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Predicting optimal back-shock times in ultrafiltration hollow fiber modules II: Effect of inlet flow and concentration dependent viscosity

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ABSTRACT

This paper concerns mathematical modeling and computational fluid dynamics of back-shocking during hollow fibre ultrafiltration of dextran T500. In this paper we present a mathematical model based on first principles, i.e., solving the Navier–Stokes equation along with the continuity equation for both the solute and the solvent.

We investigate the validity of the estimate on the optimal back-shock time, i.e., the back-shock time needed to achieve the highest permeate flux, published in a previous paper by the authors (Vinther et al., Predicting optimal back-shock times in ultrafiltration hollow fibre membranes, J. Membr. Sci. 470 (2014) 275–293 [33]).

Furthermore, the simulations have been performed with two different inlet velocities, i.e., crossflow velocities and are done with and without a concentration dependent viscosity. This enables us, for the first time, to investigate the effect of different inlet velocities and the effect of a concentration polarization on the observed rejection and the permeate flux, as a function of different back-shock times.

In all cases the average permeate flux and the observed rejection during one period of back-shocking were found to be higher than the steady-state values – representing the long time behavior of a similar separation process performed without back-shocking – when using the optimal back-shock time.

It is concluded that the estimate of the optimal back-shock time is in good agreement with the optimal time found in the simulations performed in this paper.

Furthermore, it is found that the optimal back-shock time increases when the viscosity is allowed to depend on the concentration. It is found that this can be explained by a decrease in the velocity tangential to the membrane due to the increase in viscosity where the concentration is high – resulting in a longer time for the concentration polarization to be convected tangentially along the membrane surface.

The ratio between the average flux over a back-shock cycle and the steady-state flux is found to increase with increasing inlet velocity. Furthermore, this ratio increases when the viscosity depends on the concentration. This is due to the relatively lower steady-state value when the viscosity depends on the concentration.

Moreover, an increase in observed rejection is found when using back-shocking. The increase in observed rejection is found to be largest when the inlet velocity is high and the viscosity depends on the concentration.

1. Introduction

Back-shocking, back-pulsing, or flow-reversal is a technique where the pressure difference across the membrane is periodically altered. During forward filtration the pressure on the feed side of the membrane is higher than the pressure on the permeate side of the membrane, causing the flux through the membrane to be from the feed side to the permeate side. During the time of forward filtration, concentration polarization will build up near the membrane surface. This increase in concentration results in a decrease in flux through the membrane due to an increase in the osmotic pressure. As a result of the increase in osmotic pressure, the flux will gradually decrease as a function of time, until a steady-state is reached.

When back-shocking is used, the pressure difference across the

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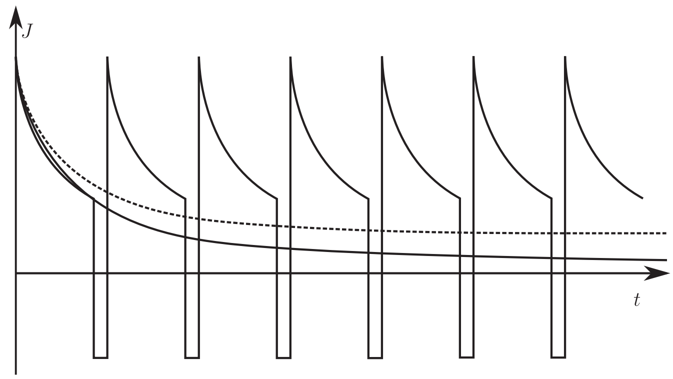

Fig. 1. Illustration of the flux during back-shocking. The line that alternates between positive and negative fluxes represents the flux with back-shocking. The flux is positive during the time between back-shocking, t_{bbs}, and negative during the back-shock time, t_{bs}. Hence, the time of a full back-shock cycle consists of the sum of t_{bs} and t_{bbs}. The full line that does not alternate represents the flux when no back-shocking is used. The flux decreases towards a steady-state value. The dotted line represents the average flux over a back-shock cycle after these cycles enter a periodic behavior. For the right choice of working parameters this value is higher than the steady-state value without back-shocking.

membrane is reversed for a period of time, denoted the back-shock time, t_{bs}. During this time period the flux is from the permeate side to the feed side. As a result of this negative flux, the concentration polarization is convected away from the membrane. Furthermore, it is convected downstream due to the crossflow velocity. After the back-shock period the pressure difference is again reversed causing the forward filtration to be resumed. At the instant where the flux is returned to a forward flux, the membrane will be clean – causing a high flux. Again, the forward flux decreases towards the steady state. The reversal of pressure difference across the membrane continues periodically. Therefore, the time of forward filtration is denoted the time between back-shocking, t_{bbs}. It is expected that if the back-shock time and the time between back-shocking are chosen correctly, the average flux during a back-shock period is higher than the steady-state flux. This is illustrated in Fig. 1.

It is obvious that the optimal back-shock time will depend on the working parameters such as the magnitude of the flux during forward filtration and during back-shocking, the crossflow velocity near the membrane surface, and the length of the membrane. It is, however, not obvious how the optimal back-shock time depends on these parameters.

As the average flux can be higher when using back-shocking as compared to the long term flux without back-shocking, the back-shock technique is increasingly being used in membrane filtration as an in situ method used to avoid or decrease the negative influence of concentration polarization, fouling, or both, on the flux during membrane filtration [1–13]. Generally, it can be said that a larger effect is observed when back-shocking is applied in microfiltration as compared to ultrafiltration. In microfiltration, the permeate flux when using back-shocking is reported to be up to 10 times higher than the long term behavior without back-shocking [14]. This is usually ascribed to the formation of a cake-layer in microfiltration [15–17]. Of the papers mentioned previously [2,3,6–13] concerns ultrafiltration. Here the highest flux reported when using back-shocking as compared to the long term flux without back-shocking was 3.9 times the long term flux [2]. The increase in flux in ultrafiltration is usually ascribed to the reduction of the effects of concentration polarization or even a gel-layer.

In this paper we shall focus only on the effect of back-shocking on the concentration polarization in hollow fibre ultrafiltration. Therefore, we will relate the findings of the papers [2,3,6–13] to the results of the paper in the discussion.

Mathematical modeling and computational fluid dynamics are increasingly being used to gain understanding of cause and effect in membrane filtration [18–33]. Of these the following papers concern back-shocking [28–33].

The removal of the cake-layer in microfiltration is the subject of the models presented in [28–32]. In [29] the dynamics of an osmotic backwash cycle is modeled.

In [33], the focus is on back-shocking of concentration polarization in ultrafiltration. Here, an estimate was given for the optimal back-shock time depending on the working parameters. This estimate was derived by calculating the path-lines during a back-shock cycle. The calculations depended on estimating the cross-flow velocity to be linear as a function of the distance from the membrane and the viscosity of the fluid to be constant. The estimate for the back-shock time was found to be

$$t_{bs} = \sqrt{\frac{2L_m}{kAp_{bs}\left(1 + \frac{p_{bs}}{p_{tmp}}\right)}}. \tag{1}$$

Here, L_m represents the length of the membrane, A is the pure water permeability, p_{tmp} is the pressure difference across the membrane during forward filtration, and p_{bs} is the pressure difference across the membrane during back-shocking. k is the velocity gradient perpendicular to the membrane, i.e., $k = \tau_w/\eta$, where τ_w is the shear stress at the membrane surface and η_s is the viscosity of the fluid considered. This value of k is approximated by the corresponding velocity gradient without any flux through the membrane. For a hollow fibre, this is given by $k = 4u_{in,av}/R$, where $u_{in,av}$ is the average inlet velocity and R is the radius of the hollow fibre. The estimate, given in Eq. (1), has been validated through computer simulations on a two dimensional domain of several times the width of the boundary layer times the length of the membrane. The results from the simulations were found to be in good agreement with the estimate.

The assumption used in [33] that the velocity tangential to the membrane is linear as a function of distance from the membrane is obviously not correct in hollow fibres for large distances away from the membrane. Instead, the full Navier–Stokes equation should be solved along with the continuity equation for both solvent and solute. The scope of this paper is to investigate the validity of the estimate for the optimal back-shock time given in Eq. (1) when the full Navier–Stokes equation is solved along with the continuity equation for the solvent and the solute. Furthermore, solving the full set of equations of motion allows for an investigation of the effect of a concentration dependent viscosity. Hence, the main objectives of this study are to investigate the effect of a concentration dependent viscosity on the back-shock time needed to optimize the flux through the membrane during a back-shock period. To the knowledge of the authors, this is the first time that back-shocking has been simulated using a mathematical model based on the fundamental physical assumptions and the effect of using back-shocking has been shown.

The mathematical model presented in the next section uses Dextran T500 as the solute and water as the solvent. The solution will be modeled at a temperature of 295.15 K, which gives the following value of the pure solvent density, $\rho_s = 999.62$ kg/m^3 and the pure solvent shear viscosity, $\eta_s = 0.001$ Pa s. The membrane parameters such as permeability of solute and solvent as well as the expressions for the osmotic pressure, the diffusion coefficient of Dextran T500, and the concentration dependence of the viscosity will be the same as given in [27] and elaborated in the following section.