Available online at www.sciencedirect.com
SCIENCE DIRECT®
ELSEVIER
Journal of Membrane Science 253 (2005) 67–79
journal of MEMBRANE SCIENCE
www.elsevier.com/locate/memsci

A suspension flow model for hydrodynamics and concentration polarisation in crossflow microfiltration

J. Kromkamp [a,b,*], A. Bastiaanse [a], J. Swarts [a], G. Brans [a], R.G.M. van der Sman [a], R.M. Boom [a]

[a] *Food and Bioprocess Engineering Group, Wageningen University, Wageningen, The Netherlands*
[b] *Corporate Research, Friesland Foods BV, Deventer, The Netherlands*

Received 3 August 2004; received in revised form 30 November 2004; accepted 21 December 2004
Available online 26 February 2005

Abstract

A new computer simulation model is proposed for suspension flow in microfiltration systems. In this model, the diffusion of the suspended microparticles is governed by the mechanism of shear-induced migration. Using an Euler–Euler approach, hydrodynamics and convection–diffusion are simultaneously resolved according to the lattice Boltzmann method. The new suspension flow model allows the complete solution of the flow field (including calculation of the actual local shear rate) in systems with complex geometries and the application of a pressure gradient over he feed flow channel as well as over he membrane. The cake layer dimensions and permeability are explicitly taken into account. For a simple cross-flow system, a comparison is made between the new suspension flow model and existing models. The more realistic approach of the suspension flow model is found to be especially significant for the calculation of the cake layer profile at the beginning and the end of the membrane. Also the effect of narrowing of the flow channel by cake formation on the suspension flow pattern (at a constant pressure gradient over the flow channel) is more realistically predicted. Finally, some examples are presented of the concentration polarisation and cake layer formation in microfiltration systems with more complex geometries. The newly developed suspension flow model has generic applicability as a design tool for microfiltration membranes, systems and processes. Extensions of the model o three-dimensional systems (including parallel computations), as well as adaptations of the diffusion model to anisotropic diffusivity can be relatively easily achieved.

Keywords: Microfiltration; Concentration polarisation; Shear-induced migration; Computer simulation; Hydrodynamics; Permeate flux

1. Introduction

The performance of microfiltration processes is in general mainly determined by concentration polarisation, which arises from the simultaneous transport of non-permeable species towards and back from the membrane surface. Modelling of flow and concentration polarisation in microfiltration systems is already often put forward as an important tool to help understand and optimise these systems. Although numerous filtration models of varying degrees of complexity and simplification have appeared in literature, most of them do not apply for microfiltration, due to the different diffusion mechanism in particulate suspensions as compared to molecular solutions.

As has been identified by Belfort et al. [1], for particulate suspensions with particle sizes between 0.5 and 30 μm, shear-induced diffusion can often be considered the relevant back-transport mechanism in the concentration polarization process. Other back-transport mechanisms are Brownian diffusion and inertial lift, which are respectively dominant for particle sizes smaller than 0.5 μm and larger than 30 μm. This paper addresses modelling of flow and concentration polarisation in the shear-induced diffusive regime. Shear-induced diffusion, also called hydrodynamic diffusion, is a transport mechanism that is caused by hydrodynamic parti-

* Corresponding author. Tel.: +31 570 695917; fax: +31 570 695918.
E-mail address: j.kromkamp@fcdf.nl (J. Kromkamp).

0376-7388/$ – see front matter © 2005 Elsevier B.V. All rights reserved.
doi:10.1016/j.memsci.2004.12.028

cle interactions in a suspension in shear flow. Excluded volume effects can then lead to particle displacements. In contrast to inertial lift, which is only relevant in regime where the Reynolds number based on the particle size is not negligible, shear-induced diffusion occurs in the slow laminar flow regime as well. A general property of shear-induced diffusion is that it increases proportionally with the shear rate.

About two decades ago, shear-induced diffusion was first introduced in relation to microfiltration theory by Zydney and Colton [2]. Their concentration polarization model is based upon the classical Lèvéque solution for mass transfer in which they replaced the Stokes-Einstein diffusivity with the shear-induced diffusivity, as determined from experimental data of Eckstein et al. [3]. In the same year as Zydney and Colton, Davis and Leighton presented a model that describes the transport of a concentrated layer of particles along a porous wall under laminar flow conditions [4]. In this model, shear-induced diffusion accounts for the lateral migration of particles away from the porous wall. Instead of the approximate fit to the data of Eckstein et al., Davis and Leighton applied data of Leighton and Acrivos [5] for shear-induced diffusion, which were about 25 times greater and were shown to better describe the viscous resuspension of a settled layer of rigid particles in shear flow.

Romero and Davis [6] extended the model of Davis and Leighton from a local treatment of the particle layer to a global model of crossflow microfiltration. This global model is able to predict the axial dependence of the permeate flux and the thickness of the concentrated particle layer under steady or quasi-steady operation. The model also describes under which conditions a stagnant layer of packed particles exists beneath the flowing layer. In a following step, the global model was converted into a transient model, which not only describes the steady-state behaviour but also the time-dependent decline of the permeate flux due to particle layer buildup [7].

In the aforementioned models, particle convection parallel to the membrane walls was ignored. As a consequence, the models are only valid for very small particle volume fractions in the bulk of the suspension ϕ_b. Davis and Sherwood overcame this limitation in their similarity solution for crossflow microfiltration under conditions where the stagnant particle layer provides the controlling resistance to flow [8]. In their solution, the stagnant particle layer grows like $x^{1/3}$, where x denotes the dimensionless distance from the filter entrance. Their solution is however only valid in the situation that the critical length needed for the stagnant layer to form is much smaller than the filter length. Pelekasis developed a model which does not have this limitation [9], although his solution is only valid in situations where the permeate flux can be considered constant over the membrane length. This model is valid over a wide range of bulk particle concentrations. It is shown that in the limit where the particle volume fraction in the bulk suspension $\phi_b \rightarrow 0$, the model of Davis and Leighton is recovered.

All the above-mentioned models have in common that they assume the bulk flow to be fully developed Poiseuille flow with a time-independent flow rate. This is valid for a straight flow channel, when the permeate velocity is much smaller than the average down channel velocity of the suspension and when the stagnant layer is much thinner than the channel half width. These conditions are often not met in reality. First of all, the flow channel may deviate from perfectly circular or rectangular, e.g. when turbulence promotors are present. Secondly, when suspensions are filtered with particles that have a relatively low cake resistance, the cake layer height can become significant compared to the channel half width. Poiseuille flow can still be considered present when the cake layer height does not vary much along the filter length (and the actual flow velocity profile can be adapted to the actual channel height). The flow pattern can however easily deviate from Poiseuille flow when the cake layer height strongly varies along the filter length, like e.g. at the beginning and at the end of the filter. Thirdly, the flow pattern can also be time-dependent, such as when oscillating cross-flow or backpulsing is applied. One should moreover realise that, in contrast to Brownian diffusion, shear-induced diffusion depends linearly on the shear rate. Local deviations of the flow field from Poiseuille flow will therefore have a large influence on the local morphology of the flowing and stagnant particle layer.

This indicates that a more generic model with broad applicability to membrane systems requires an accurate, more detailed solution of the fluid flow field. This is possible with computational fluid dynamics (CFD). So far, this technique is not often applied to membrane systems. Recently, Wiley and Fletcher [10] successfully developed a generic CFD model that incorporates the flow across the membrane wall. In their article, they also reviewed earlier attempts in this field, which in general lead to less generic solutions than their model. Another recent approach is that of Richardson and Nassehi [11]. These authors developed a finite element model for the solution of concentration profiles in flow domains with curved porous boundaries. Although both models may be extensible to modelling of concentration polarisation in microfiltration processes, with shear-induced diffusion as back-transport mechanism and with cake layer formation, up to now no results on this subject have been published.

The present work is directed at the development of a CFD model for flow and concentration polarisation in microfiltration systems with shear-induced diffusion as back-transport mechanism. We apply the lattice Boltzmann (LB) method for this aim, which is based on kinetic theory, the physical theory describing the dynamics of large systems of particles. The LB method, being a discrete version of the Boltzmann equation, is in special cases identical to the finite volume scheme as used by Wiley and Fletcher [10]. Both methods can be applied for laminar as well as turbulent flows. The LB method may however have some advantages when compared to other finite difference schemes. Complex geometries can