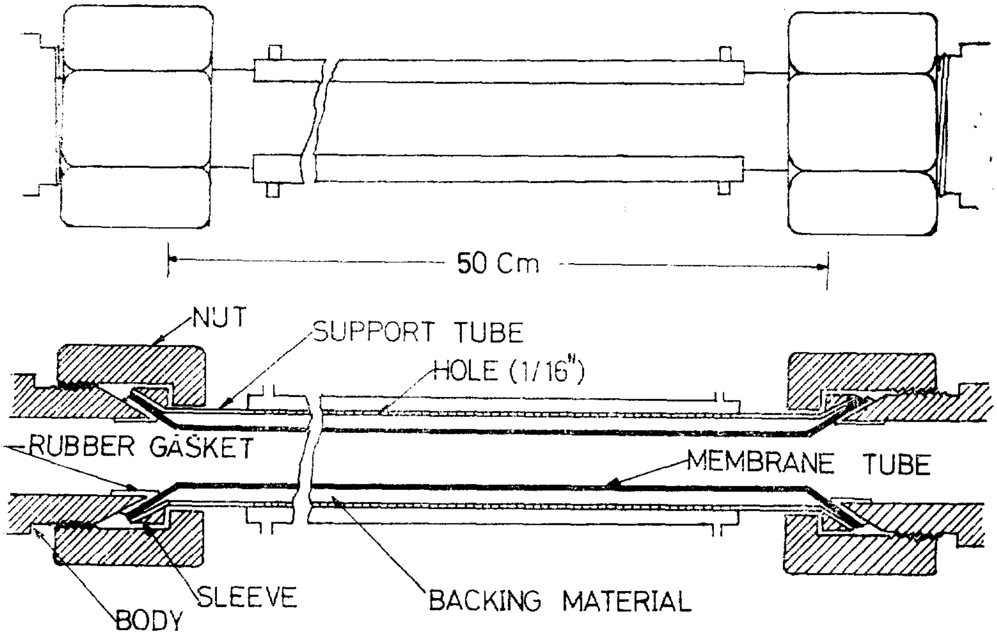


Fig. 9. Cross-section of tubular assembly.

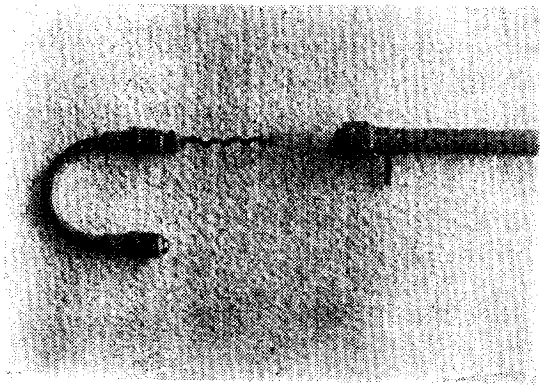


Fig. 10. Tubular assembly with end fittings.

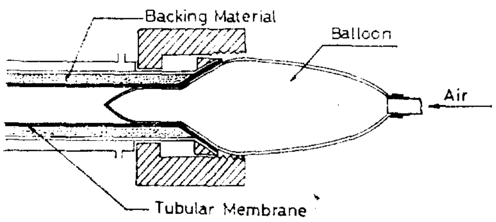


Fig. 11. Flaring of tubular membrane ends.

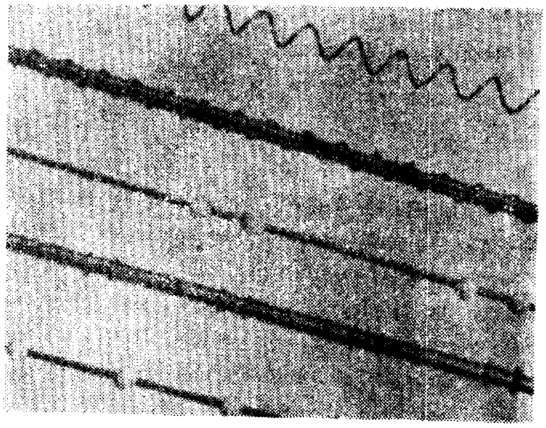


Fig. 12. Turbulence promoter configurations tested in 14-ft-long, 0.56-in-ID cellulose acetate lined reverse osmosis tubes.

made to flow at any rate with a small pressure drop. The ends of the tube were flared to prevent the leakage in connection. Tubular assembly with end fittings can also be seen in *Fig.* 10. The membrane ends to be fitted to the tube were flared by the method as depicted in *Fig.* 11.

A polyethylene string spiral-wound around a central support rod was inserted into the tube as a turbulence promoter to minimize the concentration effects. Centered by a spider inserted in the end fittings, it was detached from the membrane by a 1 mm annular spacing. This type of turbulence promoter is known to be the best among the vaious ones as shown in *Fig.* 12, although the spaced spheres are said to show greater effectiveness in fouling control.[9)]

For a nominal membrane tube outer diameter of 0. 125 cm, there was an annular gap of 0. 01 cm between the membrane tube and the support vessel. It was first filled with three layers of 100 mesh stainless sieve. They were stabilized under hydraulic load of 100 atm. The membrane which was wrapped around by one layer of nylon could then be inserted tightly into the vessel. The backing was thus composite. The metal sieve served to provide a relative porous, low resistance flow path and the nylon taffeta served to smooth out the irregularities on the surface of the metal sieve, thereby reducing pinholes in the membranes. Several other materials were tested but were not better than those used.

Results and discussion

The membranes used in the experiments were all fabricated with the evaporation time 30 seconds and the heat treatment at 82°C. The shrinkage temperature was chosen to render the membranes high selectivity based on the performance data of the flat sheet type membranes as given in *Table* 1. In any experiments, the membranes were first subjected to a pressure treatment consisting of pumping distilled water on the surface of the film at a pressure about 15 percent higher than the maximum intended operating pressure for at least an hour. The pure water permeability, PWP, and subsequently solution-permeation rate, PR, and fraction solute separation, *f*, were then measured at the intended operating pressure. The effective area of a membrane tube in each tubular unit was 198cm². The flow rate of the fluid in the vessel was set to be 522 cc/min, and an external solution was made to flow in the low pressure side of the membrane at the rate of 100 cc/min per each vessel unit with a pressure drop of 0. 4 atm.

The concentrations of NaCl solutions and sucrose solutions were determined, respectively, by the Mohr method and by refractive index measurements using a Bausch and Lomb refractometer. The accuracy of the separation data was within 1 percent in all cases. In each experiment, the fraction solute separation, *f*, was determined by

$$f=\frac{C_f-C_p}{C_p}$$

where C_f and C_p are, respectively, the molarities of the feed solution and the membrane-permeate solution.

Table 1. Performance of flat-sheet cellulose acetate membranes as a function of shrinkage temperature

T °C	PWP cc/hr	PR cc/hr	f %	C_f mole/l	C_p mole/l
76	1478	706	86. 4	0. 515	0. 07
78	1220	613	84. 4	0. 515	0. 08
80	926	456	95. 1	0. 515	0. 05

The experiments were performed on the test of the turbulence promoter inserted, and on the test of the equipment used for inducing the contacting effect of an external solution as compared with the case of no external solution involved for the sodium chloride-water and sucrose-water systems.

Results obtained with and without the detached turbulence promoter inserted in five tubular units in the operation at 40 atm using 0. 5 mole/l NaCl aqueous solution are presented in *Table* 2. The results show that under specified experimental conditions, the concentration polarization effects were significant and they

Table 2. Effect of turbulence promoter

Unit No.	Insert	PWP cc/hr	$\frac{PR}{PWP}$	f %
1	×	894	0. 522	47. 9
	○		0. 611	61. 6
2	×	786	0. 469	66. 0
	○		0. 561	71. 2
3	×	990	0. 527	42. 0
	○		0. 657	59. 6
4	×	762	0. 451	64. 0
	○		0. 563	71. 2
5	×	750	0. 484	50. 0
	○		0. 560	67. 3

Table 3. Membrane performance at 60 atm for NaCl solutions

Unit No.	PWP cc/hr	$A\times10^6$ $\frac{\text{gmole. H}_2\text{O}}{\text{cm}^2\ \text{sec. atm}}$	PR cc/hr	f %	C_f mole/l(wt. %)	C_p mole/l(wt. %)
1	1092	1.41	468	75.6	0.41(2.325)	0.10 (0.625)
2	1212	1.56	537	74.4	0.41(2.325)	0.101(0.65)
3	1104	1.42	480	80.5	0.41(2.325)	0.08 (0.5)
4	1182	1.52	525	80.5	0.41(2.325)	0.08 (0.5)
5	1056	1.36	474	80.5	0.41(2.325)	0.08 (0.5)

Table 4. Concentration of NaCl solutions at 60 atm with five units

Contact	Expt. No.	$(C_f)_i$ mole/l(wt. %)	$(C_f)_f$ mole/l(wt. %)	$(C_p)_i$ mole/l(wt. %)
	1	0.41(2.325)	0.45(2.56)	
No	2	0.45(2.56)	0.49(2.77)	
	3	0.49(2.77)	0.53(3.00)	
yes	4	0.47(2.67)	0.52(2.95)	0.47(2.67)
	5	0.52(2.95)	0.57(3.22)	0.52(2.95)

Table 5. Membrane performance at 60 atm for NaCl Solutions

Unit No.	PWP cc/hr	A $\frac{\text{gmole. H}_2\text{O}}{\text{cm}^2\ \text{sec. atm}}$	PR cc/hr	f %	C_f mole/l	C_p mole/l
1	1068	1.38	669	65.5	0.55	0.19
2	1272	1.64	819	60.0	0.55	0.22
3	1074	1.38	663	69.2	0.55	0.17
4	912	1.18	555	77.3	0.55	0.125
5	858	1.11	528	79.2	0.55	0.115
6	1062	1.37	681	62.8	0.55	0.205
7	858	1.11	489	86.3	0.55	0.075
8	1104	1.42	699	59.2	0.55	0.225
9	780	1.01	465	82.7	0.55	0.095
10	840	1.08	450	81.8	0.55	0.10
11	792	1.02	459	80.9	0.55	0.105

Table 6. Concentration of NaCl solutions at 60 atm with eleven units

Contact	Expt. No.	$(C_f)_i$ mole/l(wt. %)	$(C_f)_f$ mole/l(wt. %)	$(C_p)_i$ mole/l(wt. %)
	1	0.54(3.05)	0.59(3.33)	
No	2	0.59(3.33)	0.63(3.57)	
	3	0.63(3.57)	0.68(3.83)	
	1	0.60(3.38)	0.70(3.93)	0.47 (2.67)
Yes	2	0.70(3.93)	0.80(4.5)	0.435(2.47)
	3	0.80(4.5)	0.88(4.94)	0.405(2.31)

Table 7. Membrane performance at 60 atm for sucrose solutions

Unit no.	PWP cc/hr	A $\frac{\text{gmole. } H_2O}{\text{cm}^2 \text{ sec. atm}}$	PR cc/hr	f %	C_f mole/l(wt. %)
1	918	1. 18	774	100	0. 106(3. 7)
2	1080	1. 39	798	100	0. 106(3. 7)
3	972	1. 25	686	100	0. 106(3. 7)
4	1092	1. 41	686	100	0. 106(3. 7)
5	924	1. 19	708	100	0. 106(3. 7)

Table 8. Concentrations of sugar solution at 60 atm with five units using NaCl solution as an external solution

Contact	Expt. No.	$(C_f)_i$ mole/l(wt. %)	$(C_f)_f$ mole/l(wt. %)	$(C_p)_i$ mole/l(wt. %)
No	1	0. 111(3. 7)	0. 121(4. 0)	
	2	0. 121(4. 0)	0. 142(4. 6)	
	3	0. 142(4. 6)	0. 160(5. 1)	
	4	0. 160(5. 1)	0. 177(5. 6)	
Yes	1	0. 140(4. 5)	0. 166(5. 3)	0. 53(3. 00)
	2	0. 166(5. 3)	0. 191(6. 1)	0. 51(2. 88)
	3	0. 191(6. 1)	0. 216(6. 8)	0. 50(2. 85)

could be decreased effectively by using the turbulence promoter employed, as evidenced by the significant increase in the membrane permeation rate and the solute separation.

Five concentration units, with the membranes which were shown to exhibit the performance as given in *Table* 3 for NaCl solution systems, were used in series to test the contacting effect of NaCl external solution. The results are shown in *Table* 4. And the results of the similar experiments where eleven units were in operation with the membranes as shown in *Table* 5 are given in *Table* 6.

Using NaCl solutions as external solutions, sucrose solutions were concentrated with five units in series containing the membranes which showed the performance given in *Table* 7. The results obtained are presented in *Table* 8.

It is seen that the membranes used in the experiments exhibited about the same throughput rate but the significantly lower fraction solute separation, as compared with the performance data obtained with flat sheet type membranes.

The loss in membrane selectivity was attributed in part to the difficulty in membrane/pressure vessel sizing, but in most part, to the selection of unsuitable membrane support or backing material. The effects of support materials on membrane distortion under applied hydraulic load of 60 atm could best be appreciated visually. *Figure* 13 is an optical photomicrograph of the membrane pressured on the backing layers

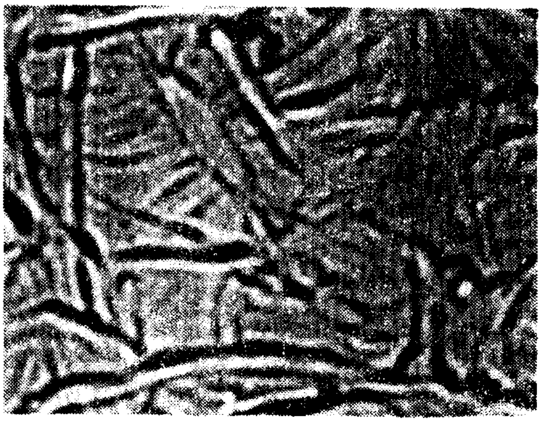


Fig. 3. Optical photomicrograph (×100) of a tubular membrane surface pressured at 60 atm for one hour on nylon taffeta/100 mesh stainless steel sieve support surface.

used. Note the impressions in the membrane with the physical appearance of the support media.

For a flow concentration process at constant operating pressure, one can easily derive the following simple equation for the fraction solute recovery $\bar{F}$ (defined as the ratio of the weight of solute in the concentrate to that in the feed solution at the entrance) during the increase in solute molality, m_f, starting with a feed solution of molality, m_i:

$$log\bar{F}=\left(1-\frac{1}{f}\right)log\frac{m_f}{m_i}$$

In the derivation, the solute separation f is assumed constant in the entire concentration range involved in the process, and is defined using molalities instead of molarities. Plots of this equation as a function of f, given in *Fig.* 14, show that the solute recovery decreases sharply with the increase in f. The loss in membrane selectivity must, therefore, have obstructed the effective concentration in the experiments.

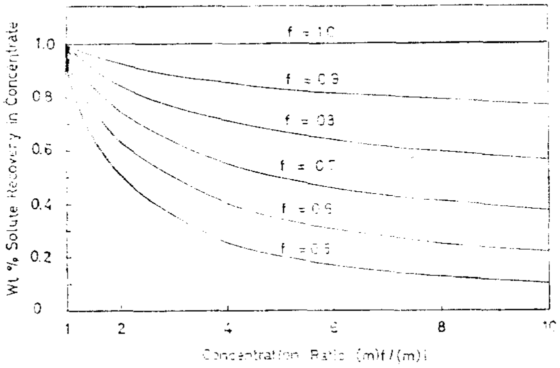


Fig. 14. Solute recovery during concentration as a function of fractional solute separation.

Since the backing was composite, with the nylon taffeta having greater flow resistance on the membrane side and with the metal sieve on the wall side of the vessel, the external solution tended to flow mainly through the metal sieve and the space between the metal sieve and the vessel wall without contacting intimately with the membrane. The above problems, experienced with the backing materials in this study, should be resolved by developing the most suitable ones.

The membranes used were of asymmetrical nature in structure with a thin dense layer (~2500Å) and a thicker porous layer (~0.013cm). In the reverse osmosis process the dense layer should always be placed toward the high pressure side of the membrane. The salt rejection is provided entirely by this layer and the thick layer serves only as a support layer. In order to induce the contacting effect, an external solution should be penetrated into the porous layer and mixed uniformly with the salt-rejected permeate. Recently Blumberg et al[2). made a study on the characterization of cellulose acetate membranes by low pressure transport. It was estimated that 92 percent of the pressure drop was across the thin dense layer. Extrapolating their result directly to high pressure transport at 60 atm, 4.8 atm still remains across the thick porous layer. It is, therefore, presumed that the external solution which was introduced at 0.4 atm in the present study could not be in good contact with the skin layer. In this regard, studies on the effect of the membrane structure on the induced reverse osmosis deserve to receive a special attention. Such studies are in progress and will be published in the near future.

Combining the above discussions in the least favorable manner leads to the experimental results that the contacting effect observed is apparently lower than expeced. It is noted, however, that concentration could still be facilitated to a great extent by the induced effect.

In concentrating sugar solution with the sodium chloride external solution, however, no salt component was found in the concentrate of sugar solution. The membranes used have pores big enough to permit the transport of sodium chloride ions through the dense layer, as the performance data indicate. This result suggests that any suitable solution which is economical and has high osmotic pressure at low concentration can be safely employed as an external solution without contaminating the feed solution.

Conclusions

1. The induced reverse osmosis process proved to have an advantage as a concentration technique based

on the theoretical and experimental study.

2. The uniform cross-flow type contact of an external solution with the feed solution along the axis of the tubular vessel provides an effective means to induce the contacting effect of an external solution.

3. In the once-through tubular flow concentration, one should consider carefully a proper selection of membrane specifications and a proper variation of concentration of an external solution with the tube length.

4. The backing layer for flow outside the membrane was observed to play a significant influence on the membrane performance and the contacting effect of an external solution. The efforts to develop the most suitable backing material are needed.

5. The asymmetric porous membranes which are appreciated in the reverse osmosis process appeared to be less beneficial in the induced reverse osmosis process.

6. The feed solution is not contaminated by the use of an external solution on the low pressure side of the membrane.

Acknowledgement

The authors wish to acknowledge the financial assistance of the Ministry of Science and Technology in carrying out the work described.

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