Cross-Flow Microfiltration with High-Frequency Reverse Filtration

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A primary method of reducing membrane fouling during cross-flow microfiltration is periodic reverse filtration. This in situ method of cleaning the membrane forces clear fluid in the reverse direction through the membrane and readjusts the particle or solute accumulation on the retentate side of the membrane. This work focuses on the design of a high-frequency, reverse-filtration strategy to maximize the flux for washed yeast suspensions through 0.2-μm cellulose acetate flat sheet membranes. Several experiments were conducted with reverse-filtration times ranging from 0.5–4 s and forward-filtration times ranging from 1–40 s. For every back-filtration time, there exists an optimum forward-filtration time that gives the maximum global average flux. The optimum average flux increases with decreasing back filtration times and feed concentrations, but shows little dependence on cross-flow velocity and reverse filtration transmembrane pressure. The optimum flux with rapid backflushing is 20 to 30 times higher than the long-term flux in the absence of backflushing. A theory presented assumes that cake formation during forward filtration follows dead-end filtration theory and the cake is instantly removed during reverse filtration. The measured average flux per cycle follows the trends predicted by the theory, but the measured values exceed the predictions, presumably due to brief delays in cake removal and cake formation at the start of reverse and forward filtration, respectively, during each cycle.

Introduction

Cross-flow microfiltration is a solid-liquid separation process with applications in the pharmaceutical, environmental and petrochemical industries. As opposed to dead-end filtration, where the suspension is forced normal to the membrane, the suspension in cross-flow filtration is forced tangential to the membrane (see Figure 1a). With time, the rejected particles build up in a cake or gel on the membrane, thus reducing the filtration rate and constricting the channel so that the shear exerted by the bulk flow increases. This build up stops after the tangential shear is large enough to prevent further particle deposition and to sweep the rejected particles in the axial direction. Thus, cross-flow operation is expected to reach a steady state, unlike dead-end filtration for which the filtrate flux (volume of filtrate per unit time per unit area) asymptotes to zero. For typical applications of cross-flow filtration in biotechnology, the steady-state flux is 2%–20% of the clean membrane flux (Blatt et al., 1970).

Backflushing is an *in situ* method of cleaning the membrane by periodically reversing the transmembrane pressure. Clear fluid is then forced in the reverse direction through the membrane (see Figure 1b), thereby lifting off the cake layer and washing it out of the filter. As reported by Michaels (1980) and Belfort et al. (1980), the average flux per cycle for backflushing may be much higher than the long-time flux when reverse filtration is not used (see Figure 2).

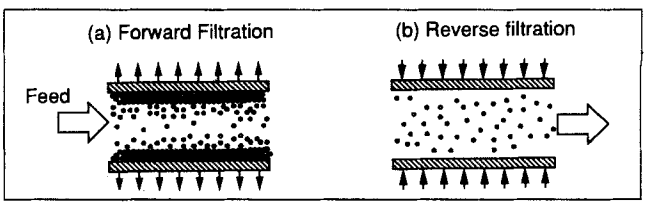

Figure 1. Forward (a) and reverse cross-flow (b) filtration.

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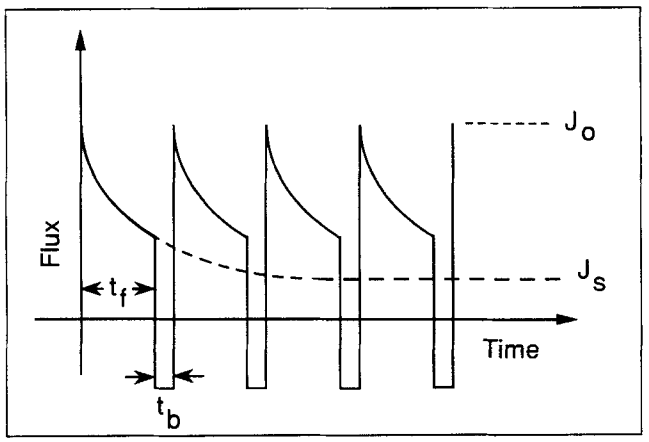

Figure 2. Flux vs. time for cross-flow filtration with backflushing (solid curve) and without backflushing (dashed curve).

Kroner et al. (1984) used backflushing during the removal of *E. coli* bacteria from a fermentation broth using polycarbonate membranes of 2,000 Daltons nominal molecular weight cutoff. The pressure was reversed at a set value of 150 kPa for 5 s every 5 min. Backflushing enhanced the average flux by almost 50% over the steady-state flux; protein transmission was also improved by backflushing, but only for short times. Matsumoto et al. (1987) used reverse transmembrane pressure for cross-flow filtration of yeast suspensions and fermentation broths. Backflushing was achieved by forcing compressed air at 50 kPa for 5 s every 2–5 min. The average filtration flux per cycle was maintained at a constant value for 3 h. For the particular backflushing time of 5 s, the maximum mean flux was achieved for a forward filtration time of 3 min. Matsumoto et al. (1988) made comparison between the following different backflushing processes: (i) stopping the feed pump; (ii) negative pressure with filtrate; (iii) negative pressure with air; (iv) suction of the filtrate through the membrane in the reverse direction with a pump; and (v) suction of air through the membrane in the reverse direction with a pump. It was found that backflushing with filtrate (ii and iv) gave a higher net flux than the other three methods. The average flux depended on the total filtrate volume used for backflushing, rather than on the backflushing interval or flow rate.

Nipkow et al. (1989) developed a cell-recycle pilot-scale system comprised of a conventional continuous flow fermenter connected to an *in situ* steam-sterilizable cross-flow ceramic filter with a backflushing device. Backflushing initially showed a 42% improvement over the flux without backflushing for *Clostridium thermosulfurogenes* suspended in a maltose medium. The long-term fouling of the filter could not be prevented, however, even with backflushing pressures of 710 kPa and cycle times from 5 min to 3 h. Kim and Chang (1991) used periodic backflushing for separating haemoglobin and dextran through Amicon hollow fiber membranes with a molecular weight cutoff of 30,000 Daltons. For a backflushing duration of 11.25 s, the optimum frequency of backflushing to give maximum permeability was approximately 0.2 min^{-1}. Although a 100% increase in the solvent flux over that of nonpulsation operation was observed, the retention coefficient of dextran decreased from 68% in nonpulsation operation to 47% in pulsation operation.

Rodgers and Sparks (1991) performed a study to determine the effect of transmembrane pressure pulsing (high-frequency backflushing) on solute rejection for an albumin and gamma-globulin mixture in ultrafiltration through a cellulosic membrane with 1,000 K daltons nominal pore size. The solute flux was found to be two orders of magnitude higher than that without pulsing. However, the observed retention of albumin was reduced from about 99 to 63%. Rodgers and Sparks (1992) also studied the effect of transmembrane pressure pulsing on the concentration polarization resistance. Solutions of 1% bovine serum albumin (BSA) at 7.4 pH in 0.15 NaCl buffered solution were filtered in a cross-flow module through cellulosic membranes. The operating pressures were from 75 to 140 kPa, while the backpulsing pressures were 5 to 30 kPa above the respective operating pressures. The frequency of backpulsing ranged from 0 to 5 Hz. The authors observed that the flux enhancement did not change with an increase in the negative pressure amplitude above a certain minimal value. They concluded that slight membrane motion or vibration might be responsible for the enhancement in the flux. As a continuation of their study, Rodgers and Sparks (1993) addressed the effects of initial concentration, pH, and ionic strength on the polarization resistance range, redevelopment time, and the average flux due to transmembrane-pressure-pulsed ultrafiltration. Ionic strength did not contribute to any observed flux change. The effect of pH was most pronounced at extremely low initial BSA concentration. The initial concentration variation had the most significant effect on the flux changes. For a constant frequency of 0.2 Hz, the average flux after pulsing was reduced by nearly 50% when the solution concentration was increased from 1% BSA to 3% BSA.

This article focuses on using high-frequency reverse-filtration (backpulsing) as an *in situ* method of periodically cleaning microfilters with the aim of maximizing the average flux. Reverse-filtration is achieved by reversing the transmembrane pressure, resulting in a permeate flow in the reverse direction through the membrane. The particles or cells in the cake layer just above the membrane are expected to become resuspended and swept away by the tangential flow. Very short forward-filtration times (1–40 s) are used in order to prevent significant cake buildup and to maintain a high value of the average flux. We have determined the forward-filtration time that maximizes the average flux in one cycle for various reverse-filtration times, backpulse pressures, feed flow rates, and feed concentrations of washed yeast cells suspended in water.

Theory

For a fixed backpulse duration, we expect that an optimum forward-filtration time exists which maximizes the average flux per cycle. This is because the ratio of filtrate collected during forward filtration to that lost during reverse filtration increases with the ratio of forward-to-reverse-filtration times for short forward-filtration times, whereas cake formation decreases the forward-filtration flux for long forward-filtration times. Romero and Davis (1991) have shown that the initial flux decline due to cake buildup during cross-flow microfil-

tration can be approximated by the dead-end filtration equation:

$$J = J_o\left(1+\frac{t}{\tau}\right)^{-0.5}, \quad (1)$$

where J is the flux, J_o is the clean membrane flux, t is the time elapsed from the start of filtration, and τ is the time constant for cake growth which can be measured by the procedures of Redkar and Davis (1993). This equation is valid only until the time t_s at which the shear exerted by the cross flow arrests the cake growth, after which the forward-filtration flux is the steady-state flux J_s (see review by Davis, 1992).

During reverse-filtration, it is assumed that the cake is instantly lifted off the membrane and then swept out of the channel by the axial flow. The negative flux during the backpulse portion of the cycle therefore has magnitude αJ_o, where $\alpha = \Delta P_b/\Delta P_f$ is the ratio of the magnitudes of the reverse and forward transmembrane pressures. Then, the average flux in one cycle is:

$$\langle J\rangle = \frac{\int_0^{t_f} J dt - \alpha J_o t_b}{t_f + t_b} = \frac{2J_o\tau\left[(1+t_f/\tau)^{0.5}-1\right] - \alpha J_o t_b}{t_f + t_b}, \quad (2)$$

where $\int_0^{t_f} J dt$ is the total filtrate volume per unit area collected during forward-filtration of duration t_f, and $\alpha J_o t_b$ is the total filtrate per unit area lost during reverse-filtration of duration t_b. This equation is based on the assumption that the permeability of the clean membrane is recovered after each cycle due to the backpulsing. If the membrane is irreversibly fouled, or if the cake is not entirely removed, then the average flux will be lower. On the other hand, the average flux for a nonfouling membrane may exceed the average flux predicted by Eq. 2, because there will be a delay in cake formation during forward-filtration as the layer of clear fluid accumulated above the membrane during reverse-filtration first passes back through the membrane during the beginning of forward-filtration, and because the cake layer formed during forward-filtration may not be instantly lifted off and its resistance would therefore reduce the rate of filtrate loss during the beginning of reverse-filtration.

For given values of t_b, τ, and α, there is an optimal value of t_f which maximizes $\langle J\rangle$. This is found from differentiating Eq. 2 with respect to t_f and setting the result to zero:

$$\left(1+\frac{t_f^{\max}}{\tau}\right)^{-0.5}(t_b - t_f^{\max} - 2\tau) + (2\tau + \alpha t_b) = 0 \quad (3)$$

This implicit equation can be solved for the optimal value, $t_f^{\max}$, which may then be substituted into Eq. 2 to provide the maximum predicted value of the average flux, $\langle J\rangle^{\max}$, for given values of t_b, τ, and α.

The global maximum value of the average flux per cycle is $\langle J\rangle^{\max} \to J_o$, which occurs when $t_b \ll t_f$, $\alpha t_b \ll t_f$, and $t_f \ll \tau$. However, this mathematical maximum is not attained in practice, because there will be a limit on how small t_b and t_f can be due to the limitations of the timing circuits and switches and minimum values of t_b and ΔP_b are needed to effectively remove the cake during reverse-filtration. The required minimum values of t_b and ΔP_b may be determined experimentally or estimated from the time constants $H/(\alpha J_o)$ and V/Q for transverse and axial flow, respectively, where H is the channel height, V is the channel volume, and Q is the feed flow rate.

Materials and Methods

In order to test the theoretical predictions for the average flux during cross-flow microfiltration with backpulsing, experiments were performed with yeast suspensions through cellulose acetate membranes. Yeast suspensions were chosen because of their importance in beverage and biotechnology industries, and because they form relatively nonadhesive cakes. The experimental setup is shown in Figure 3. The feed suspension reservoir is a pressure vessel connected to a high-pressure nitrogen cylinder. The pressure in the feed vessel is controlled with a regulator valve. A Masterflex peristaltic pump forces the feed at a constant flow rate into a Minitan-S flat plate membrane module made by Millipore Systems. The module has nine parallel channels, each of dimensions 0.4 mm high × 7 mm wide × 50 mm long. The permeate is collected in a reservoir on an electronic microbalance, which is connected to a personal computer through a DT 2801 data translation board using a RS232 configuration. The retentate is returned to the feed pressure vessel. Note that, during forward-filtration, the inlet solenoid valve is closed and the outlet is open. During reverse-filtration, the inlet solenoid valve is open and the outlet is closed. The clear-fluid reservoir, which is connected to another high-pressure nitrogen cylinder, forces clear fluid through the membrane from the permeate side to the retentate side during reverse-filtration, while the feed suspension continues to circulate. The switching of the solenoid valves is controlled by the computer through two solid-state relays. Two pressure transducers note the transmembrane pressure and send the output to the computer. The reverse-filtration flow rate is measured by a rotameter. A Watson-Marlow regenerator pump keeps the concentration in the feed vessel constant by continuously replacing the lost fluid. The operation of this pump is also controlled by the computer. A program written in Quickbasic interfaces the computer to the equipment. This setup is capable of handling reverse-filtration times of 10 ms and larger.

The suspension is made by adding 10-g Fleischmann's dry yeast (*Sacchromyces cerevisiae*) to 1,000 mL of deionized water. Washing is achieved by centrifuging the yeast at 2,750 rpm for 10 min (to allow a pellet to be formed), discarding the supernatant, and resuspending the pellet. This procedure is repeated three times. Most of the residual proteins arising out of any broken or lysed yeast cells in an unwashed yeast suspension are removed by this process. The extracellular protein concentration in a washed yeast suspension is less than 5 mg/L.

Cellulose acetate "Cellgard" membranes manufactured by Micron Separations Inc. with an average pore size of 0.2 μm are used in the module. The membranes are hydrophilic and almost symmetric. Since these membranes do not swell, pretreatment of the membranes is not necessary before the start of an experiment. The deionized water flux through the

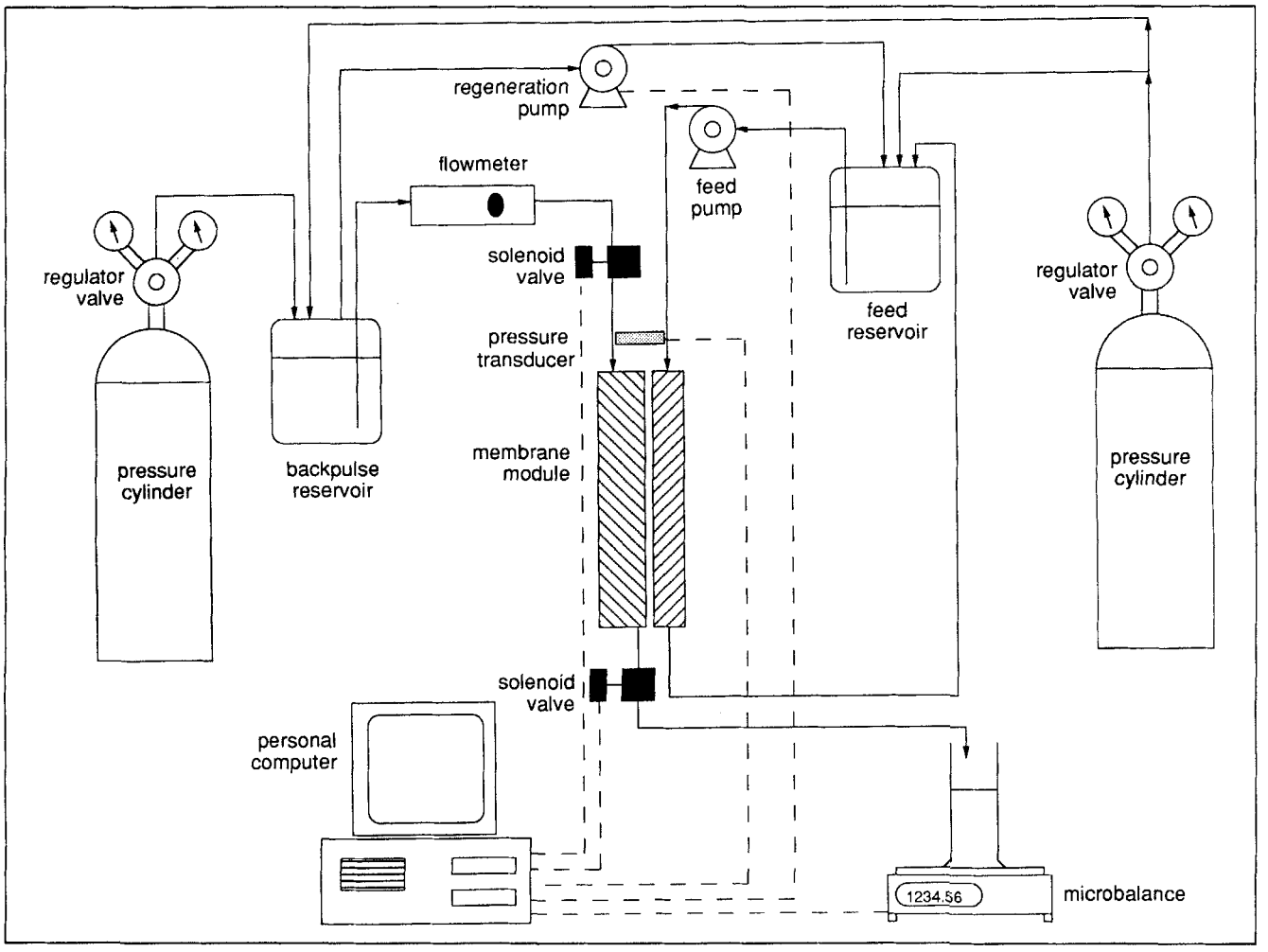

Figure 3. Experimental setup.

membrane remained constant within 10% over a period of 500 s. The average clean membrane flux was measured to be $J_o = 0.175 \pm 0.015$ cm/s at 10 psi (69 kPa) transmembrane pressure and 25°C, where the error cited for J_o is plus and minus one standard deviation for three experiments.

Experiments were done at reverse-filtration transmembrane pressures of $\Delta P_b = 0$, 5 and 10 psi (0, 34.5 and 69 kPa), reverse-filtration times of $t_b = 0.5$, 1, 2, and 4 s, bulk suspension volume fractions of $\phi_b = 0.003$, 0.03 and 0.06, and feed suspension flow rates of $Q = 6$, 8, and 10 mL/s. A cell volume fraction of 0.03 corresponds to 0.01-g dry yeast cells/mL (Szlag, 1988). The forward-filtration transmembrane pressure was held constant at 10 psi (69 kPa). Forward-filtration times from 1–40 s were investigated, with each run lasting 1,000 s. Each experiment was repeated three times (except for the set of experiments with a reverse-filtration time of 0.5 s, for which experiments were performed only once).

Microfiltration experiments without reverse-filtration were done on the washed yeast suspension, in order to find the time constant, τ, in Eq. 1, using the analysis described by Redkar and Davis (1993). Experiments were done at feed volume fractions of $\phi_b = 0.003$, 0.03, and 0.06. The forward transmembrane pressure was 10 psi (69 kPa) and the bulk flow rate was 6 mL/s. The average specific cake resistance for the three experiments is $\hat{R}_c = 4.1 \pm 1.5 \times 10^{10}$ cm^{-2}, where the error is plus and minus one standard deviation. This value is close to that measured for a suspension of washed yeast through polypropylene fibers ($\hat{R}_c = 7.0 \pm 6.0 \times 10^{10}$ cm^{-2}, Redkar and Davis, 1993). The time constant, τ, is given by:

$$\tau = \frac{(\phi_c - \phi_b)\Delta P}{2\hat{R}_c \mu_o \phi_b J_o^2}, \tag{4}$$

where ϕ_c is the volume fraction of the cells in the cake layer, ΔP is the transmembrane pressure, and μ_o is the viscosity of the clear fluid. The volume fraction of the yeast cells in the cake layer is taken to be $\phi_c = 0.78$ (Ofsthun, 1989). The time constants for $\phi_b = 0.003$, 0.03, and 0.06 as calculated from Eq. 4 are $\tau = 6.9$, 0.67, and 0.32 s, respectively. Note that the time constants decrease with increasing concentration due to the more rapid cake buildup and flux decline. These experiments were run for 5,000 s, and the corresponding steady or nearly steady fluxes, J_s, were noted. Similar experiments to find the long-term fluxes without backpulsing were also run

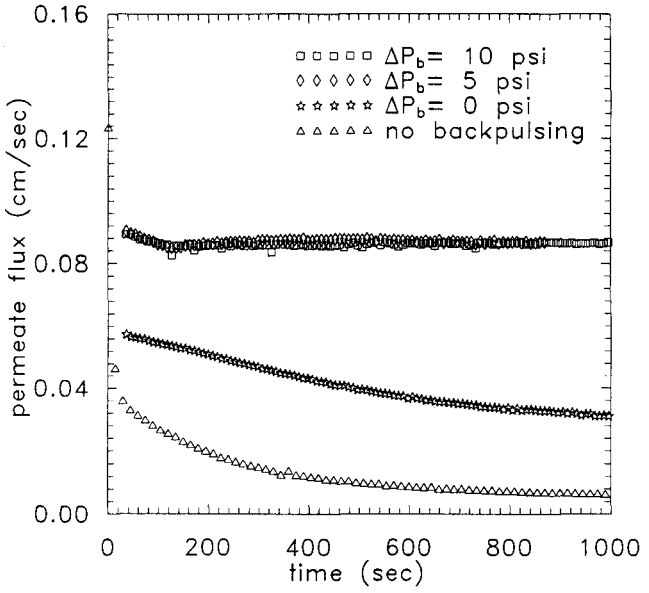

Figure 4. Average flux per cycle vs. time for filtration with backpulsing at several reverse-filtration pressures, and for filtration without backpulsing.

$\Delta P_f = 10$ psi (69 kPa), $t_f = 7$ s, $t_b = 2$ s, $Q = 6$ mL/s, and $\phi_b = 0.03$.

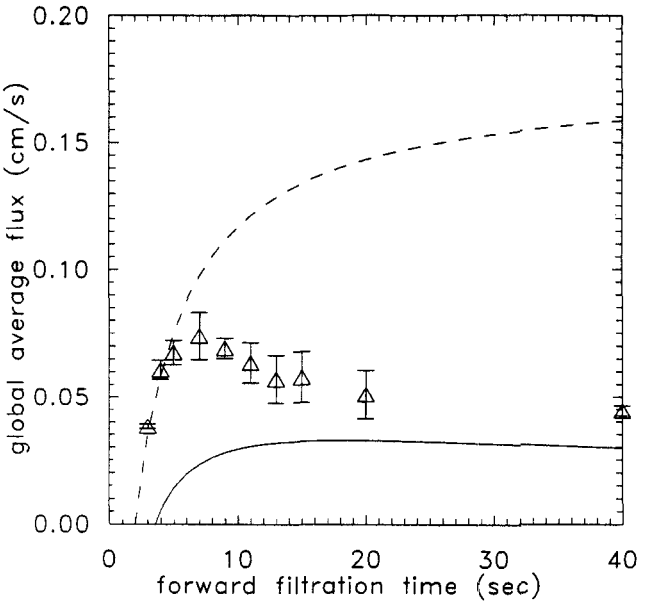

Figure 5. Global average flux vs. forward-filtration time for $\Delta P_f = 10$ psi (69 kPa), $\Delta P_b = 10$ psi (69 kPa), $t_b = 2$ s, $\phi_b = 0.03$, and $Q = 6$ mL/s.

The symbols are the averaged measured data, with ⧫ representing plus and minus one standard deviation; — is the theoretical prediction with cake formation (Eq. 2); --- is the prediction with no cake formation (Eq. 2 with $\tau \to \infty$).

for 5,000 s at cross-flow rates of $Q = 6$, 8, and 10 mL/s. We note that the time to reach steady state, t_s, may be estimated by setting $J = J_s$ in Eq. 1 and solving for $t = t_s$ (Davis, 1992). For the conditions examined, t_s exceeds 2,000 s and so is considerably greater than the maximum forward-filtration time employed during backpulsing.

Results and Discussion

Figure 4 shows a plot of the average flux per cycle vs. total filtration time for experiments with three reverse-filtration pressures of $\Delta P_b = 0$, 5 and 10 psi (0, 34.5, and 69 kPa) and a fixed forward transmembrane pressure of $\Delta P_f = 10$ psi (69 kPa). For $\Delta P_b = 5$ and 10 psi (34.5 and 69 kPa), the average flux per cycle remains nearly constant at 0.086 cm/s over the entire experiment. This indicates that the permeability of the membrane is recovered after each cycle and that a long-term reduction of the permeability due to cake buildup does not occur. For forward-filtration without backpulsing, the flux declines rapidly from $J_o = 0.175$ cm/s to $J = 0.006$ cm/s in 1,000 s. In addition, a nearly steady flux of $J_s = 0.0028$ cm/s is achieved after 5,000 s. Thus, nearly a 30-fold increase in the long-term net flux is achieved by rapid backpulsing with $\Delta P_b = 5$ and 10 psi (34.5 and 69 kPa). For $\Delta P_b = 0$, however, the average flux per cycle decreases continuously to 0.031 cm/s at $t = 1{,}000$ s. Apparently, reverse flow from the permeate side to the retentate side is required for the yeast cake to be completely removed so that the flux is regained after each cycle. Nevertheless, a considerable flux enhancement over the case of forward-filtration without backpulsing is evident. Possible reasons for this are diffusion of cells from the cake surface, erosion of the cake, decompression and subsequent washing away of the cake, and a shock wave (due to the rapid valve closing) knocking off part of the cake layer. We note that diffusion and erosion are not effective in removing a compressed yeast cake, as Redkar and Davis (1993) did not observe a flux increase upon increasing the feed flow rate during forward-filtration. From Figure 4, it is apparent that the reverse transmembrane pressures of $\Delta P_b = 5$ and 10 psi (34.5 and 69 kPa) give approximately the same flux per cycle, even though more fluid is lost during reverse-filtration for $\Delta P_b = 10$ psi (69 kPa) than for $\Delta P_b = 5$ psi (69 kPa). Apparently, the higher backpulse pressure removes the cake more completely. This is confirmed by the measurements of the permeate collected on the microbalance from forward-filtration only; the average flux during forward-filtration is 0.132 and 0.156 cm/s for $\Delta P_b = 5$ and 10 psi (34.5 and 69 kPa), respectively, even though $\Delta P_f = 10$ psi (69 kPa) in each case.

For each experiment, a global average flux is calculated based on the total fluid collected minus the total fluid lost over the entire period of the experiment. Figure 5 shows the global average flux vs. forward-filtration time for $\Delta P_f = \Delta P_b = 10$ psi (69 kPa), $t_b = 2$ s, $Q = 6$ mL/s, and $\phi_b = 0.03$. The symbols are the measured data, with the error bars representing plus and minus one standard deviation. The solid line is the predicted average flux per cycle using Eq. 2 with $J_o = 0.175$ cm/s, $\tau = 0.67$ s, $t_b = 2$ s, and $\alpha = 1$. The dotted line is the predicted average flux per cycle if no cake is formed (Eq. 2 with $\tau \gg t_f$). The measured flux increases monotonically with increasing t_f until a maximum is reached, after which it monotonically decreases, as predicted by the theory with cake formation. The measured maximum global average flux in one cycle is $\langle J \rangle^{\max} = 0.074 \pm 0.009$ cm/s, representing a 20-fold

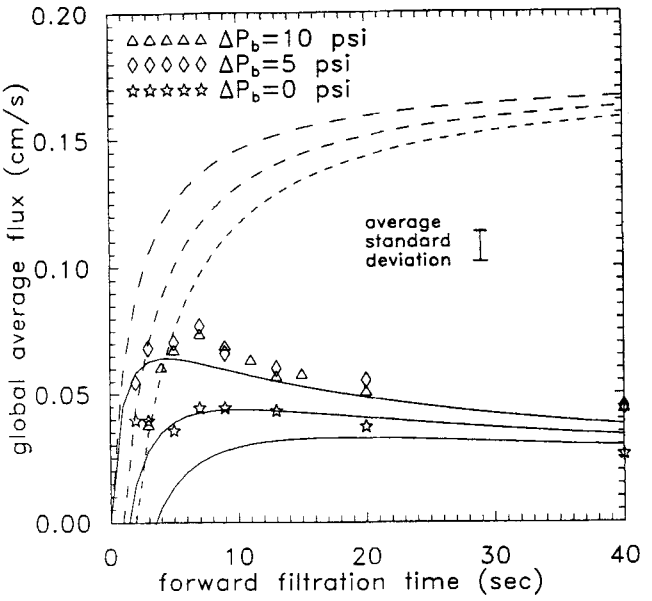

Figure 6. Global average flux vs. forward-filtration time for different reverse-filtration pressures, with $\Delta P_f = 10$ psi (69 kPa), $t_b = 2$ s, $Q = 6$ mL/s, and $\phi_b = 0.03$.

The symbols are the measured data, — are the theoretical predictions with cake formation (Eq. 2); --- are the predictions with no cake formation (Eq. 2 with $\tau \to \infty$), for $\Delta P_b = 0$, 5, and 10 psi (0, 34.5, and 69 kPa, top to bottom).

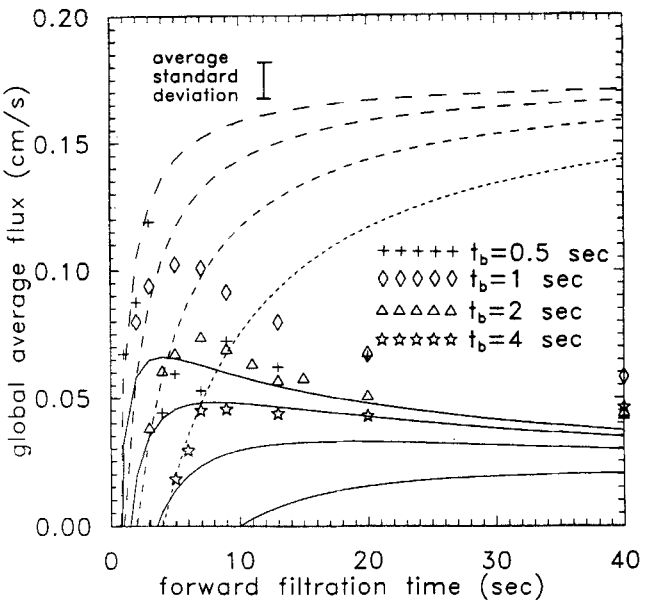

Figure 7. Global average flux vs. forward-filtration time for different reverse-filtration times, with $\Delta P_f = 10$ psi (69 kPa), $\Delta P_b = 10$ psi (69 kPa), $Q = 6$ mL/s, and $\phi_b = 0.03$.

The symbols are the measured data, — are the theoretical predictions with cake formation (Eq. 2), and --- are the predictions with no cake formation (Eq. 2 with $\tau \to \infty$), for $t_b = 0.5$, 1, 2, and 4 s (top to bottom).

increase over the steady-state flux, $J_s = 0.0028$ cm/s, for the same operating conditions without backpulsing.

For small forward-filtration times, the data in Figure 5 follow the theoretical prediction in absence of cake formation (dashed line) and overpredict the theory which includes cake formation (solid line). This may be partially explained by a delay in cake formation during forward-filtration, presumably due to the time requirement for removal of clarified fluid that was reintroduced into the channel during reverse-filtration. This time is on the order of H/J_o, which is approximately 0.2 s for the conditions used. A second reason for the average flux per cycle exceeding the predicted value is that the reverse flux during the early portion of the backpulse may be less than J_o due to the additional resistance offered by the cake layer before it is removed. At larger forward-filtration times, the measured global average flux is closer to that predicted by the theory with cake formation.

Figure 6 is a plot of the global average flux with forward-filtration time for different reverse-filtration transmembrane pressures of $\Delta P_b = 0$, 5, and 10 psi (0, 34.5, and 69 kPa). The other conditions are $\Delta P_f = 10$ psi (69 kPa), $t_b = 2$ s, $\phi_b = 0.03$, and $Q = 6$ mL/s. Each data symbol represents the average value for three experiments. A combined average standard deviation error bar for all the experiments is shown in the graph (Walpole and Myers, 1978). The global average flux for $\Delta P_b = 5$ psi (34.5 kPa) follows the same trend as that for $\Delta P_b = 10$ psi (69 kPa), and in both cases the experimental values are higher than the predicted values. The maximum average fluxes for $\Delta P_b = 5$ and 10 psi (34.5 and 69 kPa) are almost equal. In contrast, the measured data for $\Delta P_b = 0$ fall below the theory with cake formation and the theory without cake formation. For zero reverse transmembrane pressure, there is no flow of the clear fluid from the permeate to the retentate side. Hence, the cake layer is not lifted off and could only be removed by another mechanism such as erosion or diffusion. Evidently, the cake layer is not removed during the two-second period of no filtration, and so it accumulates with each cycle.

In Figure 7, the global average flux is plotted with the forward-filtration time for different reverse-filtration times of $t_b = 0.5$, 1, 2, and 4 s, while $\Delta P_f = 10$ psi (69 kPa), $\Delta P_b = 10$ psi (69 kPa), $\phi_b = 0.03$, and $Q = 6$ mL/s. The combined error bar shown is the average standard deviation for all the experiments. The data for $t_b = 1$, 2, and 4 s are the averages of three experiments, while those for $t_b = 0.5$ s are from a single experiment for each condition and show considerably more scatter. The measured fluxes for all the three cases increase according to the "no cake" line until a certain value of the forward-filtration time, after which the fluxes decline at higher t_f. The maximum global average flux increases with decreasing reverse-filtration time. As predicted by theory, this is because less clear fluid is lost during reverse filtration when the reverse-filtration time is reduced. As discussed previously, however, the measured fluxes exceed the predicted values, especially for short forward-filtration times. For long forward-filtration times, the global average fluxes for the four different backpulse times are close to each other, because the backpulsing represents only a small fraction of each cycle.

Figure 8 is a plot of the global average flux vs. forward-

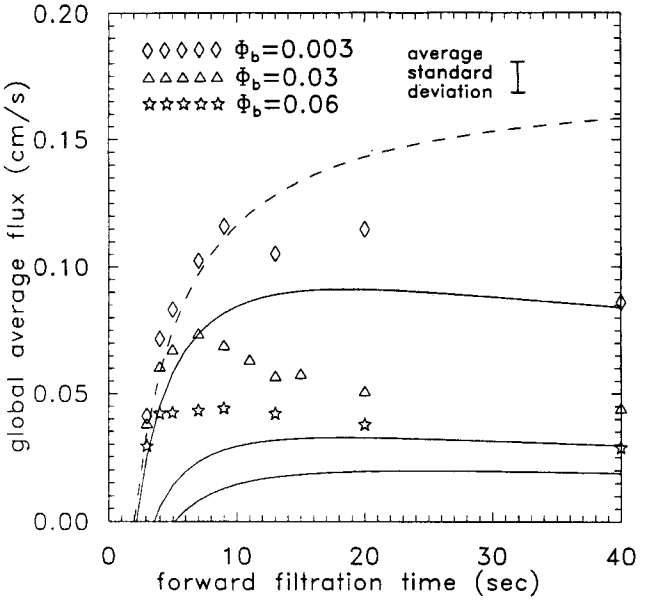

Figure 8. Global average flux vs. forward-filtration time for different bulk volume fractions, with ΔP_f = 10 psi (69 kPa), ΔP_b = 10 psi (69 kPa), t_b = 2 s, and Q = 6 mL/s.

The symbols are the measured data, — are the theoretical predictions with cake formation (Eq. 2), and --- is the prediction with no cake formation (Eq. 2 with $\tau \to \infty$), for ϕ_b = 0.003, 0.03, and 0.06 (top to bottom).

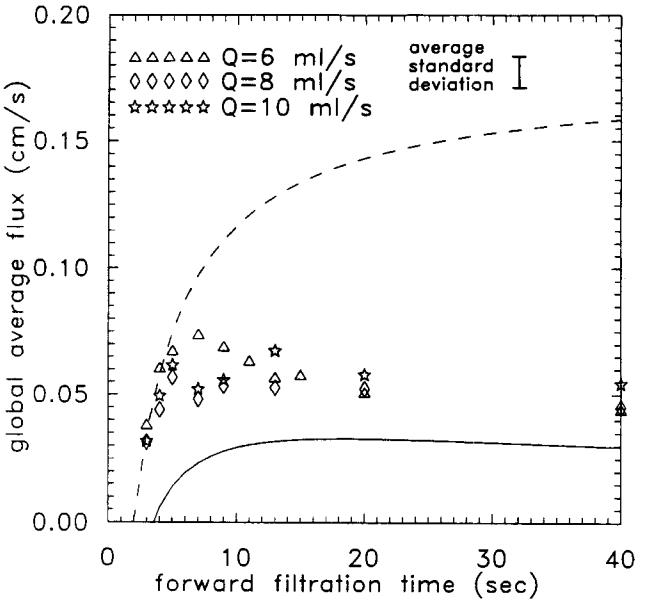

Figure 9. Global average flux vs. forward-filtration time for different feed suspension flow rates of Q = 6, 8, and 10 mL/s, with ΔP_f = 10 psi (69 kPa), t_b = 2 s, ΔP_b = 10 psi (69 kPa), and ϕ_b = 0.03.

The symbols are the measured data, — is the theoretical prediction with cake formation (Eq. 2), and --- is the prediction with no cake formation (Eq. 2 with $\tau \to \infty$).

filtration time for different bulk suspension volume fractions of ϕ_b = 0.003, 0.03, and 0.06. The other conditions are constant at ΔP_f = 10 psi (69 kPa), ΔP_b = 10 psi (69 kPa), t_b = 2 s, and Q = 6 mL/s. The trend followed by the data is similar to that discussed above. For short forward-filtration times, the average flux follows that predicted by the theory without cake formation and overshoots the theory with cake formation. With increasing forward-filtration times, a maximum is reached for each case and the average flux thereafter decreases due to cake formation. For lower feed concentrations, the formation of the cake layer is slower and a higher maximum flux is achieved.

Figure 9 shows the variation of the global average flux with forward-filtration time for three feed suspension flow rates of Q = 6, 8, and 10 mL/s. The other conditions are constant at ΔP_f = 10 psi (69 kPa), ΔP_b = 10 psi (69 kPa), t_b = 2 s, and ϕ_b = 0.03. The data for all cases are close to each other, implying that increasing the cross-flow velocity does not increase the global average flux. This result is also predicted by the theory, since it is assumed that the flux is described by the dead-end filtration equations and is unaffected by the cross-flow rate.

Table 1 lists the maximum global average fluxes, the corresponding theoretical predictions, and the steady-state values of the fluxes measured for forward-filtration without backpulsing. The maximum global average fluxes obtained using high frequency reverse-filtration are typically 20 to 30 times the corresponding steady-state fluxes. In general, the maximum average flux increases with decreasing feed concentra-

Table 1. Theoretical and Measured Maximum Fluxes and Corresponding Optimum Forward Filtration Times*

	Theoretical		Measured			
Conditions	$\langle J \rangle^{max}$ cm/s	t_f^{max} s	$\langle J \rangle^{max}$ cm/s	t_f^{max} s	J_s cm/s	$\langle J \rangle^{max}/J_s$
ΔP_b = 10 psi (69 kPa)	0.033	19	0.074 ± 0.009	7	0.0028	26.4
ΔP_b = 5 psi (34.5 kPa)	0.044	10	0.077 ± 0.008	7	0.0028	27.5
ΔP_b = 0	0.064	4	0.045 ± 0.003	8	0.0028	16.1
t_b = 0.5 s	0.066	4	0.119	3	0.0028	42.5
t_b = 1 s	0.048	8	0.102 ± 0.006	6	0.0028	36.4
t_b = 4 s	0.021	48	0.045 ± 0.006	8	0.0028	16.1
ϕ_b = 0.003	0.091	19	0.116 ± 0.006	9	0.0038	30.5
ϕ_b = 0.06	0.020	25	0.044 ± 0.004	8	0.0020	22.0
Q = 8 mL/s	0.033	19	0.057 ± 0.002	5	0.0034	16.8
Q = 10 mL/s	0.033	19	0.068 ± 0.004	13	0.0029	23.4

*Measured steady-state fluxes are shown in the absence of backpulsing. Unless specified otherwise, the operating conditions are ΔP_f = 10 psi (69 kPa), ΔP_b = 10 psi (69 kPa), t_b = 2 s, ϕ_b = 0.003, and Q = 6 mL/s.

tion and reverse-filtration time, and are nearly independent of the cross-flow rate. With the exception of the case of $\Delta P_b = 0$, the measured maximum average fluxes exceed the predictions, and the corresponding optimum forward-filtration times are generally shorter than predicted.

Conclusions

High-frequency reverse-filtration is capable of regenerating the clean membrane flux after each cycle, thus maintaining a constant value of the average flux over the duration of an experiment. This regeneration of the clean membrane flux is observed for reverse-filtration transmembrane pressures of 5 and 10 psi (34.5 and 69 kPa), but not for zero. The global average flux for each experiment increases with increasing forward-filtration time, reaches a maximum and then decreases. The measured global average flux data follow the trends predicted by the theory, although they exceed the predicted values. It is proposed that the improved performance of the experiments over theory is due to a delay in cake removal at the start of reverse-filtration and a delay in cake formation at the start of forward-filtration. The maximum global average flux increases with decreasing reverse-filtration time and decreasing feed suspension volume fraction, but shows little dependence on cross-flow velocity.

Acknowledgments

This research was supported by the Center for Separations Using Thin Films at the University of Colorado, Boulder, and by grant CTS-9107703 from the National Science Foundation. The authors would like to thank Jennifer Franzen for help in the experiments, and the National Science Foundation for supporting her through its Research Experiences for Undergraduates Program.

Notation

$\langle J \rangle$ = average permeate flux per cycle, cm/s
$\langle J \rangle^{max}$ = maximum average permeate flux per cycle, cm/s
J_o = clean membrane flux, cm/s
J_s = steady-state permeate flux, cm/s
ΔP = transmembrane pressure, psi or kPa
ΔP_b = magnitude of reverse-filtration transmembrane pressure, psi or kPa
ΔP_f = magnitude of forward-filtration transmembrane pressure, psi or kPa
Q = feed flow rate, mL/s
$\hat{R}_c$ = specific cake resistance, 1/cm^2
t = time elapsed since the start of experiment, s
t_b = reverse-filtration time, s
t_f = forward-filtration time, s
t_f^{max} = forward-filtration time at which maximum average flux is observed, s
t_s = time at which a steady state is reached for no backpulsing, s

Greek letters

α = ratio of reverse and forward-filtration pressures, $\Delta P_b/\Delta P_f$
μ_o = pure fluid viscosity, gm/cm·s
τ = time constant for dead-end filtration equation, s
ϕ_b = bulk volume fraction of cells

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Manuscript received Dec. 6, 1993, and revision received Mar. 28, 1994.