Enhancement of Ultrafiltration Performance by Natural Convection Instability Flow

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I. Introduction

To reduce or control concentration polarization and fouling in the pressure driven membrane systems, many possible methods have been suggested [1]. The most well known method is providing good fluid management in the membrane module such as increasing shear at the membrane surface by increasing cross-flow velocity or producing eddies by using turbulence promoters. One of the most effective approaches for providing good fluid management is to induce fluid instability near the membrane surface by using pulsate flow, and Taylor and Dean vortex flows [2].

Another method capable of inducing fluid instability near the membrane surface is the use of natural convection instability flow (NCIF). The natural convection flow is essentially generated in a stratified fluid in which higher-density layers overlay regions of lower-density. In UF systems, the variation of solute concentration across concentration polarization layer implies the existence of density variation so that the solution density at the membrane surface is higher than that in the bulk solution.

The occurrence of NCIF in UF systems is represented in Fig. 1. By changing the gravitational orientation (inclined 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 behavior and produce natural convection flow in the vicinity of the membrane surface. The occurrence of NCIF in the membrane module is effective to reduce or control concentration polarization and fouling because of its effects on promoting mass transfer from the membrane surface to the bulk solution.

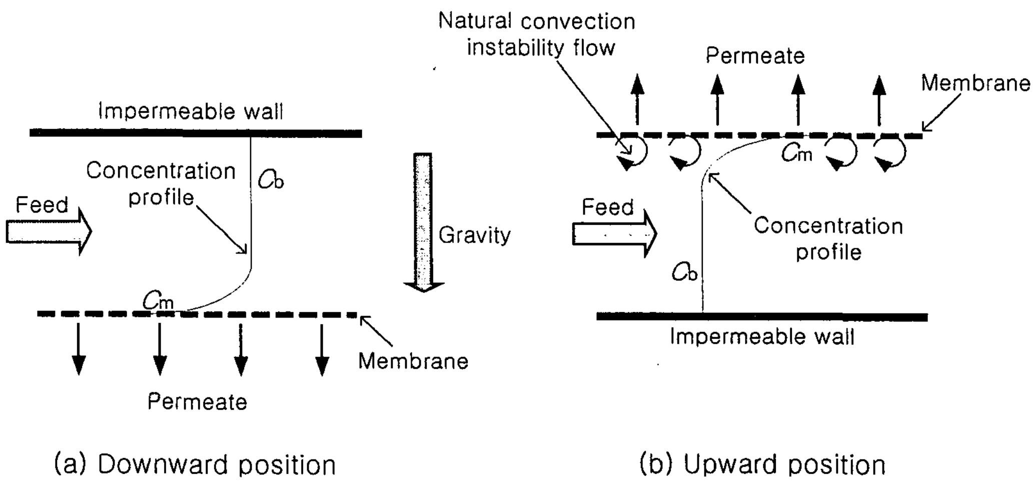

Fig. 1. Occurrence of natural convection instability flow in the membrane module.

The present paper is directly relevant to our previous work [3] and significantly extends it. In this work, the effects of NCIF on defouling are investigated in detail. Thus, we focus on the effects of NCIF, with change of the membrane gravitational orientation, on the flux enhancement of relatively fouling solute (BSA protein) in the flat channel UF test cell operated in both the dead-end and the cross-flow modes.

II. Experimental

Bovine serum albumin (BSA, average molecular weight 69,000, Fraction V, Sigma Co., USA) was used as the test protein and dissolved in salt free Milli-RO$^+$/Q$^+$(Millipore Co., USA) treated water ranged of concentrations from 0.5 to 4 kg/m^3. The pH value of BSA solutions was adjusted 5.4 by dropwise addition of 0.15 M solutions of HCl and/or NaOH. The membranes used were the SEPA-HN02 and SEPA-SN04 membrane with a nominal molecular weight cut-off (MWCO) 20,000 Da, supplied by Osmonics Co. These membranes differ from hydrophobicity; SN04 membrane is more hydrophilic than HN02 membrane. Prior to each UF experiment, a new membrane strip was first washed with pure water several times to remove storage chemicals from the membrane and then compressed at 400 kPa pressure for 2 hr, and finally measured the pure water flux.

A schematic diagram of the experimental UF system is shown in Fig. 2. The membrane cell was a thin-channel type with an effective membrane area of 85 cm^2 (active length 25 cm × width 3.4 cm, h = 0.2 cm, d_h = 0.38 cm). The inlet and outlet of this cell were connected to a piping system by means of couplings, which could provide easy rotation of the membrane cell. The electronic balance (FX-3000, AND Co., Japan) interfaced with a personal computer for on-line data acquisition of the permeate fluxes at 2-min intervals was attached to the membrane cell.

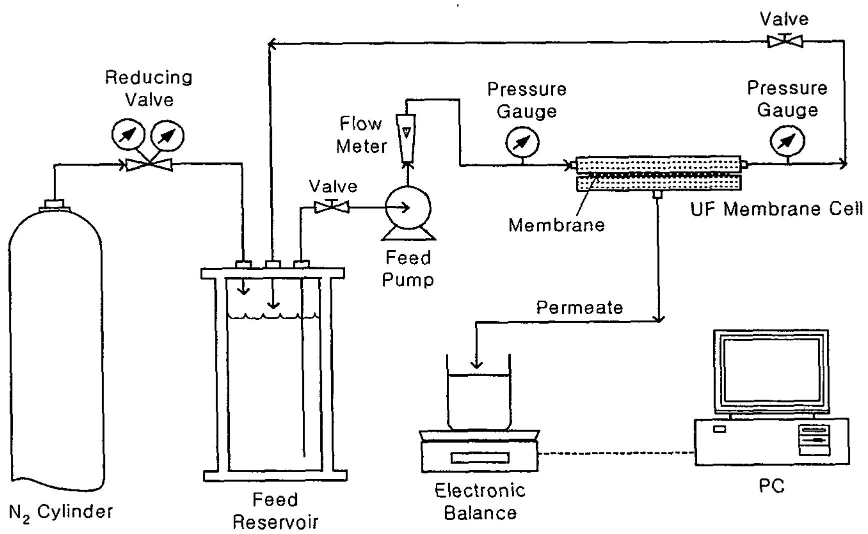

Fig. 2. UF experimental system.

UF experiments were conducted with a horizontally aligned test cell at two membrane gravitational cell orientations; the membrane surface was (1) below (0° inclined angle, downward position), (2) above (180° inclined angle, upward position) the flow channel. These orientations were obtained by simply rotating the UF membrane cell about its axis.

The effects of NCIF on the membrane flux were examined in two operating modes; the dead-end and the cross-flow UF operation. The compressed nitrogen gas was applied on the feed reservoir to adjust the operating pressure (varied from 100 to 400 kPa) of the system and to supply BSA solution into the membrane cell in case of dead-end UF operation. The inlet and outlet pressure were measured using two pressure gauges that were attached at the inlet and oulet side of the membrane cell. Here we define the transmembrane pressure, ΔP as an average value of two measured pressure values. In cross-flow UF operation, BSA solution was passed through the membrane cell with a cross-flow rate ranged from 3 to 48 *l*/hr in the laminar regime and then was returned to a feed reservoir by a diaphragm pump (DOHP-365, Whain Precision Co., Korea).

III. Results and discussion

3.1 Dead-end UF operation

To show immediately the effects of NCIF on membrane flux during dead-end UF of BSA solution, the time dependent fluxes were continuously recorded at three successive cell orientations: (1) UF at downward position for 30 min, followed by (2) the cell orientation changed to upward position and UF for 30 min, finally (3) the cell was reoriented to downward position and UF for 60 min. Flux versus time behavior in the course of successive change of the cell orientations is shown in Fig. 3. This result implies that the upward position (180° inclined angle) induces NCIF in the membrane cell, and the induced NCIF may surely promote the back transport of deposited BSA away from the membrane surface.

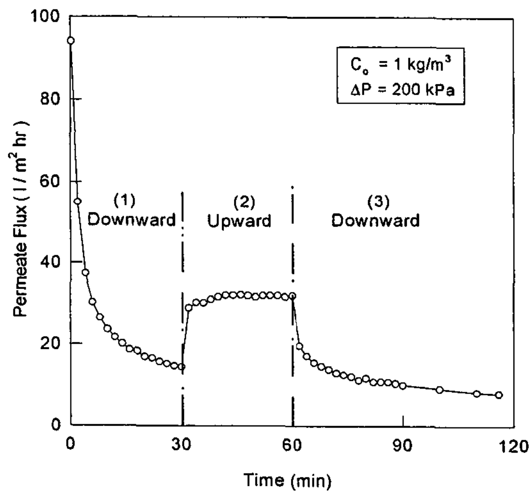

Fig. 3. Flux versus time behavior for dead-end UF with HN02 membrane during successive change of the cell orientation.

Another dead-end UF experiments were performed to measure quantitatively the effects of NCIF on the membrane flux. These experiments were executed at both downward and upward position for 60 min with change of experimental conditions (C_o = 0.5~4 kg/m^3, ΔP = 100~400 kPa). Typical flux trends with time under downward and upward position at C_o = 0.5 kg/m^3 and ΔP = 200 kPa are shown in Fig 4. Although the aspects of flux decline at both downward and upward position are apparently same (after the initial rapid drop, the fluxes decrease slowly with time), the upward position gives more improved flux trends. These improved flux trends evidently lead to increase in flux enhancements as shown in Fig. 5. Here the flux enhancement, E, is defined by J_{up}/J_{dn} in which J_{up} and J_{dn} are the flux at upward and downward position respectively. Fig. 5 shows that the permeate fluxes at upward position are enhanced up to 4 times compared with that at downward position.

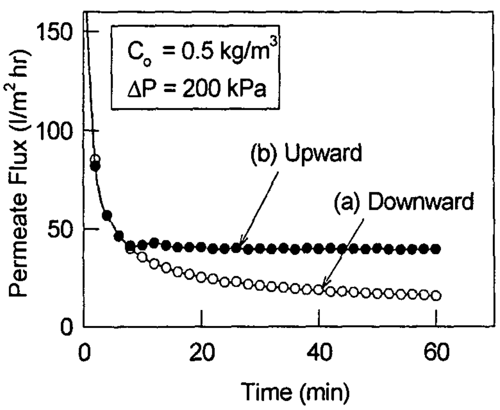

Fig. 4. Flux versus time behavior for dead-end UF with SEPA-HN02 membrane at (a) downward and (b) upward position.

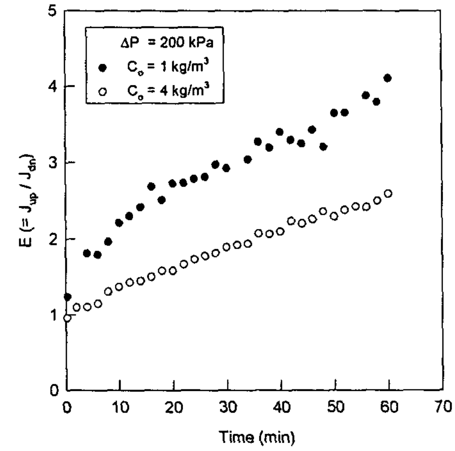

Fig. 5. Trends of flux enhancement for dead-end UF with SEPA -HN02 membrane.

3.2 Cross-flow UF operation

The effects of NCIF on the membrane flux are illustrated in Fig. 6. The fluxes versus time behaviors accompanying successive changes of the cell orientation (downward → upward → downward) were measured for four different cross-flow rates; Q = 3 *l*/hr, 6 *l*/hr, 12 *l*/hr and 30 *l*/hr. This results show that the permeate fluxes during upward position at 3 *l*/hr, 6 *l*/hr and 12 *l*/hr of flow rate were higher than that during downward position due to the effects of NCIF although the flux enhancements by NCIF (up to 2.5 times) are lower than those for dead-end UF (up to 4 times) and are not observed at 30 *l*/hr of flow rate. Fig. 6 also shows that flow rates are significant factors controlling the extent of NCIF occurrence in the cross-flow UF operation.

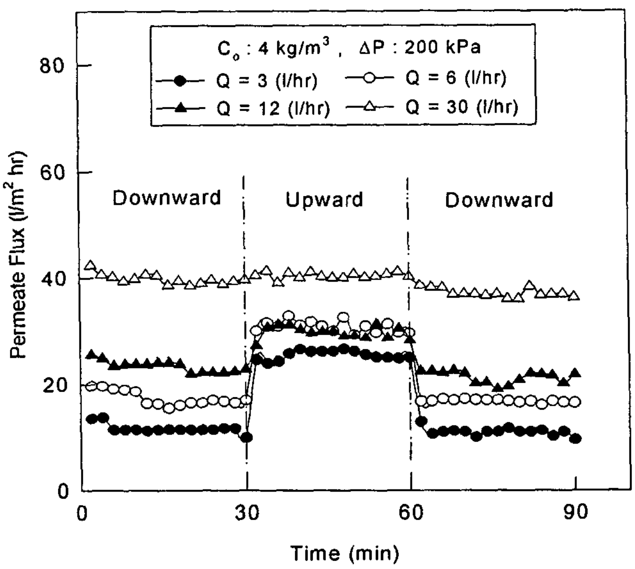

Fig. 6. Flux versus time behavior for cross-flow UF with SEPA-HN02 membrane during successive change of the cell orientation.

IV. Conclusions

The effects of natural convection instability flow on the enhancement of membrane performance have been studied in the dead-end and cross-flow ultrafiltration of BSA protein solution. The natural convection instability flow in the membrane module is induced simply by changing the gravitational orientation (inclined angle) of the flat channel membrane cell.

In dead-end operation, the permeate flux at the gravitationally unstable orientation (180°, upward position) is improved up to 4 times compared with that at gravitationally stable orientation (0°, downward position).

In cross-flow operation, the flux enhancements by natural convection instability flow occur when the cross-flow rate is below the value of around 12~30 *l*/hr (Re = 180~420). A general criterion for determining whether the effect of natural convection instability flow dominate or not is identified considering the net mass transfer in the membrane module. The natural convection instability flow is of importance when Gr/Re^2 *ca.* 10. Based on the osmotic pressure-adsorption model [4], the effects of natural convection instability flow on depolarization and defouling are determined separately. The influence of NCIF on defouling is more effective for the relatively hydrophilic membrane.

References

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