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Performance Test for Membrane Module Using Dean Vortices

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Dean Vortices를 이용한 막모듈의 성능시험

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Abstract: A curved channel duct is designed, built and used specifically to produce Dean vortices as a result of flow around a 180° curve. We present evidence using optical reflection of the existance of the vortices in the curved section and following flat section. Also, three different feed solutions(DI water, a monodispersed styrene-divinyl-benzene latex particle suspension and a yeast suspension) were used to determine the effectiveness of Dean instabilities to destabilize polarization layers. For each suspension, the flux data were compared as a function of time for flow conditions with and without Dean vortices, for a 0.2㎛ microfiltration membrane. Any permeation flux improvement was not sustained for $2.0De_c$ due to the vortex-decay in the flat section after the curved channel, but a 15~30% permeation improvement was obtained for $3.8De_c$

1. Introduction

Synthetic membrane processes are widely used in many industrial applications for concentrating and fractionating various components in solutions and suspensions. Although these processes are very attractive, several limitations still remain. Foremost, among these are the concentration of retained solutes at the solution-membrane interface and the deposit of dissolved and suspended solutes onto the membrane surface during operation. These so-called concentration polarization and fouling phenomena can have a devastating effect on membrane performance severely curtailing productivity through osmotic effects and pore plugging; the transmembrane flux may be as low as 2~10% of the pure water flux.

Concentration polarization results in a localized increase in solute concentration on or near the membrane surface. This solute buildup lowers the flux due to an increase in hydrodynamic resistance in the mass boundary layer and due to an increase in local osmotic pressure resulting in a decreased net driving force. However, concentration polarization effects are reversible, since they can be reduced by decreasing the transmembrane pressure or lowering the feed concentration. Fouling effects, on the other hand, are usually characterized by an irreversible decline in flux. Changes in fluid management techniques may only alleviate the flux temporarily or reduce the decline for a short period. Common practice to offset fouling effects is to periodically backwash the membrane and/or shut down the process

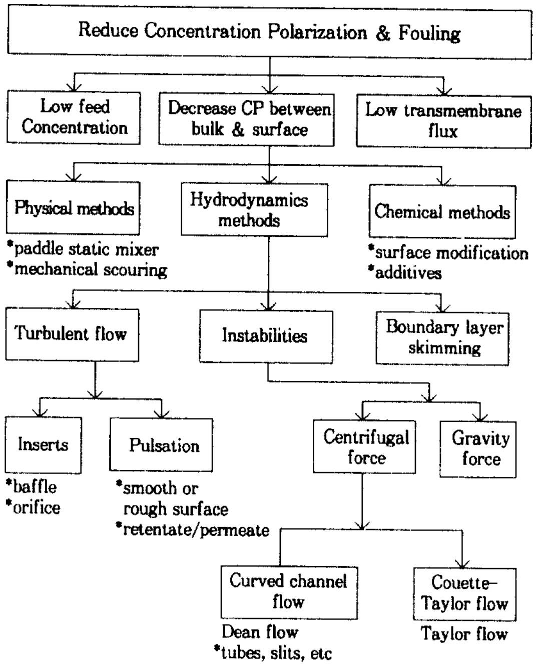


Fig. 1. Typical methods to reduce the concentration polarization and membrane fouling.

and clean the membrane by chemical or other means.

An increasing effort has been focused on these problems both with the view to understand and alleviate them. A schematic analysis of ways to overcome concentration polarization and fouling is shown in Fig. 1. Various approaches have been used : (1) treatment for lowering the solids concentration in the feed streams, (2) improved methods of operation through the use of positive displacement pumps for controlling the permeation rate and minimizing the trans-membrane pressure drop and (3) low concentration gradient between the membrane surface and bulk solution. The first strategy is of limited use since it is not often a practical solution to the problem. Recent development of membrane processes for commercial and pilot plant applications have been based on the approach of maintaining low transmembrane fluxes. This is only attractive for modules with extreamly large membrane surface area such as hollow fiber membrane modules[1]. Some researchers considered various possibilities for lowering the concentration gradient between the bulk fluid and the membrane surface including chemical modification of the membrane surface, physical methods such as scouring with sponge balls, and hydrodynamic methods such as the use of eddies during turbulent flow. These methods except membrane surface modification are based on increasing the mass transfer of suspended and dissolved solids from the membrane surface back to the bulk liquid.

Another approach to reduce concentration polarization is to induce natural convection in the vicinity of the membrane. High solid concentration near the membrane surface due to concentration polarization often results in a higher liquid density than in the bulk liquid. Other promising approaches include application of centrifugal instabilities; Couette-Taylor flow, in which the fluid is contained between two rotating coaxial cylinders, and flows in a curved channel(tube or slit) due to a pressure gradient acting around the tube or channel.

We have investigated a method of establishing vortices in a spiral wound porous channel. Fluid is allowed to pass through a porous spiral channel at sufficiently high flow rate so as to destabilize curved-channel Poliseuille flow. A neutral stability criterion was derived ensuring that the stabilizing effect of wall flux was balanced by the destabilizing effect of increasing curvature[2]. This spiral membrane module design was primarily based on optimal fluid mechanics rather than on the usual criteria of maximum packing density or of convenient size. Such Dean vortex flow has similar advantages to Taylor vortex flow but is also amenable to scale-up. In addition, it is not expected to consume unreasonable amounts of energy nor have sealing difficulties. In order to visualize Dean vortices and to determine their effect on the permeate flux, a 180° curved slit channel was constructed with transparent acrylic. After discussing the experimental aspects including the flow system, the feed solutions and the operating procedures, we present results and discuss on the presence of vortices and how they positively effect permeation flux.

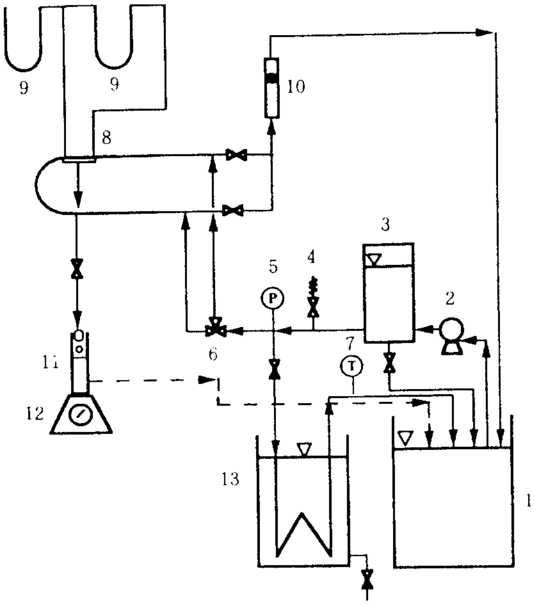


Fig. 2. Schematic flow diagram for the curved slit channel system with a porous test section. (1) reservoir, (2) diaphragm pump, (3) pulsation dampener, (4) pressure relief valve, (5) pressure gauge, (6) three-way valve, (7) thermometer, (8) curved channel, (9) mercury and water manometer, (10) rotameter, (11) graduated cylinder, (12) scale, and (13) heat exchanger.

2. Experimental

2. 1. Flow system

The flow system shown in Fig. 2 consisted of a narrow gap curved slit channel with a porous test section (referred to as CSC). The largest mean axial flow rate through the CSC was about 3.3ℓ/min under 100KPa. This was equivalent to a Dean number 3.8 times the critical Dean number for the onset of vortices. The Dean number is defined as $De = \frac{2dV}{\nu}\sqrt{2d/r_C}$, where d is half channel width, V is axial mean velocity, ν is kinematic viscosity and r_C is centerline radius of curved channel. The critical Dean number for the narrow gap channel is 36.4. A three-way valve before and two on-off valves after the CSC enabled us to compare permeation fluxes with and without vortices at about the same trans-membrane pressure. Fluid exiting the CSC passed through the rotameter and back to the reservoir.

2. 2. Porous test section

Dean vortices formed during flow around a curved 180° solid-walled channel and remained stable for some distance within the flat section that followed the curved section. The persistance of the vortices suggests the possibility that a porous test section

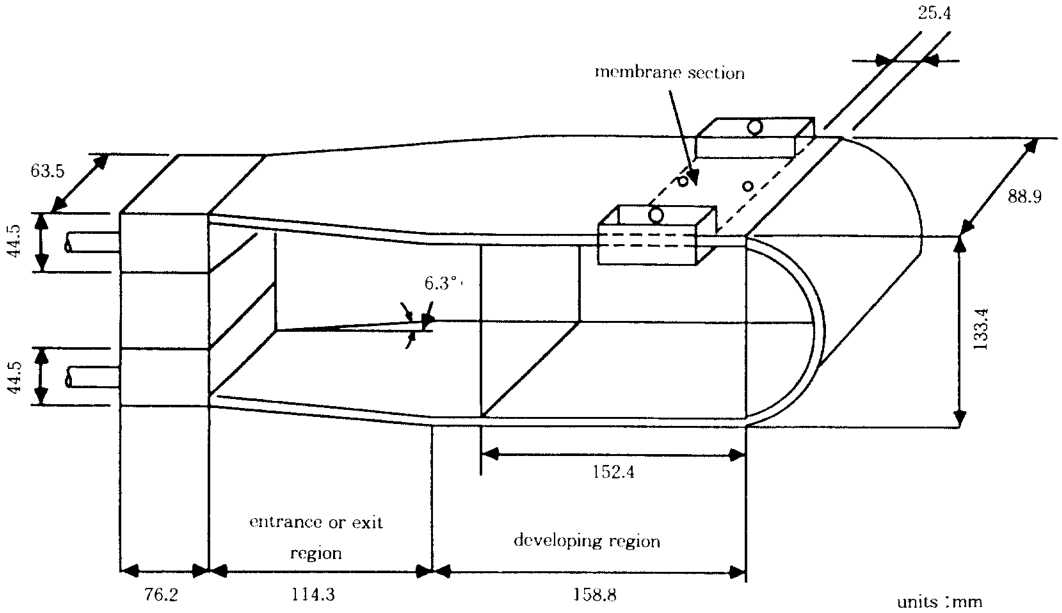


Fig. 3. The narrow gap curved slit channel(CSC) with a porous test section.

need not be placed on the curved section but after it in the flat section, substantially simplifying the design and suggesting possibilities for flat sheet modules. Details of CSC are shown in Fig. 3. The membrane(63.5 by 76.2㎜) was placed onto a removable and sealable porous test section and inserted into the lower face of the channel from the bottom. The membrane(glued to the support insert with silicon rubber, Silicon Ⅱ, General Electric Co. Waterford, NY) and O-ring sealed the system. Outer support clamps were used to pressure the insert into the channel and seal the fluid within the system. The membrane surface was aligned with the channel lower surface such that the fluid did not experience significant changes in channel height. Permeate was collected and weighed on a mass balance.

Because of pressure limitations in the CSC and time limitations to obtain a noticeable change in the permeation fluxes, high flux polysulfone microfiltration membrane was used(Model # GRM0.2PP, Dow Danske, Nakskov, Denmark). The drain channel or porous support for the membrane consisted of two sheets of simplex kint fabric(polyester fiber) stiffened with epoxy coating(FilmTec Corp., Minneapolis, MN).

2. 3. Feed solutions

Three different feed solutions and suspensions were used to determine the effectiveness of Dean instabilities to destabilize concentration polarization and fouling. They included DI water as a control, monodispersed polystyrene latex particles and yeast suspensions. Each of these feeds is described in more detail below.

The DI water was prepared by passing tap water through a reverse osmosis module(FT30, FilmTec Co., Mineapolis, MN), a mixed strong ion exchange bed, and a UV unit. This gave essentially organic-free 19 megaohm water. Monodispersed particles with a diameter of 11.9±1.9㎛ and a density of 1052 kg/m^3, prepared by suspension polymerization of styrene-divinyl-benzene(S/DVB, Dow Chemical Co., Midland, MI), were used at a suspension concentration of 0.15wt% in DI water. The third feed comprised of a commercial baker's yeast(Saccharomyces cerevisiae) at a concentration of about 0.3wt% in DI water. The yeast cells were from 5 to 30㎛ long and from 1 to 5㎛ wide[3].

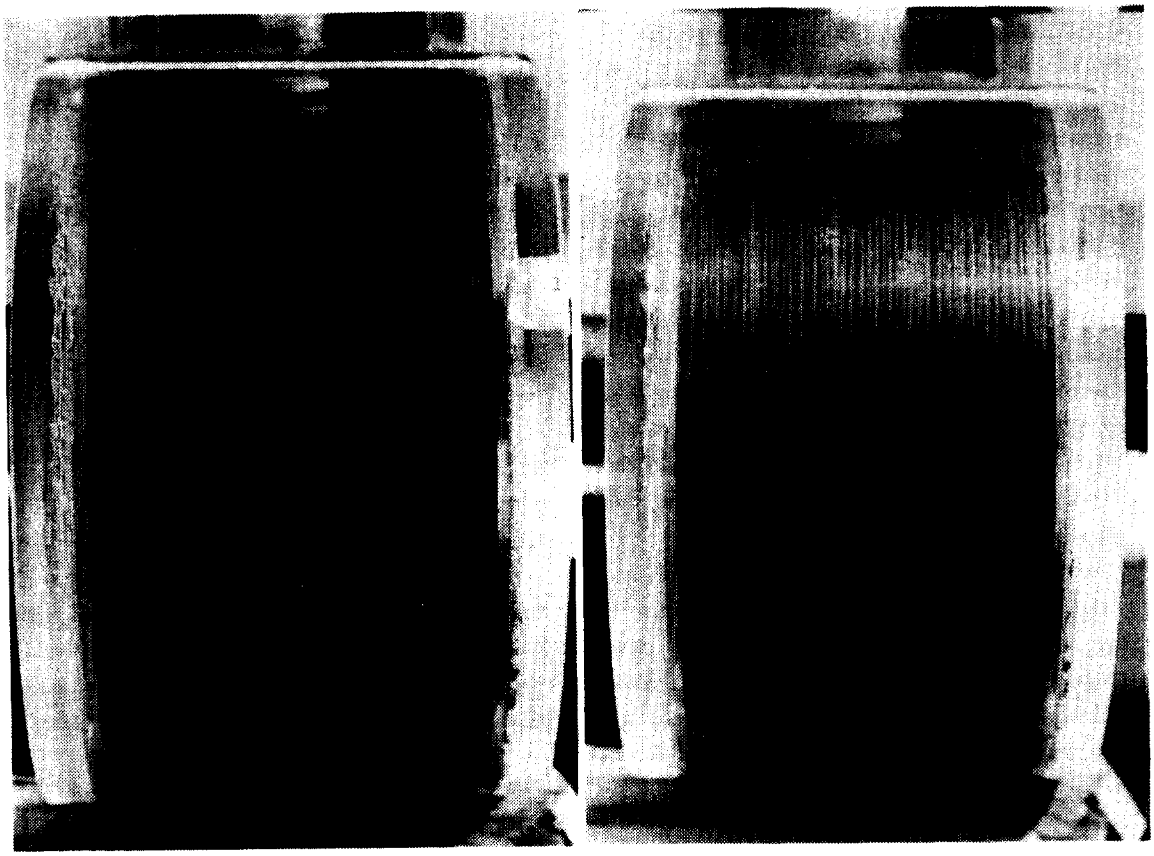
2. 4. Operating procedures

After setting the desired flow rate and trans-membrane pressure, the scale or mass balance was switched on with the graduated cylinder placed on it. Permeate volume was recorded with time to obtain a time-dependent permeate flux. Although, in principle, true steady state operation could not be reached for the suspension feeds, since a very small fraction of the solids was irreversibly deposited onto the membrane surface, pseudo-steady state could, however, be assumed, i. e. the membrane was exposed to approximately the same feed solution throughout the experiment. This was possible since real changes in concentration were very small due to the large feed reservoir volume(4ℓ working fluid) and small transport area of the membrane. Hence, relatively small permeate volumes were collected(maximum 100㎖) during the short test period(about 30min).

For each experiment the flow direction in the CSC was such that vortices could be produced over the membrane as the flow first passed through the 180° bend and then over the porous test section. Then, without switching off the pump, the flow direction in the CSC was reversed such that the fluid passed over the porous test section before passing through the curved section. By keeping the axial flow rate and trans-membrane pressure approximately the same for each flow direction, it was possible to determine the effectiveness of vortices when compared to flow without vortices to depolarize the solute from the membrane.

3. Results and Discussion

The main goal of the experiments was to determine in a well-controlled series of tests whether cross-flow with Dean vortices could be effective in destabilizing solute polarization, fouling and result in increased permeation flux over cross-flows without vortices.



(a) (b)

Fig. 4. Photographs comparing Dean flows with blue indigo dye and aluminum powder in the solution at (a) below the critical Dean number, $0.5De_C$, and (b) above the critical Dean number, $3.0De_C$, around a 180° curve.

3. 1. Existence of Dean vortices

The photographs shown in Fig. 4 were taken with a suspension of blue indigo dye and aluminum powder, and clearly show the absence(at $0.5De_C$) and presence(at $3.0De_C$) of stripes. They showed regularly spaced axial stripes as an indication of vortex formation and absence of a regular striping pattern as an indication of the lack of vortices. We have presented detailed magnetic resonace imaging (MRI), of the presence and absence of vortices, their decay with axial distance, their growth with axial flow rate(Dean number) and intra-vortex velocity contours[4].

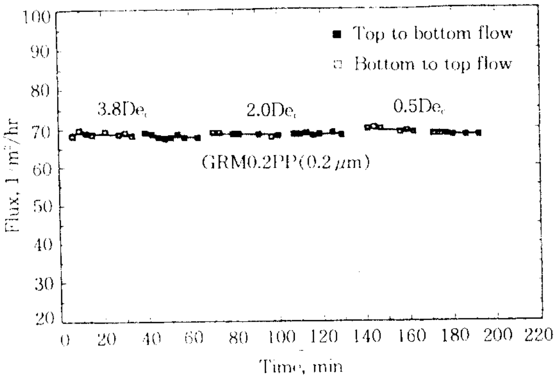
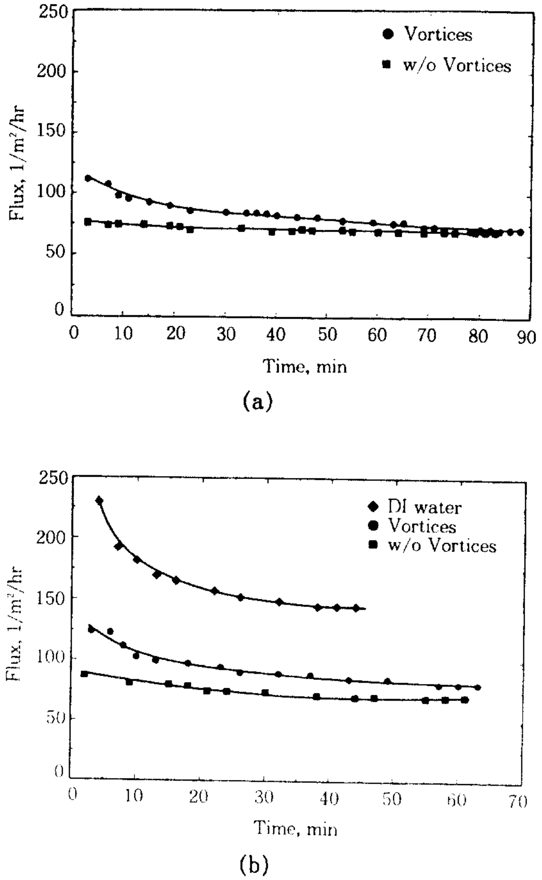


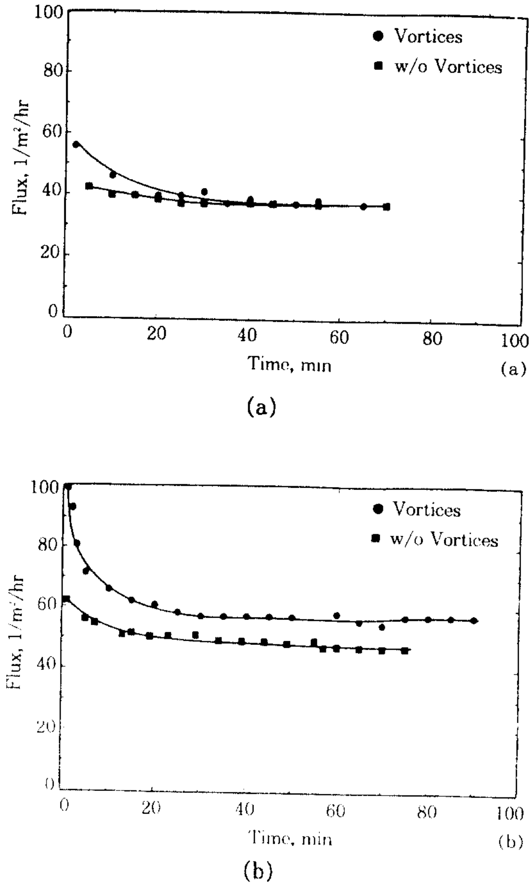
Fig. 5. Permeation flux of DI water for, with and without Dean vortices for 0.2μm membrane at 0.5, 2.0, $3.8De_C$ and $\Delta p_t = 75.2$KPa.



(a)

(b)

Fig. 6. Permeation flux of 0.15wt% suspension of 11.9㎛ S/DVB particles for with and without Dean vortices at (a) 2.0De$_C$ and at (b) 3.8De$_C$ for 0.2㎛ membrane and Δp_t=75.2KPa.



(a)

(b)

Fig. 7. Permeation flux of 0.30wt% suspension of yeast for with and without Dean vortices at (a) 2.0De$_C$ and at (b) 3.8De$_C$ for 0.2㎛ membrane and Δp_t=75.2KPa.

3. 2. Effect of Dean vortices

To determine the effect of vortices on the permeation rates(flux) of 0.2㎛ microfiltration membrane during filtration of a foulant suspension, monodispersed polystyrene latex particles and reconstituted yeast cells, were suspended in DI water and tested in the CSC. These fluxes were compared to those with DI water alone as a control. For each suspension the flux data were compared as a function of time for flow conditions with and without Dean vortices, for the microfiltration membrane. The results are shown in Figs. 5-7. The trans-membrane pressure(Δp_t) was kept constant for all runs at 75.2KPa within a 2.1KPa pressure fluctuation.

Deionized water : For the DI water, the flux values were essentially indifferent(within 1%) to the presence or absence of Dean vortices or the axial flow rate. This indifference result was expected since there was no solute build-up at the membrane-solution interface and hence no concentration polarization or external fouling. The result also showed that the membranes behaved similarly no matter the di-

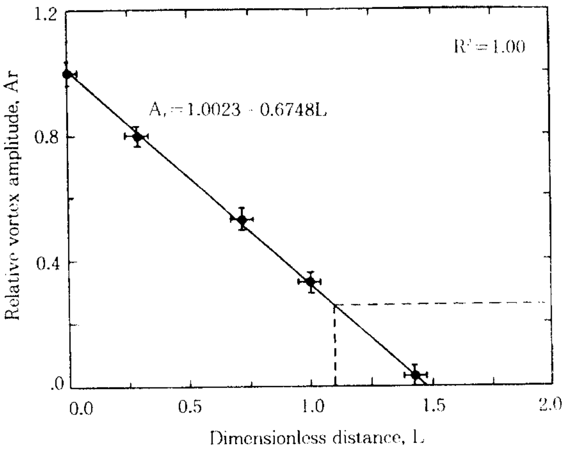


Fig. 8. Relative vortex amplitude as a function of the flat section distance from the edge of the curved section r_i=34.9㎜ and De=2.0De_C with De_C=37[4].

rection or intensity of the flow(Fig. 5).

Particulate suspension : For the 0.15wt% suspension of 11.9㎛ S/DVB particles as feed, the beneficial effects of Dean vortices on the permeation flux are seen in Fig. 6. Any permeation flux improvement was not sustained for 2.0De_C, but a 15% permeation improvement was obtained for 3.8De_C.

Yeast suspension : For a 0.3wt% suspension of reconstituted yeast cells as feed, the beneficial effects of Dean vortices on the permeation flux is seen in Fig. 7. Pumping the fluid through the CSC at intermediate flow rates(2.0De_C) showed hardly any advantage. However, with faster flow rates, the advantage of having stronger vortices(3.8De_C) versus no vortices was clear(30% improvement).

These results can be explained by the fact that the vortices decay along the axial flat membrane test section, as measured by MRI experiment(Fig. 8). The vortices almost disappeared at an axial distance of about 5㎝ after the curved section at 2.0De_C. The membrane was placed from 2.5 to 10.2㎝ after the curved section. Hence, the vortices were persistent to about the first one-third of membrane surface section and the vortex strength was much weaker than at 3.8De_C(dash lines). Therefore, significant permeation flux improvement at 2.0De_C was not expected and not measured.

4. Conclusions

Producing well-defined predictable vortices along a membrane surface has been used to depolarize and clean solutes from the membrane-surface interface. The novelty of our approach, as opposed to that with Taylor vortices, is that we can produce vortices in both curved and flat sections(following a curved section) and that our Dean vortex approach is scalable, sealable and is not expected to use exorbitant energy.

(1) For DI water the flux values were indifferent (within 1%) to the presence or absence of Dean vortices or the axial flow rate for the 0.2㎛ microfiltration membrane.

(2) The beneficial effects of Dean vortices on the permeation flux for 2.0De_C were not observed. However, the permeation flux improvements with 0.15wt% S/DVB solution at 3.8De_C was higher than S/DVB solution(30%).

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