멤브레인(Membrane Journal)
Vol.12, No.4 December, 2002, 226-239

유기용매 탈수를 위한 투과증발 판틀형 모듈의 전산모사와 공정설계

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(2002년 4월 22일 접수, 2002년 10월 16일 채택)

Simulation and Process Design of Pervaporation Plate-and-Frame Modules for Dehydration of Organic solvents

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(Received April 22, 2002, Accepted October 16, 2002)

요 약 : 유기용매의 탈수화 공정의 거동을 예측할 수 있는 투과증발 판틀형 모듈에 대한 전산모사 모델을 확립하였는데 이는 공정의 분석 및 최적화의 도구로 사용할 수 있다. 확립한 모델은 물질, 열 및 농도 수지식으로 이루어졌으며 유한요소법의 수치해석을 사용하여 각 투과 특성들은 계산하였다. 본 전산모사에서는 모듈내 각 두개의 막 사이에 있는 단일 공급유로를 기본 미분단위부피로 사용함으로써 계산과정을 단순화하고 계산시간을 단축할 수가 있었다. 또한 모델식에 각 파라메타들을 실제 공정에서 직접 구하여 사용함으로써 공정모사의 정확성을 얻을 수가 있었다. 모사모델의 타당성을 확인하기 위해서 에탄올/물 혼합물을 모델 혼합물로 선정하여 상업 투과막인 AzeoSep™-2002를 통한 투과실험을 행하여 각 투과 특성들을 얻었으며 얻은 이들 값들과 모사 모델식으로부터 계산된 값들과 비교한 결과 서로 잘 일치함을 보여 본 모사모델의 타당성을 입증하였다. 또한 모사모델을 사용하여 연속식 및 회분식 투과공정에서의 에탄올 탈수 공정을 모사하였는데 모사 결과들은 공정 분석 및 최적화를 위한 기본자료로 활용할 수 있다. 본 연구에서는 모사결과를 토대로 회분식 공정과 연속식 공정을 비교 분석하였다.

Abstract : A process simulation model of pervaporation process has been developed as a design tool to analyse and optimize the dehydration of organic solvents through a commercial scale of pervaporative plate-and-frame modules that contain a stack of membrane sheets. In the simulation model, the mass balance, the heat balance and the concentration balance are integrated in a finite elements-in-succession method to simulate the overall process. In the integration method, a feed channel between membrane sheets in the modules was taken as differential unit element volume to simplify calculation procedure and shorten computing time. Some of permeation parameters used in the simulation model, were quantified directly from the dehydration experiment of ethanol through AzeoSep™-2002 membrane which is a commercial pervaporation membrane. The simulation model was verified by comparing the simulated values with experimental data. Using the model, continuous and batch pervaporation processes were simulated, respectively, to acquire basic data for analysing and optimizing in the dehydration of

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ethanol through the membrane. Based on the simulation results, a comparison between the continuous and the batch pervaporation processes would be discussed.

Keywords : *pervaporation, simulation model, plate and frame module, dehydration*

1. Introduction

The success of pervaporation in industry is highly dependent on progress in two fields 1) the development of membrane with high selectivity and permeability and 2) the provision of engineering tools to analyse and optimize pervaporation within the concept of process design. While there has been constant progress in the field of membrane development in recent years[1], aspects of process technology have been widely neglected. From this point of view, a simulation model can be a good tool to analyse, optimize, and design the process. The modelling of mass transport through pervaporation membrane is well established on the basis of the sorption-diffusion mechanism[2-4]. Recently, the simulation models were proposed to allow the simulation and optimization of the membrane area and energy requirements in pervaporative plate-and-frame module [5-6]. The transport descriptions in these models involve a large number of phenomenological coefficients that besides being difficult to obtain lead to great problems in the set-up of simple flux equations incorporating adequate design parameters.

This study was focused on the development of an advanced simulation model based on a phenomenological/semi-empirical approach in the pervaporation dehydration of solvent. Ethanol/water mixture was used as a model mixture. Some of permeation parameters, which are used in the simulation model, were quantified directly from the real dehydration pervaporation of ethanol through a commercial hydrophilic membrane, AzeoSep^{TM}-2002. By adopting the coefficients determined from real system, the simulation model could be of a more practical value. Its application to two basic processes, that is, continuous and batch processes, could highlight the importance of process parameters such as feed concentration, feed temperature, target feed quality in the process design and optimization of pervaporation. In the following section, the theoretical development of the simulation using a finite elements-in-succession method is presented.

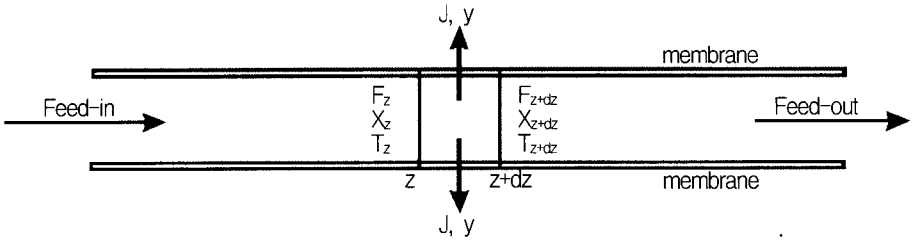
2. Theory

Plate-and frame modules are employed in this simulation since they are the commercially most established type for pervaporation units. With respects to its design, a plate-and frame module is characterized by;

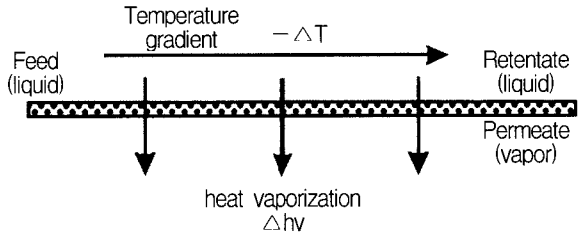
(a) Dimension of each membrane sheet, length l_{unit} and width w_{unit},
(b) Height of each feed channel
(c) Number of membrane sheets in a unit and number of units making up a module

In this study, two configurations of the feed channels are considered in a module unit: 1) series connection and 2) parallel connection.

A schematic representation of feed channel and flows through a differential element of volume (dz) is given in permeate side of membrane, a driving force, activity gradient can be created across membrane thickness, selective permeation takes place, and then feed flow rate as well as feed composition changes through the differential volume. Since the heat of evaporation is supplied from the feed side, the feed temperature falls constantly and so the flux through the membrane decreases as shown in Fig. 1. A). Therefore three different balances over the differential



A) a feed channel and the flows through a differential element of volume



B) a temperature gradient along feed flow

Fig. 1. Principal balances across as differential element of volume in feed channel.

volume are taken into account as follows;

Mass balance

$$\frac{d}{dz}F = -J(2w_{unit}) \tag{1}$$

Concentration balance

$$\frac{d}{dz}(Fx) = -Jy(2w_{unit}) \tag{2}$$

Heat balance

$$\frac{d}{dz}(Fh_F) = -J\triangle h_V(2w_{unit}) \tag{3}$$

where F denotes feed flow rate, J total flux and w_{unit} the width of unit, x the concentration of a selectively permeating component in feed, y the concentration of a selectively permeating component in permeate, h_F the enthalpy of feed flow, and △hv the heat of the evaporation of permeant. Eqs (1)-(3) can be rewritten as follows, respectively,

$$dF = -2Jw_{unit}dz \tag{4}$$

$$xdF + Fdx = -2Jyw_{unit}dz \tag{5}$$

$$FC_pdT = -2J\triangle h_Vw_{unit}dz \tag{6}$$

where C_p is the heat capacity of feed liquid. From Eqs (4) and (5), the following equation can be obtained.

$$dx = \frac{2Jw_{unit}}{F}(x-y)dz \tag{7}$$

The changes in feed flow rate, feed composition, and feed temperature along with z direction can be calculated if flux and permeate composition are expressed as a function of both feed composition and feed temperature as follows, respectively.

$$J = f(x, T) \tag{8}$$

$$y = g(x, T) \tag{9}$$

Hence, flux, feed composition and permeate composition can be also expressed as a function of location along with z direction.

An algorithm that is based on a numerical method, "a so-called succession of elements" method, carries

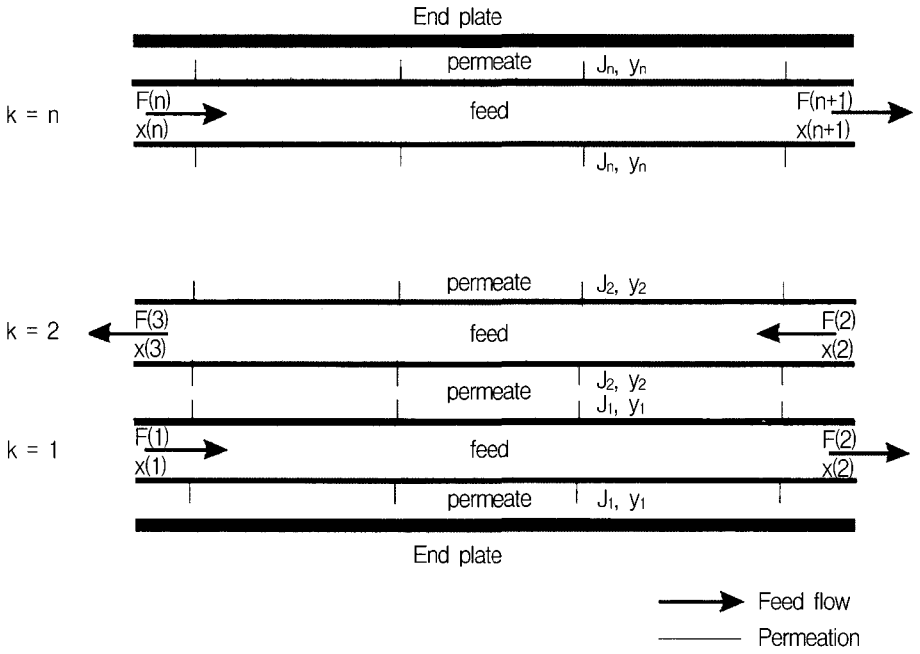


Fig. 2. Representation of the feed channels and flows in a membrane module unit.

out the simulation. This method involves dividing the unit length into finite elements. Within these elements it is assumed that the mass transfer driving force, that incorporates the activity coefficients on permeate side and feed side, as well as the component properties remain constant. The simulation of one finite element can then be completed. This approach has the advantage that the different parameters influencing the overall process can be implemented in modular form into the simulation program. By using the simulation model described above, the numerical method will be applied to simulate permeation performance in two processes, that is, a continuous process and a batch process. In a unit of plate-and-frame module, a number of membrane sheets are stacked as described in Fig. 2. The feed channels are connected each other in series (Fig. 2) or arranged in parallel. Generally, the series connection of the channels is employed in continuous pervaporation process, while the parallel connection is popular in batch process.

2.1. Continuous pervaporation process

In continuous process, feed mixture flows through a sequence of the channels as depicted in Fig. 2. Thus, the final retentate can be a product. If the each membrane sheet is not big enough for permeation through it to significantly change the feed composition or feed temperature, each feed channel can be taken as a element volume in the numerical method. Then the differential forms of the parameters involved in the above equations, Eqs (4), (6) and (7) can be transformed into the difference form of them, respectively, as follows;

$$\triangle F = F(k+1) - F(k) = -2J(k)A_m \tag{10}$$

$$\triangle T = T(k+1) - T(k) = -\frac{2J(k)\triangle h_v}{F(k)C_p}A_m \tag{11}$$

$$\triangle x = x(k+1) - x(k) = \frac{2J(k)}{F(k)}[x(k) - y(k)]A_m \tag{12}$$

where $F(k)$, $T(k)$, $J(k)$, $x(k)$, and $y(k)$ are the respective parameters at the k^{th} feed channel and A_m is a membrane area of each membrane sheet. The initial condition for each parameter can be given;

$F(1)$ = initial feed flow rate

$T(1)$ = initial feed temperature

$x(1)$ = water concentration in initial feed

$J(1) = f(x(1), T(1))$

$y(1) = g(x(1), T(1))$

Now retentate temperature, retentate composition, retentate flow rate, flux and permeate composition at a location in the module unit can be determined by the numerical method.

2.2. Batch pervaporation process

In batch process, the feed channels in a module unit are arranged in a parallel connection, so that feed mixture can feed each channel in a parallel mode. Feed mixture circulates from a feed tank through membrane module for a given period of time. During the circulation of feed mixture through the membrane module, feed volume will decrease with time as much as the amount of components permeating through the membrane sheets in the module. Therefore total mass balance for feed volume in the system for a differential time interval, dt, is given as follows;

$$dM = -JnA_m dt \tag{13}$$

where M denotes a feed mass and n is a number of sheets stacked in a membrane module unit. For a component permeating preferentially through membrane, mass balance equation is express by

$$d(Mx) = -JynA_m dt \tag{14}$$

$$xdM + Mdx = -JynA_m dt \tag{15}$$

$$dx + x\frac{dM}{M} = -\frac{JynA_m}{M} dt \tag{16}$$

Combining Eqs(13) and (16) yields

$$\frac{dM}{M} = -\frac{dx}{x+y} \tag{17}$$

Thus, rewriting Eq.(16) gives

$$dx = -\left(\frac{x+y}{y}\right)\left(\frac{JynA_m}{M}\right)dt \tag{18}$$

Feed mass at time t_k, M is expressed by initial feed mass M_o taken by permeating amount M_k through membrane accumulated for a period of time, t_k

$$M = M_o - M_k = M_o - nA_m \int_0^{t_k} Jdt \tag{19}$$

To calculate feed composition and feed mass with permeating time, the same numerical method as used in the continuous process can be adopted. Total time period is divided equally into finite element time interval, $\triangle t$. Feed mass $M(k+1)$ and concentration $x(k+1)$ at the $(k+1)^{th}$ time interval are

$$M(k+1) = M_o - nA_m \sum_{l=1}^{k} J(l) \triangle t \tag{20}$$

$$x(k+1) = x(k) - \left(\frac{x(k)+y(k)}{y(k)}\right)\left(\frac{y(k)J(k)nA_m}{M(k)}\right)\triangle t \tag{21}$$

In batch process, since the heat of evaporation is supplied from a heater equipped in feed tank, feed temperature is assumed to be constant with permeating time. Therefore, flux and permeate concentration can be a function of only feed composition at a given feed temperature in batch process. The initial condition for each parameter can be given;

$M(0) = M_o$

T_f = initial feed temperature

$x(1)$ = water concentration in initial feed

$J(1) = f(x(1), T_f)$

$y(1) = g(x(1), T_f)$

Now, feed composition, feed mass with permeating time can be determined by the numerical method.

3. Experimental

3.1. Membranes

The membrane used in this study was a commercial composite membrane, AzeoSep^{TM}-2002 (PetroSep Membrane Inc., Ontario, Canada). It is a hydrophilic membrane composed of an active layer of modified polyvinyl alcohol (PVA) and a porous layer of polyacrylonitrile (PAN). AzeoSep-2002 is very effective for the dehydration of a wide range of organic solvents, such as, alcohols, ethers, acetates, and so on.

3.2. Pervaporation

To produce permeation data for simulation model, pervaporation experiments were carried out with a lab-scale of permeation apparatus. Ethanol/water mixtures were used as a model mixture. The pervaporation apparatus is described well elsewhere[7]. The feed tank holds a volume of 4 litre of feed mixture, and has a function of temperature control. A permeation cell made of stainless steel holds a flat membrane of 154 cm^2. Feed composition ranged from 0.4 to 7 wt.% water contents. Feed temperatures used were 60-90℃. Permeate pressure was kept below 5 torr. In all measurements, feed flow rate was above 5 litre per minute to minimize a concentration polarization effect at feed mixture. The feed and permeate compositions were determined by Karl-Fisher titration. The permeate fluxes were determined by weighing the permeate samples in cold traps.

4. Results and discussion

4.1. Determination of permeation parameters and verification of simulation model

The permeation data of ethanol/water mixtures through AzeoSep^{TM}-2002 membrane, that is, flux and permeate concentration were obtained at different feed compositions and feed temperatures. The curve fitting of the permeation data was performed by using a software of Sigma Plot-2000 and produced the following dependencies of flux (J) and permeate concentration (y) on both feed composition and feed temperature temperatures, as shown in Eqs (8) and (9), respectively,

Table 1. Base Parameters Used in Both the Simulation and Experiment

Process parameters	unit	
Initial feed temperature	K	352
Module inlet temperature	K	352
Permeate pressure	torr	4
Feed flow rate	kg/h	500
Initial water concentration in feed	wt.%	7
Final water concentration in feed	wt.%	1
Initial feed amount	kg	1.05
Membrane area in module	m^2	0.0154

$$J = A_o \exp(-E_p/T)$$
$$A_o = 2995 \exp(2.8441x)$$
$$E_p = 3300.04 + 839.58x \quad (22)$$

$$y = ((ax)^{-2} + 98.3^{-2})^{-0.5}$$
$$a = 440.9 - \frac{112700}{T} \quad (23)$$

where y is a water concentration in permeate (wt.%), x a water concentration in feed (wt.%), J a flux (kg/(m^2.h)), A_o a pre-exponential factor (kg/(m^2.h)), and E_p a permeation activation energy (cal/mol). The pre-exponential factor and permeation activation energy were obtained as functions of feed composition. The determined permeation functions were in agreement with experimental data within ±4.5% in the given range of operating condition. These determined permeation parameters were used in the simulation of the pervaporation dehydration processes

In order to verify the established simulation model, the simulated values in batch process were compared with the experimental feed concentration data with permeating time. The base parameters used in the simulation are summarized in Table 1. Fig. 3 exhibits a comparison of the simulated feed composition to the

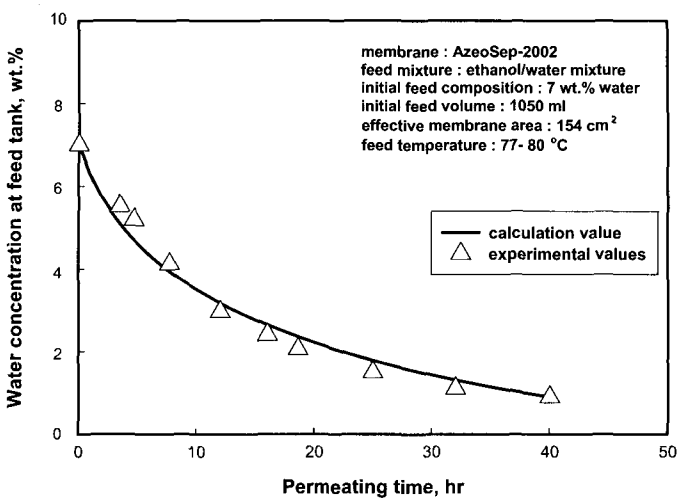


Fig. 3. A comparison of simulated feed composition to experimental value with permeating time in dehydration of ethanol through AzeoSep-2002: initial water concentration in feed = 7 wt.% and final water concentration in feed = 1 wt.%.

experimental data with permeating time. It could be found from the comparison that the simulation has an excellent agreement with the empirical data. It took 40.3 hours to reduce water concentration in feed from 7 wt.% to 1 wt.% in the real pervaporation experiment and the simulation gave 39.5 hours of permeating time for the same separation. According to these findings, it can be seen that the established simulation model is of practical value to predict and analyse the dehydration behaviour.

4.2. Simulation of pervaporation process

With help of the simulation model established in this study, the dehydration of ethanol/water mixtures through AzeoSep^{TM}-2002 membrane was simulated in a commercial scale of continuous and batch processes, respectively. In continuous process where module units are sequentially connected, the product can be obtained from the final retentate as shown in Fig. 4. On the other hand, in batch process, the final product can be taken after circulating of feed mixture through membrane module units for a period of time. Therefore, each process may have its own features because of its different module configuration and feed flow regime. The simulation of these two pervaporation processes can help to understand the difference between them and provide guidelines for the design of optimum pervaporation process. In the following sections, the simulation model described above is applied to estimate the dehydration process of ethanol in the two processes.

4.2.1. continuous pervaporation process

As mentioned earlier, pervaporation is characterized by the evaporation of the permeate, requiring the heat for evaporation. Feed side supplies the heat, so that a temperature gradient in direction of the feed can be developed as shown in Fig. 1, feed temperature falls constantly and the flux through the membrane decreases, correspondingly. In continuous process, since this effect is significant, it has to be taken in to account, especially, on an industrial scale. In the simulation, the feed was re-heated when the feed temperature fell below an acceptable module entrance temperature. That is, the temperature gradient could be compensated by installing re-heaters between different

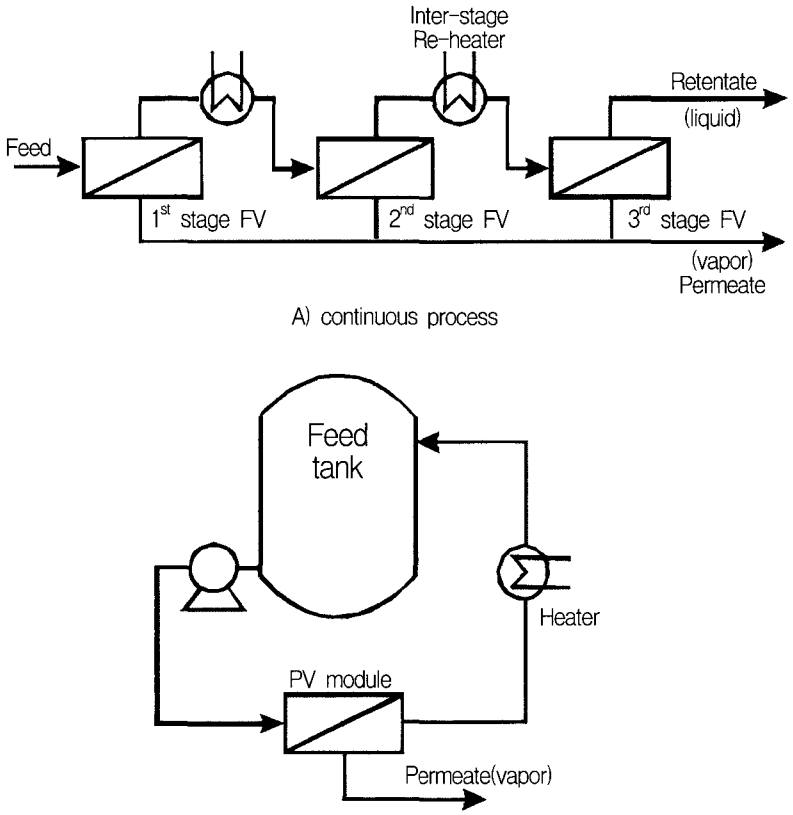


Fig. 4. Schematic representation of pervaporation processes.

module units to reheat the feed to a specified module entrance temperature (Fig. 4. A). For a given set of dehydration, the number of re-heater or the number of stages is affected by two parameters, 1) the initial feed temperature and 2) the allowable maximum temperature drop along the module unit. A typical value of maximum temperature drop is 10℃. Thus, in this study, the maximum temperature drop was fixed to be 10℃. In order to see the influence of the base parameters on membrane area and number of stages, the simulations were run for different sets of pervaporation. Table 2, the base parameters for the simulations are summarized.

4.2.1.1. Effect of feed temperature

The influence of different initial feed temperatures on the membrane area and stage number required is

Table 2. Base Parameters for Simulations of Cntinuous Pervaporation Process

Process Parameters		
Initial feed temperature	℃	70 - 90
Module inlet temperature	℃	70 - 90
Maximum temperature drop	℃	10
Initial water concentration in feed	wt.%	5
Water concentration in retentate	wt.%	4 - 0.1
Initial feed flow rate	kg/hr	100
Module Geometrics		
Module type	-	plate-and-frame
Module length	mm	800
Module width	mm	500
Feed channel height	mm	2.8

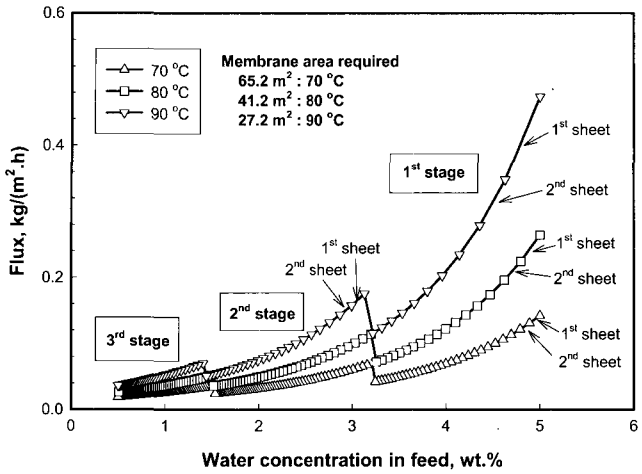


Fig. 5. Simulated flux with feed composition in the continuous pervaporation of ethanol/water mixture at different feed temperature : initial feed flow rate = 100 kg/hr.

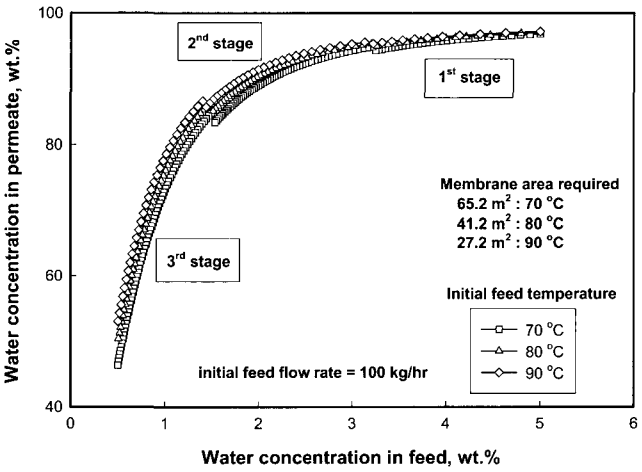


Fig. 6. Simulated permeate concentration with feed composition in the continuous pervaporation of ethanol/water mixture at different feed temperature : initial feed flow rate = 100 kg/hr.

shown in Figs 5-7 and Table 3. The membrane shows a reasonable flux and an excellent selectivity in the dehydration ethanol at the given range of operating conditions. Since the dependency of flux on temperature is an Arrhenius-type equation as described in Eq.(22), the influence of temperature on membrane performance is found to be significant to achieve a predefined separation. As feed temperature increases, the membrane area required decreases and number of membrane sheets in each stage also decreases as much. The result was also obtained from the simulation that less number of stages or re-heaters is needed at high feed temperature although it is not presented here. Looking at Fig. 5-7, each curve segment between points depicts a change in respective permeation performance with feed flowing over respective membrane sheet. The flux change is observed to be more significant at higher temperature or/and higher water content in feed (Fig. 5), resulting in more temperature drop over a membrane sheet

Table 3. Total Membrane Areas and Membrane Areas at Each Stage Calculated in the Dehydration of Ethanol at Different Initial Feed Temperatures; Initial Water Concentration in Feed = 5 wt.% and Final Water Concentration in Retentate = 0.5 wt.%.

Stage number	Required membrane area, m^2					
	Initial feed temp = 70℃		80℃		90℃	
1	12.8	Total area:	7.2	41.2	4.4	27.2
2	23.6	65.2	15.2		10.4	
3	28.8		18.8		12.4	

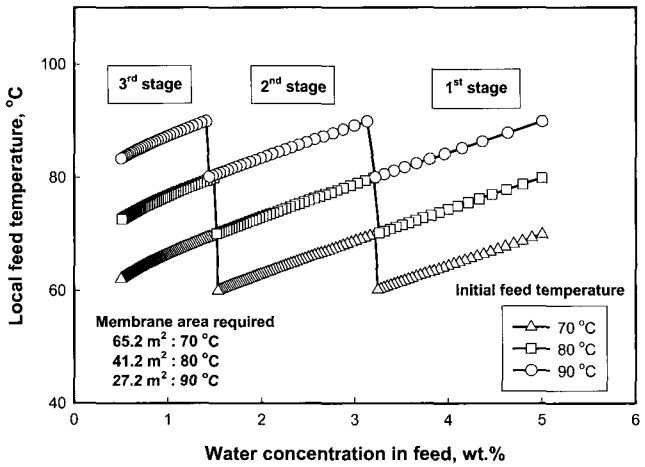


Fig. 7. Simulated feed temperature with feed composition in the continuous pervaporation of ethanol/water mixture at different feed temperature : initial feed flow rate = 100 kg/hr.

(Fig. 7) and less number of membrane sheets involved in a module unit. The permeate concentration does not change so much with feed temperature but decreases more with decreasing water concentration in feed (Fig. 6). It reflects that more separation could be achieved at higher temperature. Hence, one of the basic design rules to apply pervaporation effectively is to maintain the feed temperature as high as possible.

4.2.1.2. Effect of retentate concentration

Fig. 8 presents the membrane area required to reach the desired ethanol purity in retentate. The application of pervaporation is not restricted by the chemical equilibrium, i.e. azeotropes, and, therefore, generally any desired retentate concentration can be achieved in sense of a theoretical aspect. However, reducing the desired water concentration in retentate leads to an exponential increase in the membrane area. A decrease in the water concentration in feed leads to a decrease in the amount of water absorbed into the membrane surface. Thus the membrane mobility becomes reduced due to reducing the plasticization action of the absorbed water on membrane material. This causes a rapid decrease in flux and hence the exponential increase in the required membrane area.

4.2.2. batch pervaporation process

Unlike the continuous process, the feed mixture circulates through the membrane module units for a given period of time in batch process as shown in Fig. 4. B, so that the heat required for the evaporation is continuously supplied from feed tank by circulating the feed mixture. Thus temperature drop along feed flow is not as significant as in the continuous process

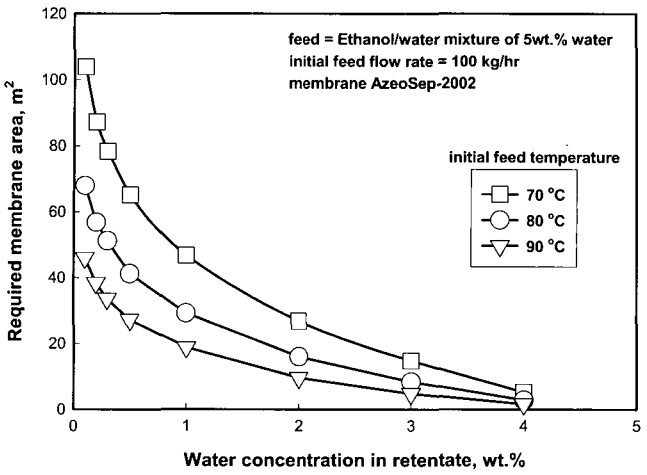


Fig. 8. Required membrane area with retentate concentration in the continuous pervaporation of ethanol/water at different temperature : initial feed flow rate = 100 kg/hr.

Table 4. Base Parameters for Simulations of Batch Pervaporation Process

Process Parameters		
Initial feed temperature	℃	70 - 90
Module inlet temperature	℃	70 - 90
Initial water concentration in feed	wt.%	5
Final water concentration in feed	wt.%	4 - 0.1
Initial feed flow rate	kg/hr	400
Module Geometrics		
Module type	-	plate-and-frame
Number of membrane sheets	ea	70
Module length	mm	800
Module width	mm	500
Feed channel height	mm	2.8

and any additional re-heater is not needed. Another different aspect of batch process from continuous process is that membrane area in the module is fixed and permeating time is adjusted to achieve a desired separation. The simulations were carried out for different sets of pervaporation to see the influence of the base parameters on permeating time. The base parameters for the simulations are summarized in Table 4.

Fig. 9 shows the plots of flux with permeating time at different feed temperatures. On the whole, flux declines with permeating time. The decline of flux with permeating time is more significant at higher feed temperature. Looking at Figs 5 and 6, when feed temperature increases, flux increases but permeate concentration is not changed so much. It reveals that separation occurs more at high feed temperature. That is why water concentration reduces more rapidly (Fig. 10) and then flux reduces as much at higher temperature. As a result, the permeating time required to reduce feed concentration from 5 wt.% to 0.5 wt.% water is smaller at higher temperature as shown in Fig. 10. The required permeating times to dehydrate ethanol up to different values of purity were calculated and the result is plotted in Fig. 11. More dehydrating of ethanol requires longer permeating time. The permeating time increases exponentially with decreasing water concentration in product. The reason for that could be explained by exactly the same principle as did for more membrane area required for less water in retentate in continuous process.

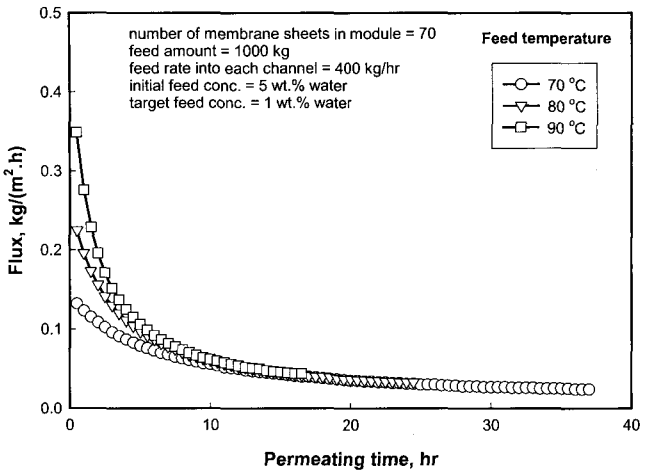


Fig. 9. Simulated flux with permeating time in batch pervaporation process of ethanol/water at different feed temperature.

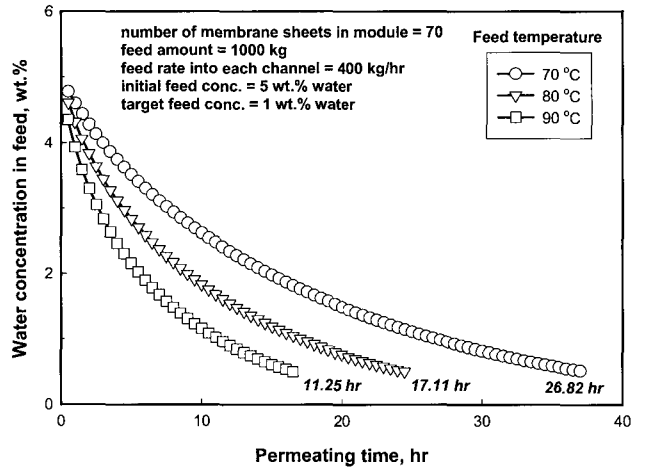


Fig. 10. Simulated feed composition with permeating time in batch pervaporation process of ethanol/ water at different feed temperature.

4.3. Comparison of continuous and batch pervaporation processes

Fig. 12 shows the required permeating time ratio between batch and continuous pervaporation processes to achieve the same degree of separation. The permeating times were calculated under an assumption that the same area of membranes are loaded and the same operating conditions are employed, such as, feed temperature, initial feed composition, final feed composition, in these two processes. The ratio ranges 1.5-1.6 regardless of either water concentration in product or feed temperature. It indicates that the continuous process is more effective for the dehydration of ethanol. However, instead, some additional re-heaters are needed to compensate the temperature drop in the continuous process, so that the process can be more expensive and more complicated in its configuration. Therefore, the design of the system and process should be compromised in terms of separation performance and equipment cost by

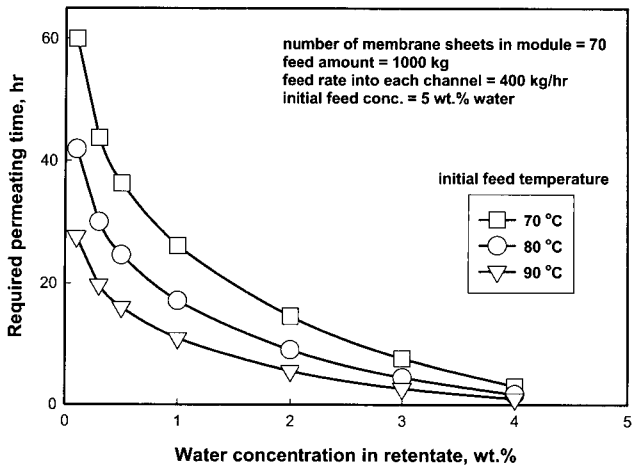


Fig. 11. Required permeating time with product concentration in batch pervaporation of ethanol/water at different feed temperature.

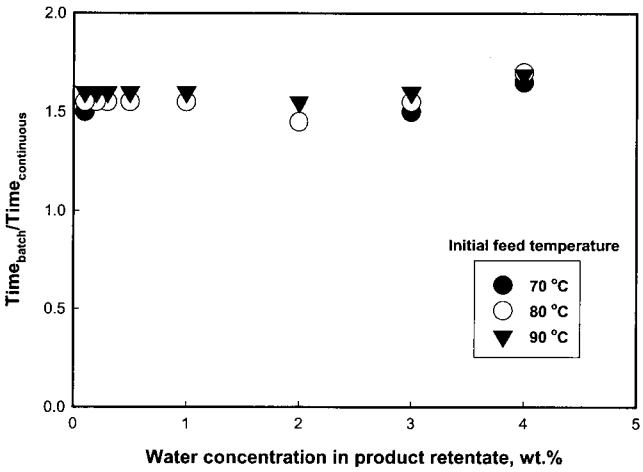


Fig. 12. Required permeating time ratio in batch process to continuous pervaporation process with product concentration at different feed temperature.

using the combined configuration of the continuous and batch processes.

5. Conclusions

A process simulation model of pervaporative plate-and-frame modules in dehydration of organic solvent has been established. With help of the model, continuous and batch pervaporation processes were simulated in dehydration of ethanol through AzeoSep™-2002, a commercial membrane, respectively, to acquire basic data for analysing and optimizing the pervaporation process. The simulation model was based on a phenomenological/semi-empirical approach. Some of permeation parameters which are used in the simulation models were quantified directly from the dehydration system of ethanol through the membrane. The simulation model was verified by comparing the simulated properties with experimental data, having an excellent agreement

with the real process. Thus it was proved that the established model is of practical value for analysing and optimizing the pervaporation process. According to the results of the simulations of both continuous and batch processes, the flux declines more rapidly with permeating time at higher temperature or/and higher water content in feed, resulting in more temperature drop over a membrane sheet and less number of membrane sheets involved in a module unit. Performing of the pervaporation at higher temperature requires more energy consumption at cost of better separation. A comparison between the continuous and the batch processes in the dehydration of ethanol gave a result that the continuous process would be more effective for the separation even if additional re-heaters are installed. Thus the design of process and system must be compromised in terms of membrane performance and cost and, also, the simulations can provide a tool for the techno-economical analysis of pervaporation dehydration for solvent recovery.

List of Symbols

A_m : effective membrane area per each membrane sheet in a module unit (m^2)
C_p : heat capacity of feed (kcal/(kg. °C)
dz : differential length of channel in z direction (m)
F : feed flow rate (kg/h)
h_F : enthalpy of feed (kcal/mole)
Δh_V : heat of the evaporation of permeant (kcal/mole)
J : flux ($kg/(m^2.h)$)
l_{unit} : effective length of each membrane sheet (m)
M : feed mass in feed tank at a time t (kg)
M_o : initial feed mass in feed tank (kg)
n : number of membrane sheets in a module unit
t : permeating time (h)
T : feed temperature (K)
w_{unit} : effect of width of each membrane sheet (m)
x : concentration of a selectively permeating component in feed (wt.%)
y : concentration of a selectively permeating component in feed (wt.%)
dz : differential channel length in a module unit (m)

References

1. G. W. Meindersma, and M. Kuczynski, "Implementing membrane technology in the process industry," *J. Membr. Sci.*, **113**, 285-292 (1996).
2. R. C. Binning, R. J. Lee, J. F. Jennings, and E. C. Martin, "Separation of liquid mixtures by pervaporation," *Ind. Eng. Chem.*, **53**, 45-50 (1961).
3. F. W. Greenlaw, W. D. Price, R. A. Shelden, and E. V. Thompson, "Dependence of diffusive permeation rates on upstream and downstream pressure: II. Two component permeant," *J. Membr. Sci.*, **2**, 141 (1977).
4. F. W. Greenlaw, W. D. Price, R. A. Shelden, and E. V. Thompson, "Dependence of diffusive permeation rates on upstream and downstream pressure: II. Single component permeant," *J. Membr. Sci.*, **2**, 202-223 (1980).
5. R. Rautenbach, C. Herion, M. Franke, A. A. Asfour, A. Bemquerer-Costa, and E. Bo, "Investigation of mass transport in asymmetric pervaporation membranes," *J. Membr. Sci.*, **36**, 445 (1988).
6. J. Won, C. K. Yeom, S. Yoon, J. Rhim, S. Bae, and B. Ha, "Modeling of pervaporation process: prediction of feed temperature distribution in a frame and plate type of membrane module," *Membrane J. (Korean)*, **6**(1), 44, (1996).
7. C. K. Yeom and K-H. Lee, "Pervaporation separation of water-acetic acid mixtures through poly (vinyl alcohol) membranes crosslinked with glutaraldehyde," *J. Membr. Sci.*, **109**, 257-265 (1996).