行政院國家科學委員會專題研究計劃成果報告

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※環狀薄膜管中設置螺旋捆線以提高超過濾效率※
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中文摘要

本研究推介一螺旋捆線型薄膜超過濾模組，以改變流體流動型態，而降低薄膜超過濾中之濃度極化效應，進而提高過濾效率。該模組之形成係將一捆線以螺旋狀環繞於一鋼棒上，再將此鋼棒以同心置入一薄膜圓管中，而螺旋狀金屬捆線的直徑恰等於模組中之環狀間隙，可使流體行螺旋狀流動。理論係基於阻力串聯模式而作質量與動量結算，以預測在各種操作條件下之濾速；實驗操作乃在各種不同的捆線傾角下，進行 detran T500 水溶液之薄膜超過濾。實驗結果佐證了理論之推測。研究結果發現，薄膜管中置入螺旋捆線，確能提高相當量之濾速，本文中並就捆線傾角對超過濾效率之影響，作詳細之討論。

Ultrafiltration In A Concentric-Tube Membrane Module Inserted with A Helical Wire for Improved Performance

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ABSTRACT

A hydrodynamic approach developed by a wired-membrane module for reducing the effects of concentration polarization and progressive fouling in membrane ultrafiltration, has been carried out. The wired-membrane module is modified from a tubular-membrane module by inserting concentrically a steel rod wrapped entirely with a tight fitting wire spiral, having a diameter nearly equal to the annular spacing, as a spacer. Experiments for ultrafiltration of dextran T500 aqueous solution in a wired-membrane module was carried out for various transmembrane pressures, feed concentrations, feed flow rates, and inclined angles of helical wire. Theoretical predictions were based on the resistance-in-series model and confirmed qualitatively with the experimental results. Considerable improvement of performance is obtainable by employing a wired-membrane module rather than using a tubular-membrane module without or even with a steel rod inserted concentrically.

Key words: Ultrafiltration; Tubular membrane; Wire rod

1. Introduction

Membrane ultrafiltration is being used increasely as a practical process for concentration and purification of macro-molecular species in aqueous solutions. It is primarily a size-exclusion-based pressure-driven membrane separation process, the pressure applied to the working fluid provides the driving potential to force the solvent to flow through the membrane. In cross-flow ultrafiltration the permeate flux generally declines with filtration time due to the phenomenon of concentration polarization by the rejected particles (Porter1972). One of the hydrodynamic approaches developed for reducing the effects of concentration polarization and progressive fouling to enhance the permeate flux, have been discussed (Gupta, 1995).

The purpose of present study is to investigate the improvement of permeate flux of ultrafiltration in a tubular membrane by inserting concentrically a steel rod wrapped entirely with a helical wire, having a diameter nearly equal to the annular spacing, as a spacer to enhance the fluid velocity and thus to reduce the resistance of ultrafiltration due to concentration polarization. The effect of the inclined angle of helical wire on permeation will be discussed, based on the same hydraulic dissipated energy.

2. Theory

The resistance-in-series model may be expressed as (Nabetani et al., 1990)

$$J(z) = \frac{\Delta P(z)}{R_m + R_f + \phi \Delta P(z)} \tag{1}$$

Consider a membrane tube of radius r_m inserted concentrically with a steel rod of radius kr_m. The annular spacing, $(1-k)r_m$ is small, say $k \geq 2/3$, in which a tight fitting wire spiral having a diameter nearly equal to the annular spacing, is wrapped on the entire steel rod as a spacer, as shown in Fig.1a. Because of the small size of the annular spacing as compared with the tube and rod diameters, it will be assumed that the geometry of this construction may be approximately considered as that of a parallel-plate conduit inclined on edge, as shown in Fig.1b.

Accordingly, the transmembrane pressure in Eq.(1) can be derived from the Hagen-Poiseuille equation as (Yeh and Chen, 2000)

$$\Delta P = P - P_p$$
$$= \Delta P_i - [mQ_i\xi - 2n\int_0^{\xi}\int_0^{\xi} J d\xi d\xi]/(G\cos^2\theta) \tag{2}$$

where

$$\Delta P_i = P_i - P_p \tag{3}$$

$$m = \frac{8\mu L}{\pi r_m^4} \tag{4}$$

$$n = \frac{8\mu L^2}{r_m^3} \quad (5)$$

$$G = (2/3)(1-k^2)(1-k)^2 \quad (6)$$

$$\xi = \frac{z}{L\sec\theta} \quad (7)$$

The average permeation flux may be defined as

$$\bar{J} = \frac{1}{L\sec\theta}\int_0^{L\sec\theta} J dz = \int_0^1 J d\xi \quad (8)$$

Substituting Eqs. (1) and (2) into Eq. (8), one has

$$\bar{J} = \int_0^1 \frac{\{\Delta P_i - [mQ_i\xi - 2n\int_0^\xi\int_0^\xi Jd\xi d\xi]/(G\cos^2\theta)\}d\xi}{R_m + R_f + \phi\{\Delta P_i - [mQ_i\xi - 2n\int_0^\xi\int_0^\xi Jd\xi d\xi]/(G\cos^2\theta)\}} \quad (9)$$

Experimental

The schematic diagram of present experimen-tal apparatus shown in Fig. 2 is the same as that in the previous work (Yeh and Wu1997), except that the membrane modules are replaced by a wired-membrane device, as shown in Fig. 1 (a). The membrane medium used in the wired module was mainly a 15 kDa MWCO tubular ceramic membrane (M2 type, Techsep, France; length L=0.4m, inside diameter $2r_m = 6mm$), with a steel rod of radius $kr_m = 2mm$, inserted concentrically. A tight fitting wire spiral having a diameter of 0.99mm which is nearly equal to the annular spacing, $(1-k)r_m = 1mm$, is wrapped on the entire steel rod as a spacer in the annulus. The tested solute was dextran T500 (Pharmacia Co., Sweden) which was more than 99% retained by the membrane used. The solvent was distillated water.

The feed solution was circulated by a high-pressure pump with a variable speed motor (L-07553-20, Cole Parmer Co.), the liquid flow rate was observed by a flowmeter (IR-OPFLOW 502-111, Head-land Co.). The feed pressure was controlled by using an adjusting valve at the outlet of the wired-membrane module, and the pressures at the inlet (P_i) and outlet (P_L) of the conduit as well as at shell side (P_p) were measured with a pressure tramsmitter (Model 891.14.425, Wika Co.). For measurement of P_i and P_L, the pressure taps were located up stream of the concentric rod at the module inlet and downstream of the rod at the module outlet. Many experimental results were obtained. Some of them are plotted in Figs.3 and 4 and the following correlation equations were also reached:

$$R_m = 5.69\times10^9 \quad (P_a\cdot m^2\cdot s/m^3) \quad (10)$$

$$\phi = \phi_0(\cos\theta)^{1.42u_i^{0.64}C_i^{-0.132}} \quad (11)$$

$$R_f = R_{f,0}(\cos\theta)^{0.44u_i^{-0.124}C_i^{0.29}} \quad (12)$$

where

$$\phi_0 = 1.024\times10^5 u_i^{-0.62}C_i^{0.387} \quad (m^2\cdot s/m^3) \quad (13)$$

$$R_{f,0} = 3.284\times10^9 u_i^{-0.509}C_i^{0.355} \quad (P_a\cdot m^2\cdot s/m^3) \quad (14)$$

$$U_i = \frac{Q_i}{\left[\pi r_m^2\left(1-k^2\right)\cos\theta\right]} \quad (15)$$

The average values of permeate flux may be predicted from Eq. (9) with the use of the correlation equations, Eqs. (10), (11), and (12), as well as the parametric equations, Eqs. (4)-(7), in which L= 0.4m, r_m= 0.003m and the fluid viscosity may be estimated by (Cheng, 1992)

$$\mu = 0.894\times10^{-3}\exp(0.408C_i)\ , \quad kg/m\cdot s \quad (16)$$

Some correlation predictions for permeate flux were calculated and the results are compared with the experimental data, as show in Figs. 3 and 4. It is seen from these figures that the predicting values are qualitative agreement with the experi-mental results.

Discussion and Conclusion

Increasing fluid velocity in the cross-flow type membrane modules has two conflict effects on ultrafiltration. One, the decrease in resistance to permeation due to reduction in concentration polarization, is good for ultrafiltration, while the other, the decrease in average transmembrane pressure due to increase in frictional pressure loss, is bad for ultrafiltration. It appears, therefore, that proper adjustment of fluid velocity as well as proper arrangement of the geometry of flow channel with a specified volumetric feed rate, might effectively suppress any undesirable resistance to permeation due to concentration

polarization while still maintaining an effective transmembrane pressure, and thereby lead to improved permeate recoveries.

In the present study the inner steel rod in the tubular-membrane module was wrapped by a tight fitting wire spiral having a diameter equal to the annular spacing for rising fluid velocity. For a specified volumetric feed rate, fluid velocities in the flow channels of a wired-membrane module change with the inclined angle of helical wire θ. For example, the velocity in the wired-membrane module with $\theta = 45^0$ is 1.414 $(1/\cos 45°)$ times that in the concentric-tube membrane module without wraping a helical wire, as seen in Eq. (15). Therefore, fluid velocities in present modified modules can be further adjusted and controlled. It is seen in Figs. 3 and 4 that properly increasing θ in the modified modules can really enhance the fluid velocities, resulting in decrease of permeation resistance and improvement in ultrafiltration.

List of symbols

C_i concentration of feed solution (wt% of dextran T500)

J volume permeate flux of solution in a wired-membrane module $(m^3/m^2 \cdot s)$

$\bar{J}$ average value of J $(m^3/m^2 \cdot s)$

k ratio of the radius of inner steel rod to inside radius of ceramic-membrane tube (m)

L length of tubular-membrane module (m)

m constant defined by Eq. (4) $(Pa \cdot s/m^3)$

n constant defined by Eq. (5) $(Pa \cdot s/m)$

P pressure distribution on the tube side (Pa)

P_i pressure at the inlet (Pa)

P_L pressure at the outlet (Pa)

P_p permeate pressure on the shellside (Pa)

ΔP transmembrane pressure, $P - P_p$ (Pa)

ΔP_i $P_i - P_p$ (Pa)

Q_i volume flow rate at the inlet of a wired -membrane module (m^3/s)

R_f resistance due to solute adsorption and fouling $(Pa \cdot s/m)$

$R_{f,o}$ R_f in the module without a helical wire $(Pa \cdot s/m)$

R_m intrinsic resistance of membrane $(Pa \cdot s/m)$

r_m inside radius of tubular membrane (m)

z axial coordinate (m)

Greek letters

μ viscosity of solution $(kg/m \cdot s)$

ϕ proportional constant defined in Eq. (1) $(m^2 \cdot s/m^3)$

ϕ_0 ϕ in the module without a helical wire $(m^2 \cdot s/m^3)$

ξ z/L

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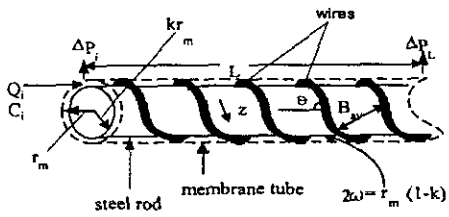
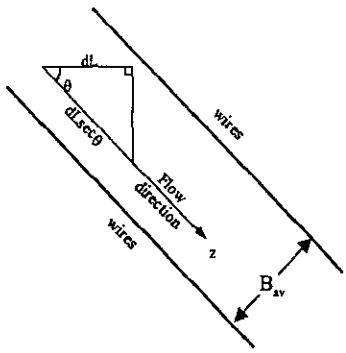


(a) wired-membrane module



(b) flow channel

Fig. 1. Tubular membrane with a twisted wire rod assembly.

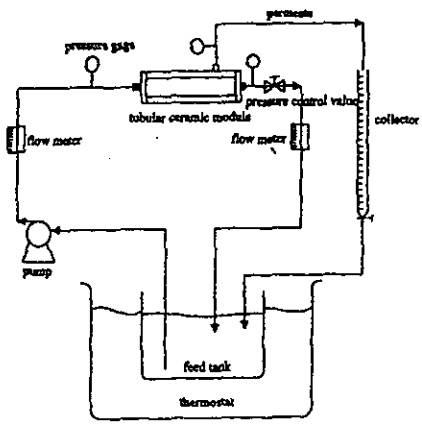


Fig. 2. Experimental apparatus.

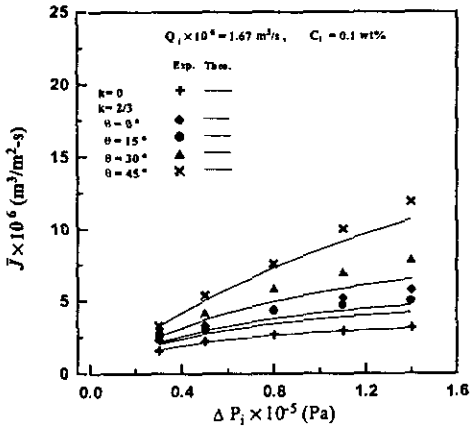


Fig. 3. Compassion of theoretical predictions of $\bar{J}$ vs. ΔP_i with experimental results for $Q_i = 1.67 \times 10^{-6}\ m^3/s$

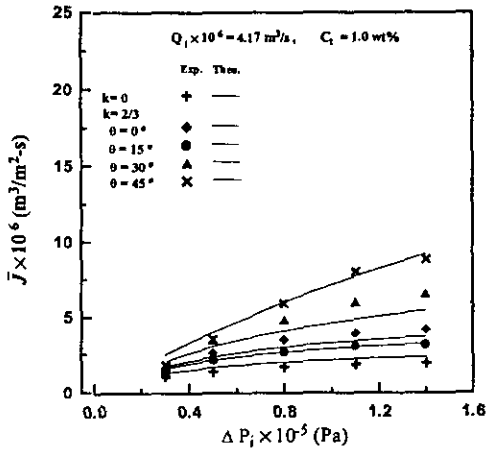


Fig. 4. Compassion of theoretical predictions of $\bar{J}$ vs. ΔP_i with experimental results for $Q_i = 4.17 \times 10^{-6}\ m^3/s$