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A Pseudophase-Change Solution-Diffusion Model for Pervaporation. I. Single Component Permeation

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ABSTRACT

A pseudophase-change solution-diffusion (PPCSD) model, which assumes the pervaporation process is a combination of liquid permeation mechanism and vapor permeation mechanism in series, is proposed. A pseudophase change of permeant is located at the interface between these two mechanisms. Using the assumptions of thermodynamic equilibrium, simple concentration-dependent solubility, and diffusivity, we derive a set of analytical equations to express the pervaporation flux, the lengths of the liquid and vapor permeation mechanisms. The PPCSD model was tested for its validity and showed good agreement with literature data in terms of the effect of feed pressure and permeate pressure. The length of the permeation zone that behaves as a liquid permeation mechanism as well as the pressure and concentration profiles within the membrane also can be calculated. Comparison among three different membrane separation processes (namely, pervaporation, vapor permeation, and liquid permeation) showed that the permeation flux is nearly the same for pervaporation and vapor permeation processes under the assumption of thermodynamic equilibrium. On the other hand, the permeation flux for the liquid permeation process is always lower unless a certain high feed pressure is reached.

Key Words. Pervaporation; Pseudophase-change solution-diffusion model; Theory; Single component permeation

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INTRODUCTION

A well-established mass transport model is essential for engineering membrane separation processes. Unlike other membrane separation processes, mass transport through a pervaporation membrane process involves more complicated physicochemical interactions between permeants and the membrane. A satisfactory pervaporation model is still a crucial issue in the area of pervaporation membrane separation processes. Three approaches have been used to describe the pervaporation process: the solution-diffusion model, the pore-flow model, and irreversible thermodynamics.

In the solution-diffusion model the permeants first dissolve into, then diffuse through a membrane due to a chemical potential gradient. The separation occurs due to the differences in solubility and diffusivity of permeants in a membrane. As early as in 1961, Binning (1) qualitatively described the mass transport in pervaporation as a combination of solution phase and vapor phase zones but did not establish a quantitative model. Subsequently, Long (2) used Fick's law with the concentration-dependent diffusivity to establish a theory framework to explain the experimental data. Huang and coworkers (3-6) further incorporated Fujita's free volume theory and Flory-Huggins thermodynamics with Fick's law to predict and interpret the pervaporation performance of a given pervaporation system. Mulder and Smolders (7, 8) presented a similar approach to model the separation of ethanol/water mixtures. However, the interaction parameters required in modeling are experimentally complicated. On the other hand, Greenlaw et al. (9, 10) proposed a simple model to treat nearly ideal mixtures. On the same basis as the model developed by Greenlaw et al. but with the hypothesis that diffusivities are exponentially dependent on permeant concentration, Brun et al. (11, 12) suggested a "six-coefficients exponential model." All the model parameters have to be determined by fitting the flux equations to experimental data. To facilitate mathematical calculation, Blume et al. (13) treated pervaporation as a liquid evaporation step followed by a vapor permeation step, and the overall separation factor was given as the product of the separation factors of the two steps. Heintz and Stephan (14, 15) developed a generalized solution-diffusion model and took into account nonideal multicomponent solubility, nonideal diffusivity behavior, and coupling diffusion by using the UNIQUAC model and the Maxwell-Stefan theory. Doong et al. (16), on the other hand, presented a pervaporation model combining a penetrant solubility model and a hybrid diffusivity model. All the models mentioned above are based on the solution-diffusion mechanism.

Recently, Matsuura and coworkers (17-19) proposed a transport model applicable to pervaporation on the basis of the pore flow mechanism. It is assumed that the mass transport is a combination of liquid and vapor permea-

tion in series through straight cylindrical pores of a membrane. This model clearly pictures the phase change of permeants in pervaporation, but arguments might arise for the existence of pores in dense pervaporation membranes. However, the size of pores in this model may be viewed as being on the molecular scale. Tyagi and Matsuura et al. (20-22) also provided another approach to describe the phase change of permeant in a membrane by using a chemical potential gradient as the driving force. This pervaporation transport model predicted a possibility of concentration polarization inside the membrane during steady-state pervaporation.

Kedem (23), in the other way, proposed a model based on irreversible thermodynamics to explain the role of coupling in pervaporation. The word "coupling" has often been used for the thermodynamic interaction between components in the solution-diffusion model (7). Here it denotes a relation between two individual component flows, so that a component can flow without or even against its own driving force. It shows that even with the assumption of constant coefficients, one cannot necessarily expect linear concentration profiles as does the conventional solution-diffusion model.

Although the solution-diffusion model is accepted by the majority of membrane researchers due to its successful description of mass transport in terms of the physicochemical nature of the pervaporation process, it should be further refined to meet the phenomena of coupling flux and phase change of permeants occurring in pervaporation. The objective of this series paper is to develop a pseudophase-change solution-diffusion model that includes the phenomena of coupling effect and pseudophase change of permeants into the solution-diffusion model to illuminate these features of pervaporation. We first treat the case of a pure component permeating through the membrane to establish a fundamental theory framework for further modeling of binary mixtures permeating through the membrane.

THEORY

Mass Transport through the Membrane System

In the case of a single Component i permeating through a polymer membrane, the polymer membrane can be considered as a binary system, a membrane system, composed of Component i and the polymer itself. The mass balance of this membrane system for a stationary coordinate and one-direction diffusion is given by (24)

$$n_i = \omega_i(n_i + n_p) + n_{iD} \quad (1)$$

where n_i and n_p are the mass flux of Component i and polymer, respectively; n_{iD} is the mass flux of Component i due to diffusion; and ω_i is the mass fraction of Component i in the membrane system. This equation shows the

mass flux of Component i through the membrane system is the sum of the mass flux resulting from the bulk motion of the membrane system (the first term in the right-hand side) and the diffusion superimposed on the bulk flow (the second term in the right-hand side). Since the polymer is stationary in this system, there is no mass flux of polymer. Thus Eq. (1) can be reduced to

$$n_i = \frac{n_{iD}}{1 - \omega_i} \quad (2)$$

Merten (25) proposed an equation to relate the diffusion flux with the chemical potential gradient, and it has been adapted by several workers (7, 26):

$$n_{iD} = -\rho_i m_i \frac{d\mu_i}{dx} \quad (3)$$

where m_i is the mobility and μ_i is the chemical potential of Component i in the membrane system.

The mass flux of Component i through the membrane system can be rewritten by substituting Eq. (3) into Eq. (2) as

$$n_i = -\frac{\rho_i m_i}{1 - \omega_i} \frac{d\mu_i}{dx} \quad (4)$$

The Pseudophase-Change Solution-Diffusion (PPCSD) Model

Most membrane separation processes operate in the same phase at the feed and permeate sides, i.e., either the gas (vapor) phase such as in the gas separation/vapor permeation processes or in reverse osmosis/ultrafiltration processes (liquid permeation process). The unique feature of phase change of permeant in pervaporation distinguishes itself from the other membrane separation processes. In pervaporation, the feed stream is in the liquid state while the permeate stream is in the vapor state. The permeation starting from the liquid feed should first exhibit the same mechanism as in liquid permeation process, and it will be followed by the vapor permeation mechanism from some point within the membrane until reaching the vapor permeate side, where the same mechanism as in a gas/vapor permeation process will be exhibited. Therefore, the mass transport mechanism in pervaporation can be considered as a combination of the liquid permeation mechanism and the vapor permeation mechanism in series. A pseudophase change can be assumed to occur at the interface between these two permeation mechanisms for the pervaporation process.

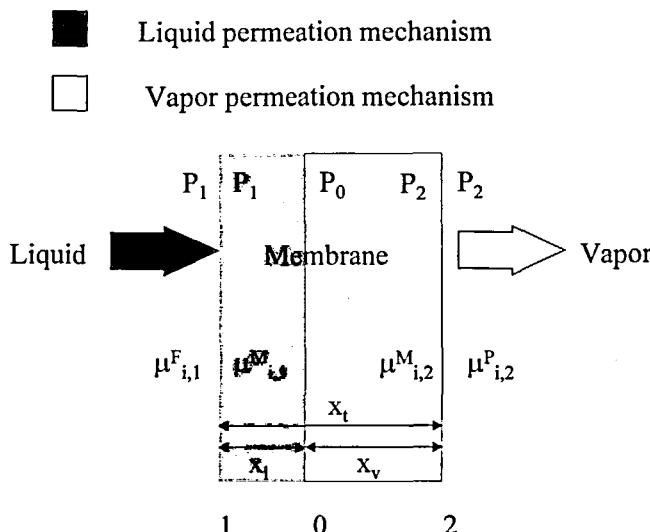


FIG. 1 Schematic description of the pseudophase-change solution-diffusion (PPCSD) model.

The mass transport of Component i through the membrane system can be described schematically as shown in Fig. 1. The liquid Component i first dissolves into and diffuses through the membrane system via a liquid permeation mechanism. At some point within the membrane system the liquid permeation mechanism is transformed into the vapor permeation mechanism and diffuses through the rest of the membrane system via this mechanism. Finally, Component i desorbs as vapor from the permeate side of the membrane system.

In order to incorporate the phenomenon of pseudophase change, the following assumptions are made for the pseudophase-change solution-diffusion (PPCSD) model:

1. Permeation of Component i through the membrane system obeys the solution-diffusion mechanism in both liquid permeation mechanism and vapor permeation mechanism.
2. Thermodynamic equilibrium exists at the interfaces of membrane system.
3. Component i undergoes a pseudophase change from liquid permeation mechanism to vapor permeation mechanism within the membrane system during pervaporation operation.
4. The pressure at the surface of the membrane system is equal to the adjacent applied pressure.
5. Then pervaporation process is an isothermal process.

The primary differences between the previous solution-diffusion model and the proposed PPCSD model are that the pressure within the membrane is not uniform throughout the membrane system and that a pseudophase change of permeant occurs within the membrane system. Therefore, we can characterize the mass transport mechanism within the membrane system as a combination of liquid permeation process and vapor permeation process. We will discuss the two zones in detail as follows.

Pervaporation Flux of Component *i* for the Liquid and Vapor Permeation Process

In the liquid permeation process the chemical potential of Component *i* in an isothermal membrane system is a function of activity and pressure of Component *i* and can be written as (26)

$$\mu_i = \mu_{i0} + RT \ln a_i + \int_{P_0}^P V_i dP \quad (5)$$

where μ_{i0} is the chemical potential of Component *i* in the membrane system at reference state; a_i is the activity of Component *i* in the membrane system, which is primarily concentration-dependent; P is the pressure of the membrane system; V_i is the partial molar volume of Component *i* in the membrane system; T is the absolute temperature of the membrane system; and P_0 is the saturation vapor pressure of Component *i*.

The mass flux of Component *i* for the liquid permeation process can be rewritten by substituting Eq. (5) into Eq. (4) as

$$n_i = - \frac{\rho_i m_i}{1 - \omega_i} \left(RT \frac{d \ln a_i}{dx} + V_i \frac{dP}{dx} \right) \quad (6)$$

Thermodynamic equilibrium has been assumed at the interfaces of the membrane system, and the activity inside the liquid permeation zone can be treated as a constant. Therefore,

$$n_i^l = - \frac{\rho_i m_i V_i}{1 - \omega_i} \frac{dP}{dx} \quad (7)$$

where l denotes the liquid permeation process.

Assuming that the concentration and mobility of Component *i* in the membrane system is independent of pressure and that the partial molar volume of Component *i*, V_i , is constant as assumed by Lonsdale et al. (27). By integrating Eq. (7) with boundary conditions, we obtain

$$n_i^l = \frac{\rho_i m_i V_i}{(1 - \omega_i) x_l} (P_1 - P_0) \quad (8)$$

where x_l is the thickness of membrane system which behaves as a liquid permeation process.

For the vapor permeation process, the chemical potential can be written as

$$\mu_i = \mu_{i0} + RT \ln a_i \quad (9)$$

The mass flux of Component i for the vapor permeation process, by substituting Eq. (9) into Eq. (4), is

$$n_i^v = -\frac{\rho_i m_i}{1 - \omega_i} \left(RT \frac{d \ln a_i}{dx} \right) \quad (10)$$

The concentration and mobility of Component i in the membrane system is a function of permeant concentration in the membrane system. Let us consider the simplest relationship (9)

$$c_i = K_{ci} a_i = K_{ci} \frac{P}{P_0} \quad (11)$$

and

$$m_i = K_{mi} c_i \quad (12)$$

where K_{ci} and K_{mi} are constants. c_i is the solubility of Component i in polymer, which has the unit of mass of Component i per mass of polymer. The mass concentration, ρ_i , and the mass fraction, ω_i , can be expressed in terms of c_i :

$$\rho_i = \frac{c_i d_m}{(1 + c_i)} \quad (13)$$

and

$$\omega_i = \frac{c_i}{1 + c_i} \quad (14)$$

where d_m is the density of the membrane system and assumed to be a constant.

For the liquid permeation process, the solubility of Component i in polymer can be evaluated at unity activity. Therefore, the permeation flux through the zone which behaves as a liquid permeation process, from Position 1 to Position 0, will be

$$n_i^l = \frac{K_{mi} K_{ci}^2 V_i d_m}{x_1} (P_1 - P_0) \quad (15)$$

This equation shows that the flux in the zone that behaves as a liquid permeation process is proportional to the pressure difference ($P_1 - P_0$).

In the zone that behaves as a vapor permeation process, the activity is equal to that in the feed solution at Position 0, while the activity at Position 2

$$\mu_{i,2}^M = \mu_{i,2}^P \quad (16)$$

Therefore,

$$a_{i,2}^M = a_{i,2}^P \quad (17)$$

By applying the expression in Eq. (11)–(14) into Eq. (10), and integrating with the boundary conditions, we obtain

$$n_i^v = \frac{K_{ci}^2 K_{mi} d_m RT}{2 x_v P_0^2} (P_0^2 - P_2^2) \quad (18)$$

Equation (18) shows that the flux in the zone that behaves as a vapor permeation process is proportional to $(P_0^2 - P_2^2)$.

Under steady state, the permeation fluxes of Component i through the zone that behaves as a liquid permeation process, the zone that behaves as a vapor permeation process, and the whole membrane system are the same.

$$n_i^t = n_i^v = n_i^l \quad (19)$$

where n_i^t is the overall flux of Component i through the membrane system. Rearranging Eqs. (15) and (18) via Eq. (19), we obtain

$$x_l = \frac{K_{mi} K_{ci}^2 V_i d_m}{n_i^t} (P_1 - P_0) \quad (20)$$

$$x_v = \frac{K_{mi} K_{ci}^2 d_m RT}{2 n_i^t P_0^2} (P_0^2 - P_2^2) \quad (21)$$

Furthermore,

$$x_t = x_v + x_l \quad (22)$$

where x_t is the total thickness of the membrane system. Combining Eqs. (20)–(22) and rearranging, we obtain

$$n_i^t = \frac{A}{x_t} (P_1 - P_0) + \frac{B}{x_t} (P_0^2 - P_2^2) \quad (23)$$

where

$$A = K_{mi} K_{ci}^2 V_i d_m \quad (24)$$

$$B = \frac{K_{mi} K_{ci}^2 d_m R T}{2 P_0^2} \quad (25)$$

Equation (23) is the mass flux of Component i through the membrane system with respect to the overall thickness of the membrane system. Note that this flux equation has exactly the same form as that from the pore flow model (18).

RESULTS AND DISCUSSION

Effects of Feed and Permeate Pressure on the Pervaporation Flux

Greenlaw et al. (9) studied the effect of feed and permeate pressure on pervaporation flux of hexane through a polyethylene membrane in some detail. We will adapt their experimental data to fit into the PPCSD model. The parameter values so obtained are:

$K_{ci} = 0.128 \text{ g/g polymer}$; $K_{mi} = 4.75 \times 10^{-13} \text{ gmol}\cdot\text{cm}^2/\text{mmHg}\cdot\text{cm}^3\cdot\text{s}$
and some required physical properties and operation conditions are:

$V_i = 131.6 \text{ cm}^3/\text{gmol}$; $d_m = 0.9 \text{ g/cm}^3$; $T = 303 \text{ K}$; $x_t = 0.00254 \text{ cm}$;

$$P_0 = 188 \text{ mmHg}; R = 62365.6 \text{ mmHg}\cdot\text{cm}^3/\text{gmol}\cdot\text{K}$$

Figure 2 shows the effect of feed pressure on pervaporation flux for three different permeate pressures. Theoretically, the pervaporation flux increases

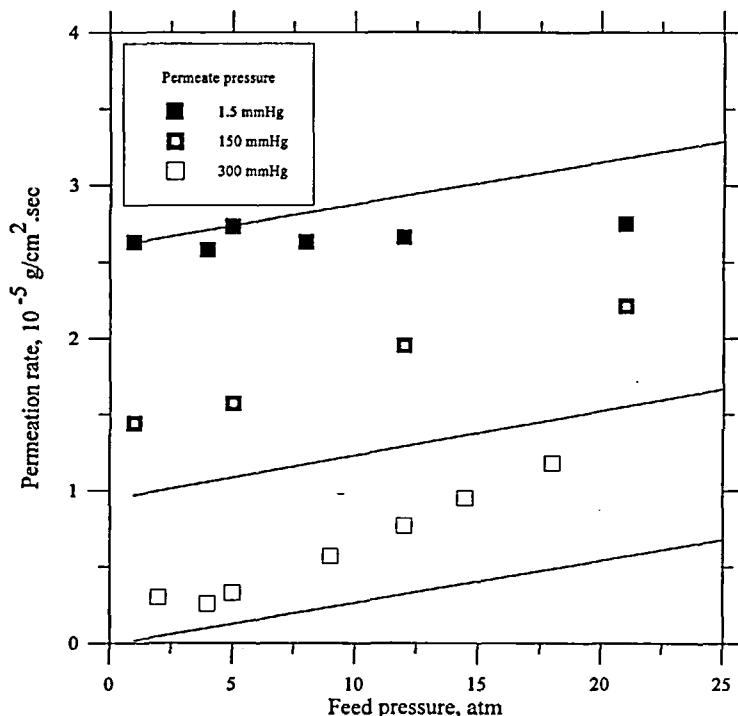


FIG. 2 Effect of feed pressure on pervaporation flux for different permeate pressures. (theoretical curves: upper, 1.5 mmHg; middle, 150 mmHg; lower, 300 mmHg), $T = 30^\circ\text{C}$.

linearly with the same slope as increasing the feed pressure. By examining the experimental data, negative deviation from the theoretical calculation is observed for low downstream pressure while positive deviation for higher downstream pressure is observed. Since we use a linear activity-dependent solubility and concentration-dependent diffusivity, positive deviation is expected, while the negative deviation at lower permeate pressure might result from a more packed membrane structure due to a greater pressure difference between the feed and permeate sides. The different theoretical result of the effect of feed pressure between the PPCSD model and the Greenlaw's model is attributed to the different assumption about the pressure within the membrane system.

On the other hand, the change of permeate pressure has a great impact on the pervaporation flux, especially near the saturation vapor pressure. When permeate pressure is below the saturation vapor pressure of Component i , mass transport in the pervaporation process can be described by Eq. (23) which includes liquid and vapor permeation mechanisms. Once the permeate pressure exceeds the saturation vapor pressure, the liquid permeation takes control and the transport mechanism can be illustrated by Eq. (20). Figure 3 shows the flux curves versus permeate pressure for three different feed pressures; a dramatic change of permeation flux is observed when the permeate pressure is increased, especially near the saturation vapor pressure. Basically, the trend of the flux curves is in good agreement with the experiment data. The positive deviation of experimental data may result from the simple assumption of Eqs. (11) and (12) (9). More complicated sorption and diffusion models are available in the literature (3–6, 14–16).

The Length Ratio of Liquid and Vapor Permeation Mechanisms within the Membrane System

In the PPCSD model the entire membrane system is assumed to comprise a liquid and vapor permeation mechanism in series. It is essential to discuss the length ratio of these two zones with respect to the total thickness of a membrane system.

Dividing Eqs. (20) and (21) by (23), we obtain

$$\frac{x_l}{x_t} = \frac{V_i(P_1 - P_0)}{V_i(P_1 - P_0) + \frac{RT}{2P_0^2} (P_0^2 - P_2^2)} \quad (26)$$

$$\frac{x_v}{x_t} = \frac{\frac{RT}{2P_0^2} (P_0^2 - P_2^2)}{V_i(P_1 - P_0) + \frac{RT}{2P_0^2} (P_0^2 - P_2^2)} \quad (27)$$

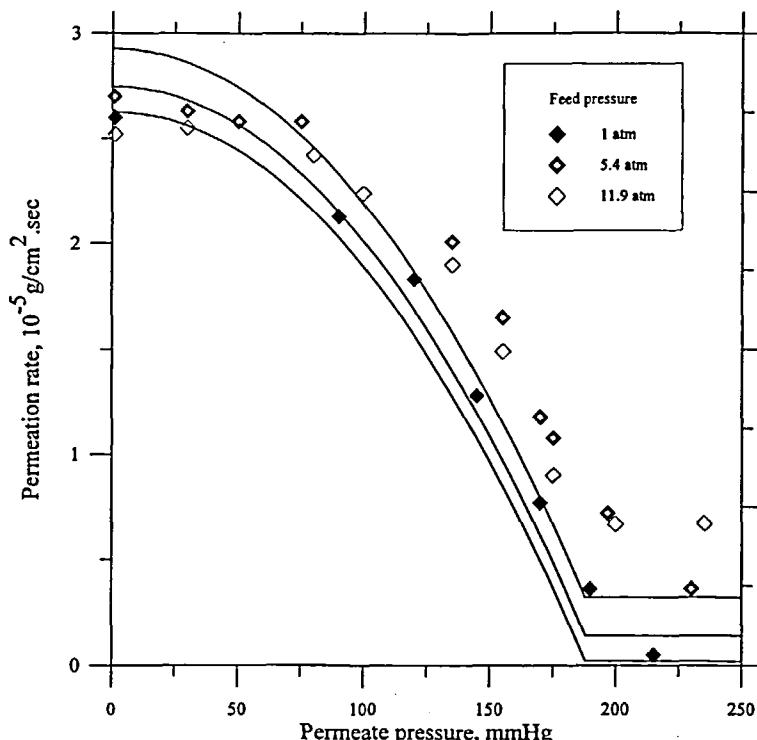


FIG. 3 Effect of permeate pressure on pervaporation flux for different feed pressures. (theoretical curves: upper, 11.9 atm; middle, 5.4 atm; lower, 1 atm), $T = 30^\circ\text{C}$.

These two equations show that the length ratio of the liquid and vapor permeation mechanism within the membrane thickness is a function of the partial molar volume and the saturation vapor pressure of Component i , the operating temperature, the feed pressure, and the permeate pressure. For hexane permeating through a polyethylene membrane at 30°C , the effects of permeate and feed pressure on the length of permeation zone that behaves as a liquid permeation process is shown in Fig. 4. At a feed pressure equal to 1 atm, the practical operation condition for pervaporation, the ratio of the liquid permeation mechanism remains below 1% and increases dramatically to 100% when the permeate pressure approaches the saturation vapor pressure of Component i , i.e., 188 mmHg in this case. Furthermore, once the permeate pressure exceeds the saturation vapor pressure, the permeate is in the liquid state and the whole membrane system is subject to the liquid permeation

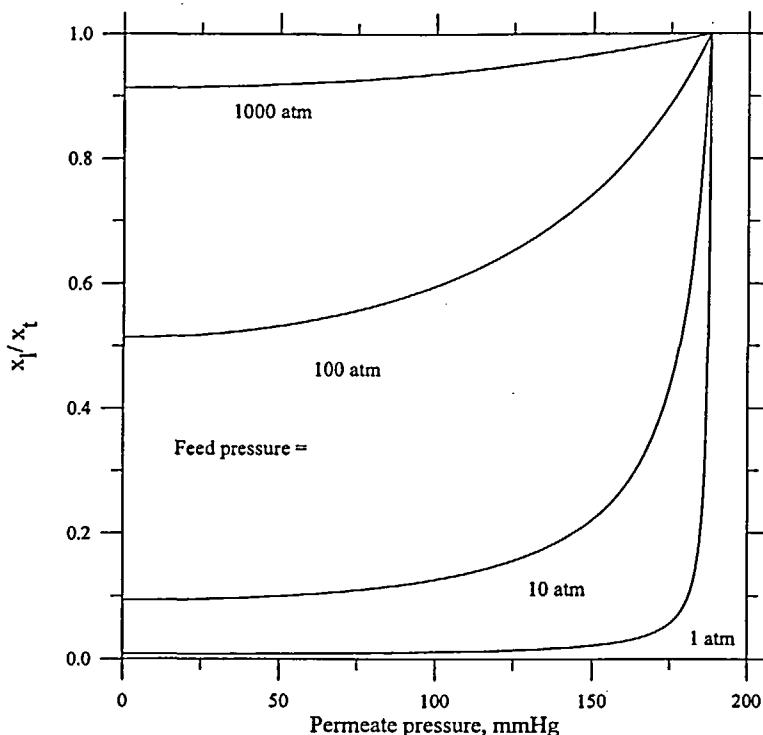


FIG. 4 Effect of feed and permeate pressure on the length ratio of the liquid permeation mechanism within the membrane system.

mechanism. As for the influence of feed pressure, also shown in Fig. 4, the ratio of the liquid permeation zone increases and gradually approaches 100% when the feed pressure increases to infinite value.

The Pressure and Concentration Profiles within the Membrane System

It has been assumed in the PPCSD model that the pressure is not uniform throughout the membrane system. Therefore the pressure profile within the membrane system needs to be investigated. The pressure in the zone that behaves as a liquid permeation process can be calculated by combining Eqs. (7) and (8):

$$dP = \frac{P_0 - P_1}{x_1} dx \quad (28)$$

Integrating Eq. (28) with boundary conditions, we obtain

$$P = (P_0 - P_1) \frac{(x - x_1)}{x_1} + P_1 \quad (29)$$

where $x_1 \leq x \leq x_0$. Equation (29) shows that the pressure profile in the liquid permeation zone has a linear relationship with its position.

In the zone that behaves as a vapor permeation process, the pressure profile can be obtained by combining Eqs. (10) and (18):

$$PdP = \frac{P_2^2 - P_0^2}{2x_v} dx \quad (30)$$

Integrating with boundary conditions, we obtain

$$P = \sqrt{\frac{x - x_0}{x_v} (P_2^2 - P_0^2) + P_0^2} \quad (31)$$

where $x_0 \leq x \leq x_2$. Equation (31) shows the pressure distribution in the vapor permeation zone.

Figure 5 shows the pressure profile within the membrane system for $P_1 = 760$ mmHg and $P_2 = 0$ mmHg. The pressure drops abruptly, according to Eq. (29), from feed pressure to saturation vapor pressure at the interface of the feed side and the membrane system in the zone that behaves as a liquid permeation process, while in the zone that behaves as a vapor permeation process, the pressure decreases slowly, according to Eq. (31), to 0 mmHg at the interface of the permeate side and the membrane system. The pressure distribution within the membrane system is significantly different from the assumption made by the conventional solution-diffusion model, which is that it is constant.

The concentration profile within the membrane system is also a major issue for pervaporation modeling. The concentration of Component i in the zone that behaves as a liquid permeation process is almost unaffected by pressure (27). Therefore, it should remain constant in this zone and can be taken as $P = P_0$ in Eq. (11):

$$c_i = K_{ci} \quad (32)$$

In the zone that behaves as a vapor permeation process, the concentration of Component i is proportional to the activity. We can calculate the concentration profile in this zone by using Eqs. (11) and (31):

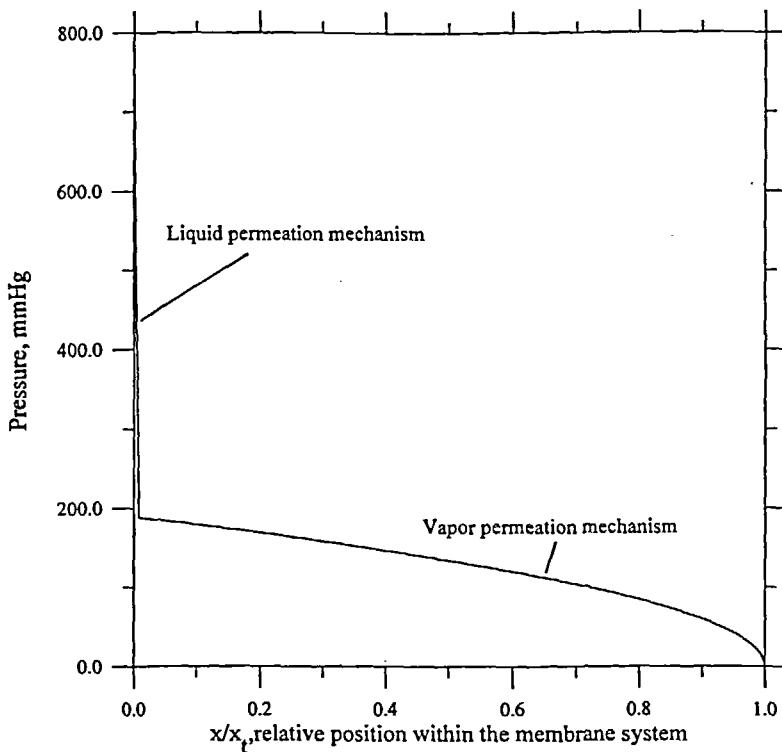


FIG. 5 The pressure distribution within the membrane system for the PPCSD model. $P_1 = 760 \text{ mmHg}$, $P_2 = 0 \text{ mmHg}$.

$$c_i = K_{ci} \sqrt{\frac{x - x_0}{x_v} \left[\left(\frac{P_2}{P_0} \right)^2 - 1 \right] + 1} \quad (33)$$

Figure 6 shows the concentration profile within the membrane system for $P_1 = 760 \text{ mmHg}$ and $P_2 = 0 \text{ mmHg}$. The concentration decreases gradually and drops to 0 as the interface of the permeate side and membrane system is approached.

Comparison among Pervaporation, Vapor Permeation, and Liquid Permeation Processes

In this work we have treated the membrane system in pervaporation as a combination of liquid and vapor permeation processes in series. Therefore, the flux equations, i.e., Eqs. (15) and (18), developed in this work can also

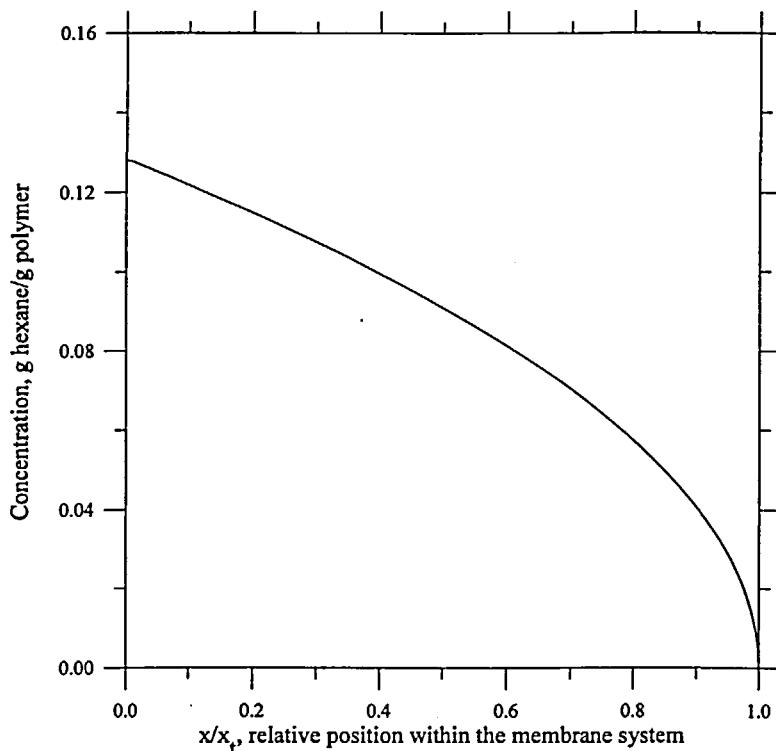


FIG. 6 The concentration profile within the membrane system for the PPCSD model. $P_1 = 760 \text{ mmHg}$, $P_2 = 0 \text{ mmHg}$.

be applied to individual liquid and vapor permeation processes, respectively. For a vapor permeation process, both the feed and permeate sides are in the vapor state, and for a liquid permeation process, both the feed and permeate sides are in the liquid state, and this can be considered to be a particular situation in the PPCSD model. For the vapor permeation process, the permeation flux is described by Eq. (18) when $P_1 \leq P_0$, and the liquid permeation process by Eq. (15) when $P_2 \geq P_0$. In the case of hexane permeating through a polyethylene membrane, the permeation flux for the pervaporation process is calculated using $P_1 = 760 \text{ mmHg}$ and $P_2 = 0 \text{ mmHg}$, while the flux for the vapor permeation process is calculated using $P_1 = 188 \text{ mmHg}$ and $P_2 = 0 \text{ mmHg}$ (in both cases the driving force is the same, i.e., the chemical potential gradient is the same). If the assumption of thermodynamic equilibrium is true for the two processes, the flux is almost the same (as shown in Fig.

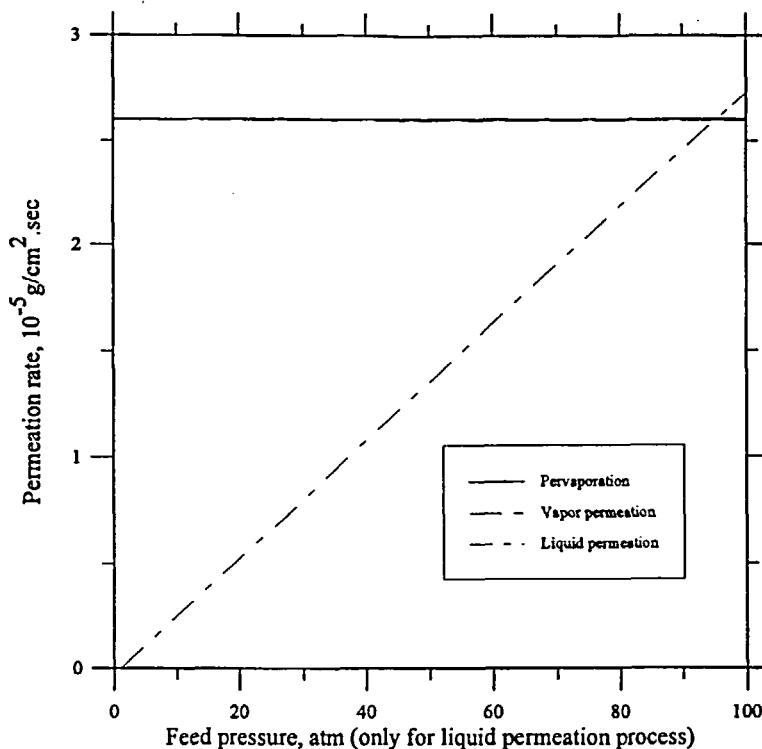


FIG. 7 Comparison of different membrane separation processes. Pervaporation: $P_1 = 760$ mmHg, $P_2 = 0$ mmHg. Vapor permeation: $P_1 = 188$ mmHg, $P_2 = 0$ mmHg. Liquid permeation: $P_1 = \text{variable}$, $P_2 = 1$ atm. $T = 30^\circ\text{C}$.

7). However, the flux for the liquid permeation process (permeate pressure = 1 atm) is always lower than for the other two processes until the feed pressure reaches about 97 atm.

CONCLUSION

1. The PPCSD model assumes that phase change occurs within the membrane system. Two types of permeation processes, namely, liquid and vapor permeation, coexist.
2. Both feed pressure and permeate pressure have influence on the flux. However, the effect of permeate pressure is much more significant than that of feed pressure.

- According to the PPCSD model, the pressure within the membrane system drops linearly in the zone that behaves as a liquid permeation mechanism, while the pressure drops gradually in the zone that behaves as a vapor permeation mechanism. The concentration profile of Component i within the membrane system, however, shows a gradual decrease from one side to the other side.
- In a pervaporation process with $P_1 = 760 \text{ mmHg}$ and $P_2 \approx 0 \text{ mmHg}$, almost the entire membrane system is subject to a vapor permeation mechanism, and has nearly the same flux as the vapor permeation process when the driving force is theoretically the same under the assumption of thermodynamic equilibrium. However, the flux of the liquid permeation process is always lower unless a very high feed pressure is reached.

SYMBOLS

a_i	activity of Component i
d_m	density of the membrane system (g/cm^3)
c_i	solubility of Component i in polymer (g/g)
K_{ci}	constant in Eq. (18) (g/g)
K_{mi}	constant in Eq. (20) ($\text{gmol}\cdot\text{cm}^2/\text{mmHg}\cdot\text{cm}^3\cdot\text{s}$)
m_i	mobility of Component i in membrane system ($\text{gmol}\cdot\text{cm}^2/\text{mmHg}\cdot\text{cm}^3\cdot\text{s}$)
n_i	mass flux of Component i ($\text{g}/\text{cm}^2\cdot\text{s}$)
n_{iD}	mass flux of Component i due to diffusion ($\text{g}/\text{cm}^2\cdot\text{s}$)
n_p	mass flux of polymer ($\text{g}/\text{cm}^2\cdot\text{s}$)
P	pressure (mmHg)
P_0	saturation pressure of Component i (mmHg)
R	ideal gas constant ($= 62365.6 \text{ mmHg}\cdot\text{cm}^3/\text{gmol}\cdot\text{K}$)
T	absolute temperature (K)
V_i	partial molar volume of Component i (cm^3/gmol)
x	thickness of membrane system (cm)
μ_i	chemical potential of Component i joule/gmol
μ_{i0}	chemical potential of Component i at reference state (joule/gmol)
ρ_i	mass concentration of Component i in membrane system (g/cm^3)
ω_i	mass fraction of Component i in membrane system (g/g)

Subscripts

- position of interface between liquid and vapor permeation zones
- position of interface between feed side and membrane system
- position of interface between permeate side and membrane system

Superscripts

F feed side
M membrane system side
P permeate side
l liquid permeation process
t overall
v vapor permeation process

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