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Flux Enhancement with Glass Ball Inserted Membrane Module for the Ultrafiltration of Dextran Solution

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Abstract−The glass-ball-inserted membrane module has been designed to enhance the filtration of a flat-sheet membrane. Three different modes of filtration experiments were conducted and compared to demonstrate the flux enhancement due to the presence of glass balls: normal dead-end filtration, vortex flow filtration, and enhanced vortex flow filtration using glass balls. In the case of enhanced vortex flow filtration, the permeate flux was found to be three times as large as that of dead-end filtration and two times larger than vortex flow filtration. In addition, the flux decline was observed to be relatively low. The effect of the amount of glass balls on the permeate flux was also investigated by changing the glass ball volume fraction from 0.059 to 0.356. It has been observed that the permeate flux shows a maximum value of the volume fraction of 0.119. For the glass-ball-inserted membrane module, the permeate flux tends to increase with the feed flow rate.

Key words: Membrane, Glass Ball, Vortex Flow, Flux Enhancement, Dextran

INTRODUCTION

Membranes and membrane processes have been widely used in various industrial processes such as water or wastewater treatment [Aim and Peuchot, 1991], foods or proteins industry [Mueller and Davis, 1996], medical engineering [Shiraha et al., 1996], catalytic membrane reactors [Choi et al., 2000], and gas separation [Kim et al., 2001; Kim and Hong, 1999]. Membrane processes offer some clear advantages over traditional separation processes: separation can be carried out continuously under mild conditions; energy consumption is generally low; no additives are required; scale-up can easily be accomplished due to the modular structure; membrane properties are variable and can be adjusted; and the possibility of hybrid processing [Howell et al., 1993].

In spite of all the advantages, the use of MF and UF membrane processes is still limited due to the problems arising from concentration polarization, cake formation, and membrane fouling. To reduce these adverse phenomena, many researchers have considered various approaches for lowering the concentration gradient between the bulk fluid and the membrane surface. These include chemical modification of the membrane surface such as polymer blending, polymer modification, surfactant treatments and surface coating with hydrophilic agent [Musale and Kulkarni, 1998; Kobayashi et al., 1996; Maartens et al., 2000], physical methods, and hydrodynamic methods such as the use of eddies during turbulent flow [Chung et al., 1996; Chung, 1992; Vigo et al., 1986]. Several researchers have considered physical methods such as paddles or static mixer, mechanical souring with tight-fitting sponge balls, air sparging [Ghosh et al., 1998], back-washing or back-flushing [Matsumoto et al., 1987], and various inserts have also been developed [Millward et al., 1995]. Most of these techniques have been shown to be effective in enhancing UF and MF, in terms of increasing the permeate flux. Takadono et al. [1984] used a sponge ball cleaning device to improve the filtration of potato juice waste at a starch factory. Lowe and Durkee [1971] investigated the effect of spheres in flow channel on orange juice concentration in reverse osmosis (RO) and obtained flux improvement of up to 300%. Cui and Wright [1996] obtained the experimental flux data of gas-liquid two-phase crossflow UF in the downward flow membrane module, and showed that the flux increment for dextran solution was up to 320%, compared to the single liquid phase UF.

In this study, a membrane module configuration, which induces a rotational shear in addition to the usual axial shear, was developed to reduce the effect of concentration polarization near the membrane surface and cake layer formation on the membrane surface.

EXPERIMENTAL

1. Materials

Polysulfone membranes with a nominal molecular weight cut-off value of 300,000 Dalton, effective diameter of 7.0 cm, and effective membrane area of 38.485 cm^2 were used to investigate the filtration behavior of an aqueous dextran (Mn=260,000; supplied by Sigma-Aldrich, USA) solution with a concentration of 2,000 ppm. The membrane was manufactured by SaeHan Co. Ltd. (Korea) and was supplied in a flat sheet. The dextran solution of 2,000 ppm was prepared by combining 30 g of dextran powder with 15 L of deionized water. To prevent growth of microorganisms in the solution, sodium azide (Junsei, Japan) of 30 mg was added in the solution. The concentrations of dextran in the feed and permeate solutions were analyzed by a refractometer (R403, Waters, USA).

2. Membrane Module

A membrane module with glass balls was used in the experiment to reduce the effect of concentration polarization and to enhance the permeate flux. The module housing was made of polyacrylate. As shown in Fig. 1, the feed solution was supplied into the module in two opposite directions perpendicular to the permeate flow, there-

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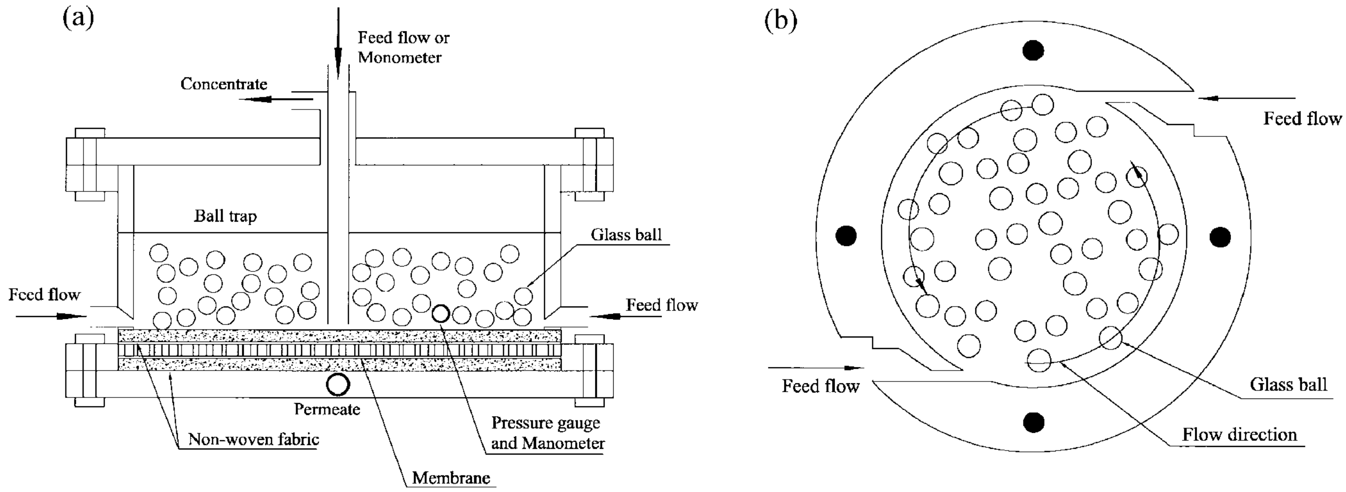

Fig. 1. (a) Schematic diagram of glass ball inserted membrane module. (b) Feed flow at bottom of the membrane module.

by inducing a vortex flow. As a result of induced vortex flow, a fluctuation or rotation occurs of glass balls placed in the membrane module, which reduces concentration polarization near the membrane surface and membrane fouling as well. The glass balls were of average diameter 4 mm and average weight 0.08 g, which gives an average density of 2.39 g/cm^3. Polysulfone membranes were protected from the applied transmembrane pressure and the movement of glass balls inserted in the module by placing a sheet of non-woven fabric on both sides of the membrane.

3. Experimental Apparatus

Fig. 2 shows the apparatus constructed for the experiments. The experiments were operated in a vortex flow or dead-end filtration mode. Dextran solution in the feed tank was pumped round the loop by using centrifugal pump. To maintain a constant temperature, cooling coil is equipped in the feed tank. The dextran solution flowing through the loop first passes through a flowmeter and then through the membrane module. There is a pressure transducer (PMSB0005-KAAA, Korea Instrument, Korea) mounted in the module to measure the applied pressure and manometer filled with tetrachloromethane (CCl_4, J. T. Baker HPLC Reagent, M=153.82 g/mol, 1 L=1.59 kg) equipped in this section of the module to measure the pressure difference between the center and the wall of the module.

To maintain pressure in the module and a feed flow rate through the module, a needle valve was equipped with a retentate and pump-bypass section, respectively. The permeate flows in a beaker placed on a load cell (BC3 & CI-5010A, CAS, Korea). The voltage out-

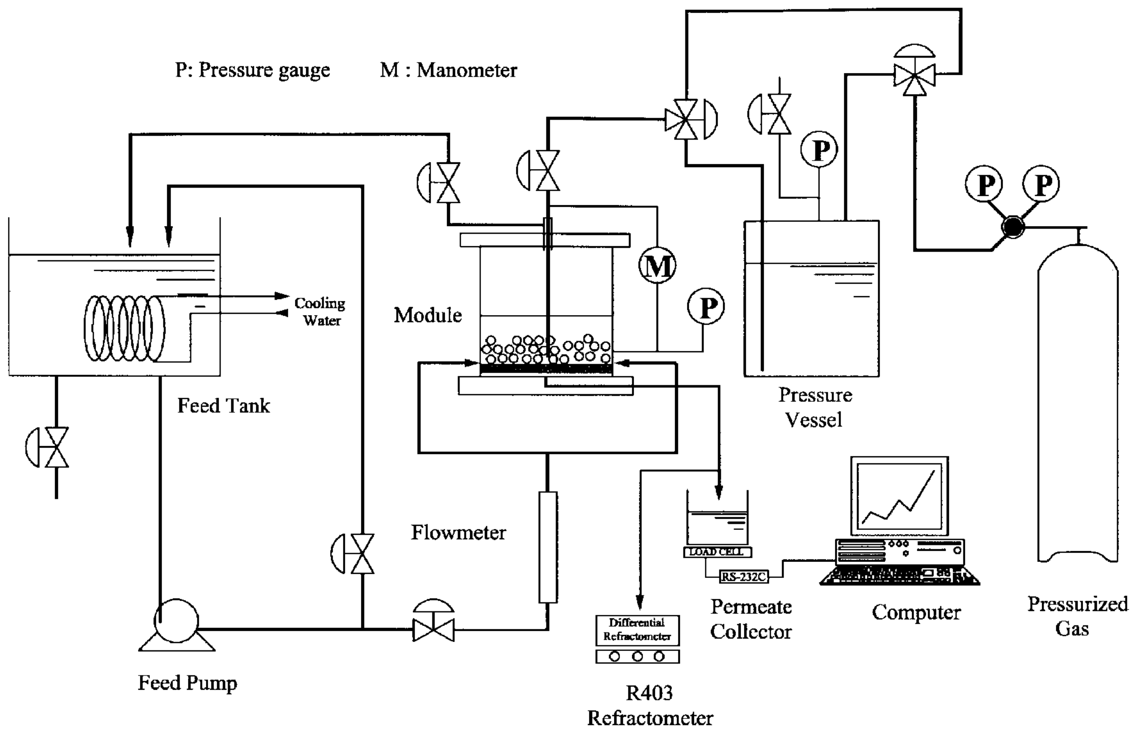

Fig. 2. Schematic diagram of the experimental apparatus.

put of the load cell is fed via an analogue-to-digital converter into a personal computer, which converts the signals into flow rate and stores them as disk files. The feed solution temperature was maintained constant (20 °C) during the course of an experiment. To maintain the feed concentration, the apparatus was operated in a total recycle mode for which the retentate and permeate are returned to the feed reservoir.

RESULTS AND DISCUSSION

1. Pressure Difference

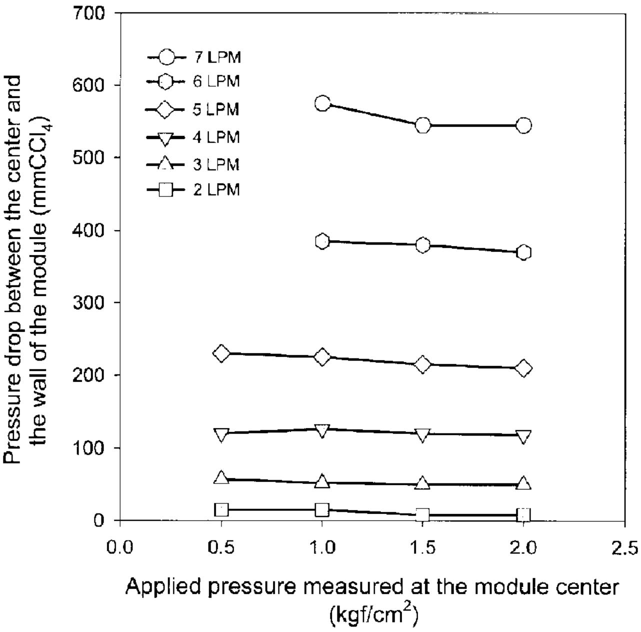

Fig. 3. Variations of pressure difference between the center and the wall of the module with applied pressure measured at the module center for variable feed flow rate.

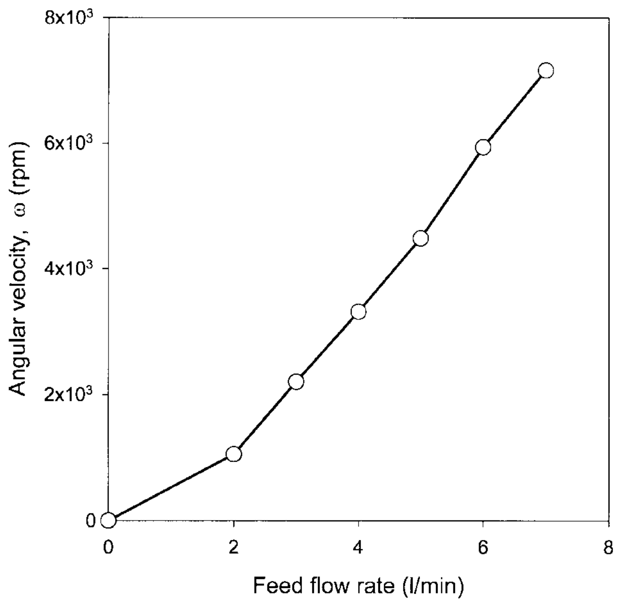

Fig. 4. Angular velocity as a function of feed flow rate.

The variations of the pressure difference between the center and the wall of the module with applied pressure measured the module center for variable feed flow rates are shown in Fig. 3. Pressure difference will depend upon r, because of the centrifugal force and upon z, because of gravitational force [Bird et al., 1960]. The pressure difference is very important in a vortex flow filtration system. Increasing the feed flow rate increases with angular velocity; as a result, the pressure difference increases. From measured pressure difference and Eq. (1) we find angular velocity (Fig. 4).

$$\Delta P=\frac{1}{2}\rho\omega^2 r^2 \tag{1}$$

Where ΔP is the pressure difference between the center and the wall of the module, ρ is the density of feed solution, ω is the angular velocity, and r is the radius of the module.

2. Minimum Fluidizing Velocity

In the module with glass balls, the minimum fluidizing velocity is a very important factor to determine the operating limitation. For uniform, spherical, and tetrahedral packing lattices of glass balls, a maximum packing fraction (ϕ_{max}) is 0.74. Therefore, from Eq. (2) [Van Vlack, 1985; Hall, 1972]

$$\phi_s=\left(\frac{\text{Surface of sphere}}{\text{Surface of particle}}\right)_{\text{both of same volume}} \tag{2}$$

sphericity, $\phi_s=1$ for a sphere.

The superficial velocity at minimum fluidizing conditions, v_{mf}, in general, gives [Kunii and Levenspiel, 1969]

$$\frac{1.75}{\phi_s\varepsilon_{mf}^3}\left(\frac{d_p v_{mf}\rho_b}{\mu}\right)^2+\frac{150(1-\varepsilon_{mf})}{\phi_s^2\varepsilon_{mf}^3}\left(\frac{d_p v_{mf}\rho_b}{\mu}\right)=\frac{d_p^3\rho_b(\rho_s-\rho_b)g}{\mu^2} \tag{3}$$

Table 1. Data to find minimum fluidizing velocity

ϕ_s	ε_{mf}	d_p	μ	ρ_b	ρ_s	g
1	0.26	0.4	1.00	1.00	2.39	980

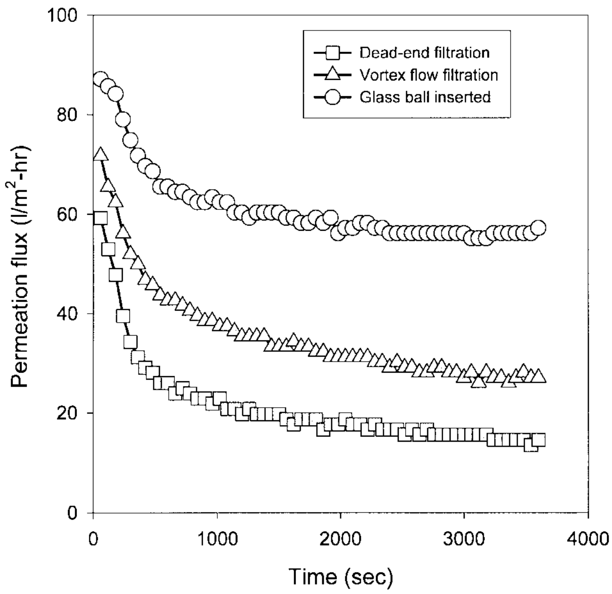

Fig. 5. Variations permeation flux as a function of time at different operating conditions (f_v=0.119).

From Eq. (3) and Table 1, the minimum fluidizing velocity of the feed is calculated to be 2.34 cm/s for our vortex flow filtration membrane module with glass balls having a diameter of 4 mm and a density of 2.39 g/cm^3. The observed value of the minimum fluidizing velocity was about 2.1 cm/s, which is somewhat less than the calculated value.

3. Effect of Operating Conditions

Three different modes of filtration experiments were conducted and compared to demonstrate flux enhancement due to the presence of glass balls: a normal dead-end filtration, a vortex flow filtration, and an enhanced vortex flow filtration using glass balls. All experiments were performed for fixed values of the applied pressure (1.60 kg$_f$/cm^2 at the wall of the module) and vortex flow velocity (4 L/min). As shown in Fig. 5, for the case of a glass-ball-inserted membrane module, the permeate flux was found to be three times as large as that of dead-end filtration and two times larger than vortex flow filtration. In addition, the flux decline was observed to be relatively low.

4. Effective Volume Fraction

The effect of the number of glass balls on the permeate flux was also investigated by changing the values of glass ball volume fraction from 0.059 (250 balls) to 0.356 (1500 balls). It has been observed that the permeate flux shows a maximum value of the volume fraction of 0.119 (500 balls). For enhanced vortex flow filtration, the permeate flux tends to increase with the effective volume fraction up to 0.119, but at the higher, tends to decrease (Fig. 6).

5. Effect of Angular Velocity

To investigate the effect of the angular velocity, which is directly related to the feed flow rate, on the permeate flux, filtration experiments with glass balls were carried out using an dextran solution of 2,000 ppm concentration for an hour at a applied pressure of 1.6 kg$_f$/cm^2 and various angular velocities of 1,050, 3,300, 4,500, and 5,900 rpm. As easily seen in Fig. 4, these angular velocities correspond to the feed flow rates of 2, 4, 5, and 6 L/min, respectively. In the presence of glass balls, the variations in the permeate flux as a function of time for different angular velocities are illustrated in Fig. 7. This figure shows that the permeate flux not only increases, but also tends to reach a steady state value faster as the angular velocity increases. For example, the value of the steady state permeate flux was found to be 29 L/m^2 hr at an angular velocity of 1,050 rpm, while it was 70 L/m^2·hr at 5,900 rpm, leading to about 240% enhancement in the permeate flux.

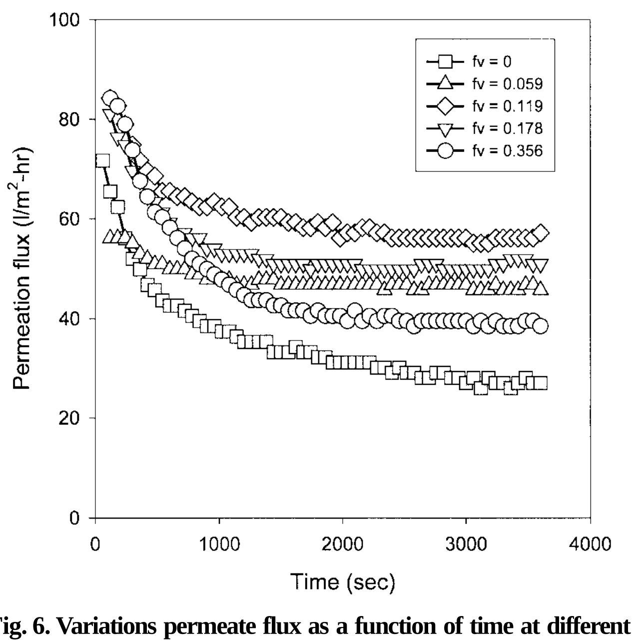

Fig. 6. Variations permeate flux as a function of time at different number of glass balls.

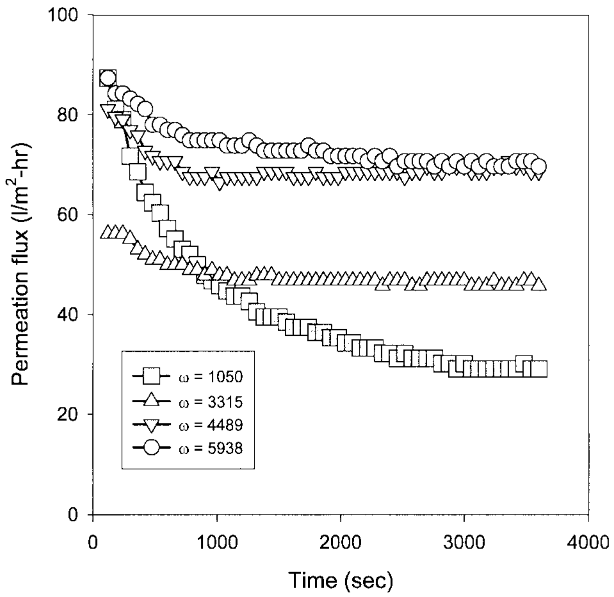

Fig. 7. Variations in the permeate flux as a function of time at different feed flow rates (f_v=0.059).

From these observations, it is evident that the insertion of glass balls into the module is more effective for alleviating the flux decline due to concentration polarization and fouling. The flux enhancement due to the presence of glass balls can be considered to result from the depolarization effects arising from the movement of glass balls on the membrane surface.

CONCLUSIONS

Permeate flux enhancement with a glass-ball-inserted membrane module was studied experimentally. The experiments were carried out in UF membranes by using dextran with a molecular weight of 260,000 aqueous solution. The permeate flux was measured under various operating conditions. In this work the enhancement in permeate flux was mainly dominated by the operating condition, the glass ball volume fraction, and angular velocity. For three different modes of filtration experiments, in the case of the glass-ball-inserted membrane module, the permeate flux was found to be three times as large as that of the dead-end filtration and two times larger compared with the vortex flow filtration. The effect of the amount of glass balls on the permeate flux revealed that the permeate flux shows a maximum value of the volume fraction of 0.119. For the glass ball inserted membrane module, the permeate flux tends to increase with the angular velocity.

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This paper is dedicated to Professor Wha Young Lee in memory

of his retirement.

NOMENCLATURE

d_p : particle diameter [cm]
fv : effective glass ball volume fraction in the module
g : acceleration of gravity [980 cm/s^2]
ΔP : pressure difference between the center and the wall of the module [Pa]
r : radius of the module [cm]
v_{mf} : minimum fluidizing velocity [cm/s]
ε_{mf} : void fraction in the glass ball in the membrane module at minimum fluidizing
ϕ_s : sphericity of inserted glass ball
μ : viscosity of feed solution, where is 1.00 cp
ρ : density of feed solution, where is 1.00 g/cm^3; Eq. (1)
ρ_b : density of feed solution, where is 1.00 g/cm^3
ρ_s : density of glass ball [g/cm^3]
ω : angular velocity [/min]

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