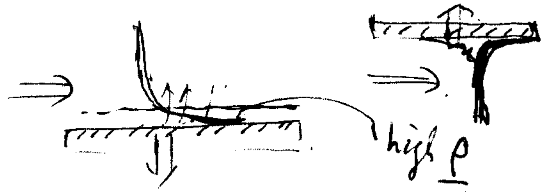

특별강연 II

Effects of Natural Convection Instability on Membrane Performance in Dead-end and Cross-flow Ultrafiltration

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1. Introduction

An inevitable problem feature of membrane processing is concentration polarization (CP) which is a result of the accumulation of retained solutes at the membrane surface. In ultrafiltration (UF), this accumulation can lead to fouling due to the irreversible deposition of macromolecules both at the membrane surface and in the membrane pores. To reduce or control CP and fouling, many possible methods have been considered [1]. One of the most effective approaches is to induce fluid instability near the membrane surface by using pusation flow [2,3], Taylor [4] and Dean [5,6] vortex flows. Winzeler and Belfort [6] have comprehensively reviewed several possible attempts to use fluid instabilities for improved membrane performance.

Another method capable of inducing fluid instability near the membrane surface is the use of natural convection flow. The variation of solute concentration across CP layer implies the existence of density variation so that the solution density at the membrane surface is higher than that in the bulk solution. By changing the gravitational orientation (angle) of the membrane module, the density inversion in which higher-density solutions overlay lower-density solutions is obtained. This density inversion may lead to unstable fluid behaviour and produce 'natural convection (buoyancy or secondary) flow' in the vicinity of the membrane surface.

The occurrence of natural convection instability (NCI) may be effective to reduce CP and fouling because of its effects in promoting mass transfer from the membrane surface to the bulk solution. Furthermore, if NCI is superimposed on the cross-flow (forced convecton flow), it may be expected that the membrane performance will be significantly improved.

This research aims to obtain some information concerning the effects of NCI on depolarization and mass transfer in UF membrane systems. Thus, we focus on the effects of NCI, with change of the membrane gravitational orientation, on the UF performance of relatively non-fouling solutes in the flat channel test cell operated in both the dead-end and the cross-flow modes. Using a direct analogy between heat and mass transfer, a criterion for determining whether NCI is likely to affect the flux enhancement in cross-flow operation is identified. A mass transfer correlation, suitable for the combined natural and forced convection (mixed convection) membrane system, is presented.

2. Experimental

The UF cell was a thin-channel type with an effective membrane area 50.8 cm^2. Inlet and oulet of this cell were connected to piping system by means of couplings which could provide easy rotation of the test cell. The experimental set-up is given in Fig. 1. The membrane used was a HFK-131 polysulphone membrane with a molecular weight cut-off of 5,000 Da, supplied by Koch Membranes Inc. In most experiments dextran 500T (M_w = 526,000, Sigma Co.) was used as the test solute. Bovine serum albumin (BSA, M_w = 68,000, Calbiochem Co.) was also used as a test for the dead-end UF experiments. UF experiments were run

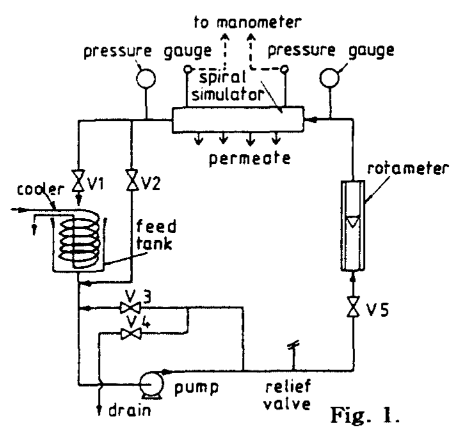


Fig. 1.

using a horizontally aligned test cell, at three membrane gravitational cell orientations; the membrane surface was (1) below(stable, designated 0°), (2) vertical(semi-stable, 90°), (3) above (unstable, 180°) the flow channel. The effects of NCI on the UF flux were examined in two operating modes; the dead-end and the cross-flow operation. In the dead-end operation, an empty (without spacer) cell was tested. In the cross-flow operation, both an empty and spacer (80MIL-1) filled cells were tested.

3. Results and Discussion

1) Dead-end UF

The flux-time behaviours for dextran and BSA solutions during the four successive stages are shown in Figs. 2 and 3 respectively. During stage 1 (0°), the fulx declines very rapidly in the first few minutes and then continues to decline until the cell orientation is changed to 180°. During stage 2 (180°), the flux increases rapidly for 5 to 10 minutes and then reaches the enhanced steady value. In stage 3 (90°), we also obtain enchanced steady values although these are less than flux obtained at 180°. In stage 4 (0°), the flux decreases rapidly in the first few minutes and then declines slowly as the usual dead-end flux trends.

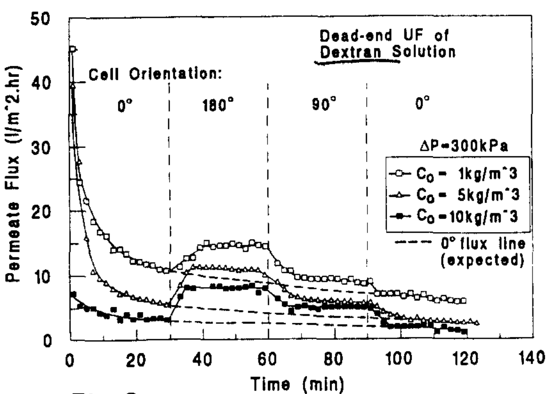


Fig. 2.

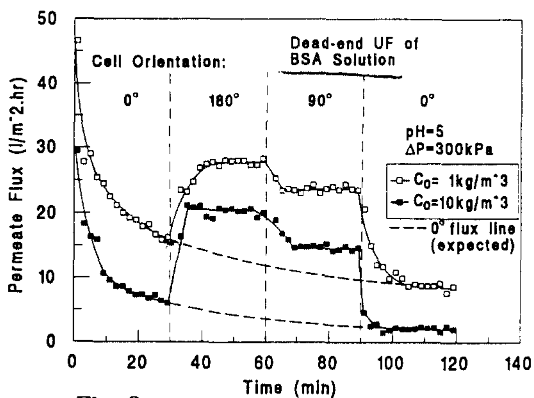


Fig. 3.

2) Cross-flow UF

The effects of NCI on UF performance in cross-flow operation are illustrated in Fig. 4. The fluxes with time in an empty and a spacer filled cell with accompanying successive changes of the cell orientation ($0° \rightarrow 180° \rightarrow 90° \rightarrow 0°$) were measured for three different flow rates; 3.4, 19.5 and 62.8 L/hr. Flux enhancements by NCI at 180° cell orientation observed for cross-flow UF in the empty channel at 3.4 L/hr and 19.5 L/hr although they are lower than those obtained for the dead-end UF and are not evident at 62.8 L/hr. Moreover flux enhancements are obtained only at 3.4 L/hr for the 90° cell orientation of the empty channel and the 180° cell orientation of the spacer-filled cell; no flux improvements are found at 90° cell orientation in the spacer-filled cell.

To obtain a general criterion for determining whether NCI effects dominate, the cross-flow UF results are represented in Fig. 5. as $(k_M - k_F)H/ReD$ as a function of Gr/Re^2. $(k_M - k_F)H/ReD$ indicates the net mass transfer by NCI to the bulk solution of unit flow rate since Re is the dimensionless flow rate by definition. Figure 5 shows that the net mass transfer is nearly zero at the small value of Gr/Re^2, however increases with increasing Gr/Re^2 beyond its threshold value at which the mass transfer may be enhanced appreciably by NCI. Also Fig. 5 shows that the net mass transfer are more large for the empty cell and the complete density inversion case (180° cell orientation). Here it is worth noting that Gr/Re^2 can be suitable for determining the relative influence of natural and forced convection effects on the membrane performance. Gr/Re^2 characterises the dominant mode of mass transfer in mixed convection membrane system. The threshold value of Gr/Re^2 for the empty and spacer-filled cells at 90° and 180° cell orientations are summarised in Table 1.

Mass transfer correlation for mixed convection membrane system was performed only for the empty cell at 180° cell orientation because it represents more higher mass transfer enhancement by NCI so that it has enough data for correlation. Using a direct anology between heat and mass transfer, we can write the Sherwood number for mixed convection Sh_M as follow:

$$Sh_M = 0.22\,Re^{0.46}\,Sc^{1/3}\left[1+\frac{Ra}{1.25\times10^{6}\,Re^{2}}\right]^{1/6}$$

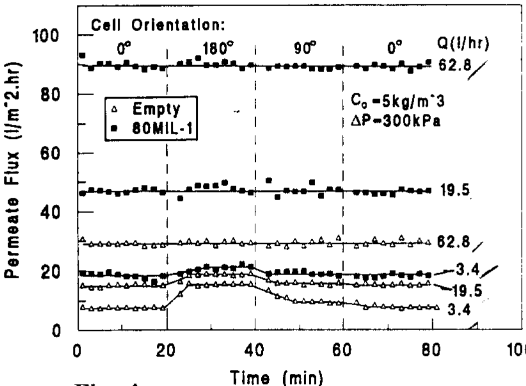


Fig. 4.

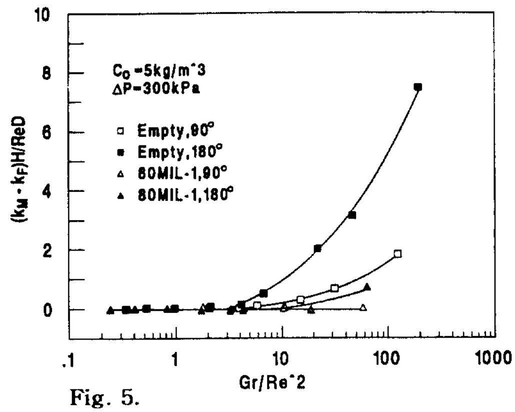
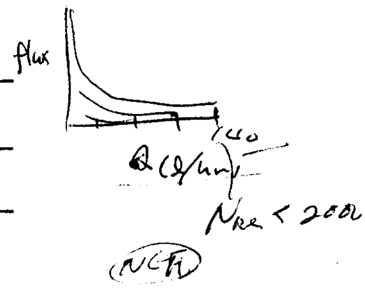


Fig. 5.

Table 1. Threshold values of Gr/Re^2.

Channel type		Feed concentration (kg/m^3) 1	5	10
Empty	180°	10	4	3
	90°	28	12	8
80MIL-1	180°	32	18	11
	90°*	-	-	-

*No natural convection instability effects are detected.



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