Effect of Ring Density on the Performance in a Tubular Ultrafiltration Membrane Inserted concentrically with a Ring Rod

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Abstract

The effect of hydraulic behavior on membrane ultrafiltration in a tubular module inserted concentrically with a steel rod wrapped by rings with various ring densities but uniform ring distance along the flow channel, was investigated. It is concluded that attaching rings with proper ring density on the solid rod inserted concentrically in a tubular membrane may enhance the performance of ultrafiltration due to the creation of turbulent flow, resulting in decrease of concentration polarization while still preserving the effective transmembrane pressure.

***Key Words*:** Ultrafiltration, Ring-Rod Tubular Membrane, Ring Density, Permeate Flux

1. Introduction

Ultrafiltration (UF) of macromolecular solutions has become an increasingly important separation process. Today, the following applications have been proven to be economically attractive and useful [1–3]: industrial effluents, oil emulsions, wastewater, biological macromolecules, colloidal paint suspensions and medical therapeutics. The transmembrane pressure applied is usually in the range of 69 to 690 kPa. The rapid development of this process was made possible by the advent of anisotropic, high-flux membranes capable of distinguishing among molecular and colloidal species in the 0.001 to 10 μm size range.

The advantage of UF as compared to other dewatering processes, such as evaporation and freezing, is the absence of a change in phase or state of the solvent. Evaporation requires the input of about 2326 kJ/kg of water evaporated while freezing requires about 335 kJ/kg of water frozen, merely to effect the change of water from liquid to vapor and liquid to solid, respectively. A less obvious advantage is the fact that no complicated heat-transfer or heat-generating equipment is needed, only electrical energy to drive the pump motor is required.

In cross-flow UF the permeate flux generally declines with filtration time due to the phenomenon of concentration polarization by the rejected particles [4–6]. Several hydraulic approaches developed for reducing the effects of concentration polarization (CP) and progressive fouling to enhance the permeate flux, have been discussed thoroughly [7–19]. The use of inserts, such as metal grills [7], static rods [8], spiral wire [9], disc and doughnut shape inserts [10] and helical baffles [11–14], in a tubular membrane have been tried to different membrane processes. Da Costa et al. performed an extensive study of UF flux by net-type spacers [15–17]. The applications of combined [18] and multipass [19] systems in hollow-fiber modules were also reported.

The performances for UF in tubular membranes with a steel rod inserted [20] and with a twisted wire-rod assembly [21] were investigated in previous works. It was found that proper adjustment of fluid velocity distribution along the flow channel as well as proper arrangement of the profile of flow channel with a specified volumetric feed rate, might effectively suppress any undesirable resistance to permeation due to CP while still pre-

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serving an effective transmembrane pressure, and thereby lead to improved permeate recoveries. In the previous study of twisted wire-rod modules, however, only laminar flow with the constant angle of wire spiral through the flow channel were considered. For further study of the hydraulic behavior in tubular-membrane modules, the effect of creating the turbulence by wrapping rings on the solid rod inserted concentrically in a tubular membrane, on performance will be investigated in present work. Consider a modified tubular-membrane module of radius r_m inserted concentrically with a steel rod of radius kr_m, on which several rings having a diameter smaller than the annular spacing, is wrapped with uniform distance on the steel rod as buffles to create turbulent flow, as shown in Figure 1. In present study, we will investigate the effect of ring density (i.e. ring number, L/λ) on the reduction of CP resistance and transmembrane pressure, as well as on the enhancement of permeate flux.

2. Experimental

The experimental apparatus, materials and procedure were exactly the same as those in previous work [21], except that instead of spiral wires, several rings with uniform distance along the flow channel were used, as shown in Figure 1. The membrane medium used in the ring-rod module was mainly a 150 kDa MWCO tubular ceramic membrane (M2 type, Techsep, France; length, $L = 0.4$ m, ID $2r_m = 6$ mm) with a steel rod of radius, $kr_m = 1.5$ mm ($k = 1/2$), inserted concentrically. Several rings of 5 mm diameter made of a steel wire having the diameter equal to 1 mm, was wrapped tightly with uniform distance, λ, on the entire steel rod as buffles in the annulus. The experiment was conducted with $L/\lambda = 5$, 10 and 15, as well as with $L/\lambda = 1$ (without ring) for comparison.

The tested solute was dextran T500 (Pharmacia Co., Sweden) which was more than 99% retained by the membrane used, while the solvent was distillated water. The feed solution concentrations C_i were 0.1 and 0.5 wt% dextran T500. Figure 2 shows the schematic diagram of the experimental apparatus. The feed solution was circulated by a high-pressure pump with a variable speed motor (L-07553-20, Cole Parmer Co.), and the feed flow rates Q_i were controlled by a flowmeter (IR-OPFLOW 502-111, Headland Co.) to be 2.50, 3.33 and 4.17 cm^3/s. The pressures were controlled by the pressure control valves and were measured with a pressure transmitter (Model 891.14.425, Wika Co) at the inlet (P_i)

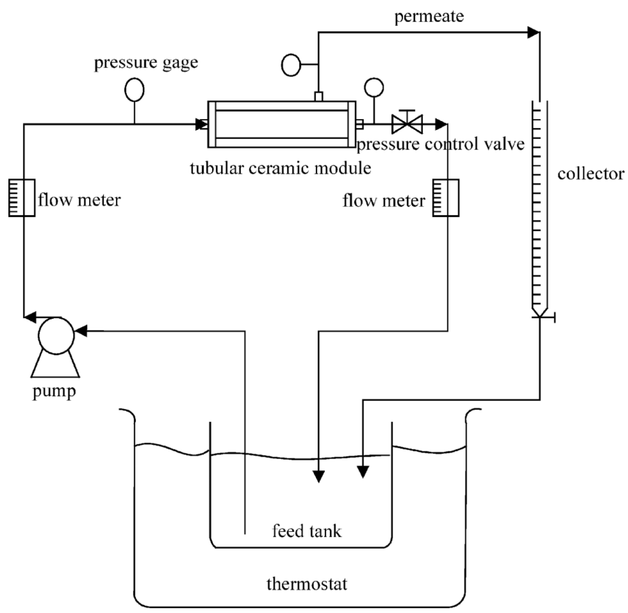

Figure 2. Experimental apparatus.

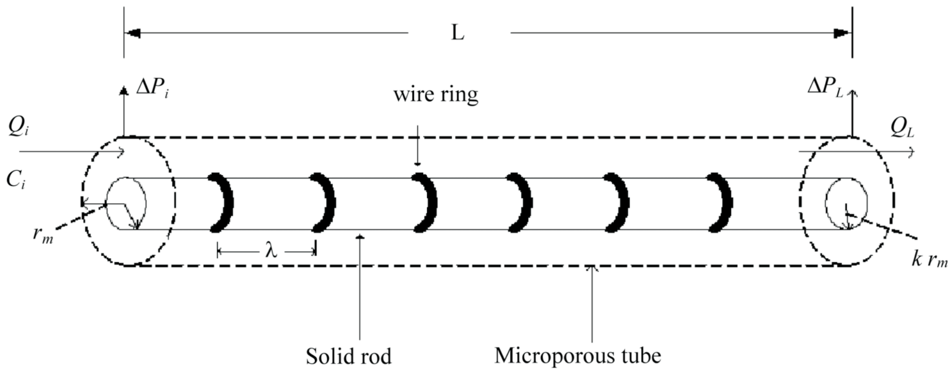

Figure 1. Schematic diagram of a ring-rod tubular-membrane ultrafilter.

and outlet (P_L) of the conduit as well as at shell side (P_p). The inlet transmembrane pressures ΔP_i were 30, 50, 80, 110 and 140 kPa. In all experiments the feed solution temperature was controlled as 25 °C by a thermostat.

3. Results and Discussions

3.1 Effects of Operating Parameters on Performance

Many experimental results of average permeate fluxes, $\bar{J}$, were obtained, as shown in Tables 1 and 2, and some of them are plotted in Figure 3 to show the effect of dimensionless ring distance (λ/L), as well as ring number (L/λ), on average permeate flux. It is seen that the application of rings on the solid rod inserted concentrically in a tubular membrane really enhances the performance of UF. As expected, the permeate flux increases with the transmembrane pressure but decreases as the feed concentration increases. However, the fluid velocity as well as the volume flow rate nearly does not affect the performance due to the low flow rates employed, as compared with the stronger effect of turbulent flow applied.

Table 1. Permeate flux of Dextran T500 aqueous solution with C_i = 0.1 wt%

$Q_i \times 10^6$ (m^3/s)	$\Delta P_i \times 10^{-5}$ (Pa)	$\bar{J} \times 10^6$ (m^3/m$^2 \cdot$ s)			
		$L/\lambda = 1$	$L/\lambda = 5$	$L/\lambda = 10$	$L/\lambda = 15$
2.50	0.3	0.7866	0.8133	0.7600	0.6800
	0.5	1.5600	1.5600	1.4533	1.3600
	0.8	2.7733	2.8400	2.3600	2.2933
	1.1	3.9067	3.9867	3.3600	3.3600
	1.4	5.1867	5.4000	4.4267	4.2667
3.33	0.3	0.7867	0.9067	0.8000	0.6400
	0.5	1.5333	1.6800	1.4533	1.3067
	0.8	2.7467	2.8933	2.3867	2.3200
	1.1	3.8533	4.1333	3.4000	3.3200
	1.4	5.0400	5.4000	4.4667	4.3867
4.17	0.3	0.7733	0.9600	0.7733	0.6267
	0.5	1.5200	1.7600	1.4000	1.3067
	0.8	2.6667	2.9733	2.5733	2.2667
	1.1	3.9333	4.2933	3.4667	3.3600
	1.4	5.0800	5.5467	4.5600	4.2800

Table 2. Permeate flux of Dextran T500 aqueous solution with C_i = 0.5 wt%a

$Q_i \times 10^6$ (m^3/s)	$\Delta P_i \times 10^{-5}$ (Pa)	$\bar{J} \times 10^6$ (m^3/m$^2 \cdot$ s)			
		$L/\lambda = 1$	$L/\lambda = 5$	$L/\lambda = 10$	$L/\lambda = 15$
2.50	0.3	0.7333	0.7467	0.7733	0.7600
	0.5	1.3600	1.4400	1.4133	1.4533
	0.8	2.2667	2.2933	2.2800	2.3600
	1.1	3.2133	3.2823	3.2267	3.3600
	1.4	4.0533	4.3467	4.1733	4.4267
3.33	0.3	0.6933	0.7600	0.7600	0.8000
	0.5	1.3333	1.3467	1.3200	1.4533
	0.8	2.2000	2.3867	2.2267	2.3867
	1.1	3.1867	3.3067	3.2533	3.4000
	1.4	4.0933	4.3600	4.1733	4.4667
4.17	0.3	0.7067	0.7733	0.6933	0.7733
	0.5	1.3333	1.3867	1.3200	1.4000
	0.8	2.3867	2.3467	2.1733	2.5733
	1.1	3.2400	3.3200	3.2933	3.4667
	1.4	4.0000	4.1333	4.2000	4.5600

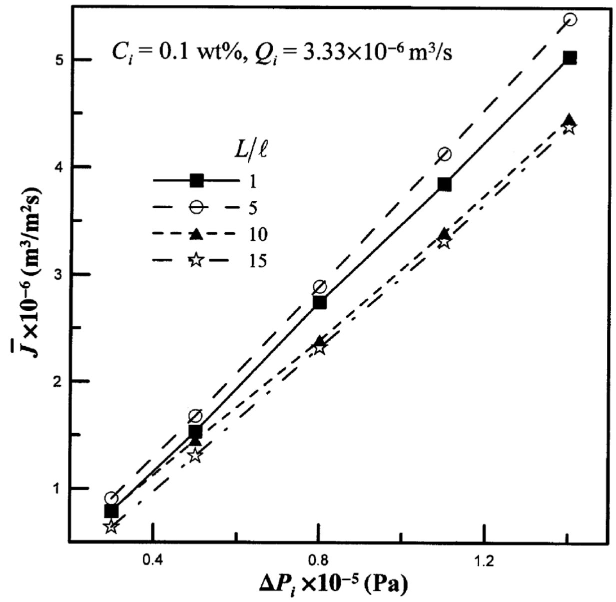

Figure 3. Permeate flux vs. transmembrane pressure for C_i = 0.1 wt% and $Q_i = 3.33 \times 10^{-6}$ m^3 s^{-1}

3.2 Effect of Ring Density on Performance

Actually, creating the turbulence in the cross-flow type membrane modules has two conflicting effects on UF: one, the decrease in resistance to permeation due to reduction in CP, is good for UF; while the other, the decrease in average transmembrane pressure due to increase in frictional pressure loss, is bad for UF. Therefore, proper adjustment of the strength of turbulence, as well as the ring density (L/λ), along the flow channel with a specified volumetric feed rate, might effectively suppress any undesirable resistance to permeation due to CP while still preserving an effective transmembrane pressure, and thereby lead to improved permeate recoveries. For lower concentration of solution, C_i = 0.1 wt%, the CP resistance is rather small and thus, moderate strength of turbulence created by the attached rings with L/λ = 5, is sufficient to reduce CP resistance while still preserving an effective transmembrane pressure, as shown in Table 1 and Figure 3. On the other hand, the CP resistance is larger for C_i = 0.5 wt% and stronger turbulence is needed with L/λ = 15, as indicated in Table 2.

3.3 Effect of Ring Density on the Hydraulic Dissipated Powers

In addition to the improvement in permeate flux , application of rings on the solid rod to create the turbulent flow also leads to increased the hydraulic dissipate powers and should be taken into consideration. The hydraulic dissipated powers may be estimated by

$$H = (\rho\, Q_i)\frac{(\Delta P_i) - (\Delta P_L)}{\rho} = Q_i(\Delta P_i - \Delta P_L)$$

The results are calculated and listed in Table 3. It is seen

Table 3. Hydraulic dissipated power for C_i = 0.5 wt%

$Q_i \times 10^6$ (m^3/s)	$\Delta P_i \times 10^{-5}$ (Pa)	L/λ = 1		L/λ = 15	
		$\Delta P_L \times 10^{-5}$ (Pa)	H × 10^4 (hp)	$\Delta P_L \times 10^{-5}$ (Pa)	H × 10^4 (hp)
1.67	0.3	0.29314	0.02	0.24206	0.13
	0.5	0.48706	0.29	0.42278	1.73
	0.8	0.77946	0.46	0.70364	2.16
	1.1	1.07053	0.66	0.98098	2.67
	1.4	1.35926	0.91	1.25244	3.30
2.50	0.3	0.28824	0.39	0.22732	2.44
	0.5	0.48216	0.60	0.41116	2.98
	0.8	0.77166	0.95	0.68796	3.76
	1.1	1.06301	1.24	0.96824	4.42
	1.4	1.35436	1.53	1.24872	5.07
3.33	0.3	0.28334	0.74	0.20678	4.16
	0.5	0.47726	1.02	0.39396	4.74
	0.8	0.76865	1.40	0.67228	5.70
	1.1	1.06148	1.72	0.95256	6.58
	1.4	1.35044	2.21	1.22598	7.77
4.17	0.3	0.27942	1.15	0.19110	6.09
	0.5	0.47432	1.44	0.37632	6.92
	0.8	0.76638	1.88	0.65562	8.07
	1.1	1.05762	2.37	0.93296	9.34
	1.4	1.34848	2.88	1.20944	10.66

that though the hydraulic dissipated powers increase rapidly with the ring numer, the values are still small and may be ignored.

4. Conclusion

The effect of hydraulic behavior on membrane UF in a ring-rod tubular module has been investigated by wrapping rings on the solid rod to create turbulence. Along the flow channel of a tubular membrane, the CP resistance increases while the transmembrane pressure decreases. It is found that the creation of turbulent behavior by wrapping rings on the solid rod may reduce the CP, resulting in increase of permeate flux. However , rising the strength of turbulence in the flow channel of a cross-flow membrane ultrafilter also results in an undesirable effect of decreasing transmembrane pressure. For low concentration of solutions, the CP layer is thin and moderate turbulence is sufficient to reduce the CP resistance while still preserving an effective transmembrane pressure. On the other hand, larger ring density is needed for higher concentration of solutions where the CP resistance is larger. It is concluded that attaching rings on the solid rod inserted concentrically in a tubular membrane may enhance the performance of UF, however, the ring density (ring number) must be properly adjusted and controlled along the concentration of solution.

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