



Theoretical investigation of cross flow ultrafiltration by mixed matrix membrane: A case study on fluoride removal



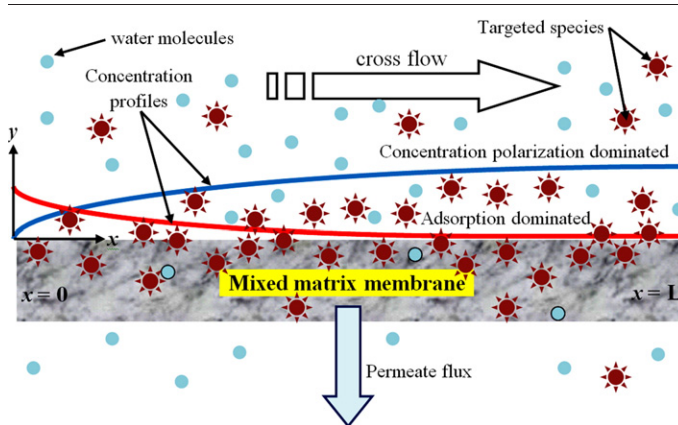
Sourav Mondal, Somak Chatterjee, Sirshendu De*

Department of Chemical Engineering, Indian Institute of Technology Kharagpur, Kharagpur 721302, India

HIGHLIGHTS

- Modeling performance of mixed matrix membrane in cross flow ultrafiltration
- The model includes concentration polarization coupled with adsorption.
- Ultrafiltration of fluoride using alumina doped mixed matrix membrane
- Experimental validation and sensitivity analysis of the model parameters

GRAPHICAL ABSTRACT



The present analysis captures the physics of simultaneous concentration polarization and adsorption during ultrafiltration in mixed matrix membrane.

ARTICLE INFO

Article history:

Received 7 January 2015
Received in revised form 11 March 2015
Accepted 12 March 2015
Available online 19 March 2015

Keywords:

Mixed matrix membrane
Ultrafiltration
Adsorption
Cross flow
Transport

ABSTRACT

Selective membrane filtration with high throughput can be achieved using mixed matrix membrane (MMM). The application of MMM in integrated membrane processing requires a continuous mode of operation. Therefore, understanding the mechanism of cross flow ultrafiltration of MMM is important from the design and operational point of view. Theoretical analysis based on first principles presented in this study takes into account the simultaneous occurrence of adsorption in the matrix and spatially developing concentration polarization layer over the membrane surface. The change in the filtration regime from adsorption dominated to diffusion governed can be identified. The developed model is validated with cross flow ultrafiltration experiments of fluoride contaminated solution using activated alumina MMM, for different operating conditions. The impact of the adsorption isotherm constants on the system performance is also evaluated.

© 2015 Elsevier B.V. All rights reserved.

1. Introduction

The main advantage of mixed matrix membrane (MMM) is the separation of the targeted solute with enhanced selectivity and high

throughput. Typically, MMMs are prepared by doping inorganic filler into the base matrix, to impart the desired characteristics [1–3]. Several researchers have reported the use of MMM for the separation and purification of gas mixture [4–7]. The primary removal mechanism is the adsorption of the targeted species into the membrane matrix. However, in the case of filtration of liquid stream, the species diffusion and convection along with adsorption occur simultaneously [8,9]. In membrane

* Corresponding author.
E-mail address: sde@che.iitkgp.ernet.in (S. De).

filtration, the solutes are screened by physical sieving and the balance between diffusion and convection is the prevailing mechanism for transport species across the membrane. On the other hand, physical adsorption occurs in the matrix of the MMM, resulting in reduced membrane surface concentration compared to that without adsorption.

Adsorption study on the membrane was first reported by Matthiasson, who found that adsorption had a significant influence on ultrafiltration [10]. The first mathematical analysis was developed by Doshi (1986) considering the simultaneous occurrence of adsorption and concentration polarization [11]. He derived a steady state model for two limiting cases of adsorption or diffusion dominating. In the case of adsorption limited process, the solute concentration at the membrane surface is negligible due to its desorption from the membrane to the permeate side. In the case of diffusion limited process, he indicated that ultrafiltration was dominated by the difference in osmotic pressure. In the modeling of protein ultrafiltration, Gekas et al., combined both adsorption and concentration polarization in a single model [12]. The theory was based on the generalized integral approach for concentration boundary layer, with a sink term for adsorption in the boundary condition at the membrane solution interface. Numerical computation for the system of equations was carried out with the finite discretization technique. The discrepancies in the modeling approach by Gekas et al., were corrected and an improved version of the model was reported by Bevia et al. [13]. They suggested that the adsorption dynamics could not be solved explicitly as the system of equations were coupled with the boundary layer equation, which was not considered by Gekas et al. They also clarified the convention of co-ordinate system selected in calculating the diffusive term. The quantification of the permeate concentration was not included in their model. Extending the analysis of coupled adsorption in MMM, Mondal et al., presented a comprehensive analysis incorporating the modifications suggested by Bevia et al., to predict the system performance for ultrafiltration in dead end configuration [8]. They developed a transport model for ultrafiltration which could predict both permeate flux and permeate concentration in batch filtration considering the effects of volume reduction with time and adsorption isotherms.

The present study aims to develop a theoretical understanding of performance of MMM during cross flow ultrafiltration. Being continuous in operation, the cross flow mode of operation is important from the practical standpoint. The effect of forced convection on concentration polarization in the presence of adsorption is highlighted in this study. The transient state nature of the system is analyzed considering the adsorption dynamics which is an order of magnitude higher than the time dependent concentration term in the species convection-diffusion equation. The developing concentration boundary layer is solved using the integral method of solution. Further, the model predictions are validated for the ultrafiltration of the fluoride solution using activated alumina-cellulose acetate phthalate membrane. The model sensitivity analysis is also reported for the model parameters and constants of adsorption isotherm.

2. Theoretical development

The transport mechanism of concentration polarization together with adsorption in the mass transfer boundary layer (Fig. 1) for a rectangular geometry, is described by two-dimensional convective-diffusive species transport equation. In this work, a more generalized approach of developing concentration polarization layer is considered and therefore, boundary layer thickness is not constant and varies with the axial location.

$$\frac{\partial c}{\partial t} + u \frac{\partial c}{\partial x} + v \frac{\partial c}{\partial y} = D \frac{\partial^2 c}{\partial y^2} \quad (1)$$

The assumptions involved in theoretical consideration are: (i) the transient term in Eq. (1) is significantly less than the order of magnitude

of the remaining terms, especially beyond 100 s of filtration [8]. Therefore, one can take recourse to quasi steady-state analysis for the determination of the concentration boundary layer profile compared to adsorption dynamics; (ii) The thickness of the concentration boundary layer is small, so that the transverse velocity is approximated to the permeation velocity at the wall [14]; (iii) laminar flow in the channel; (iv) solute diffusivity and solution viscosity are constant; (v) rheology of the fluid is Newtonian; (vi) uniform rate of adsorption in the membrane matrix and the flow channel does not contain any spacers.

According to assumption (ii) the transverse velocity is expressed as,

$$v = -v_w \quad (2)$$

The x -component velocity, expressed by the Poiseuille velocity for a rectangular channel is given as,

$$u = \frac{3}{2} u_p \left(2 \frac{y}{h} - \frac{y^2}{h^2} \right) \quad (3)$$

where, u_p is the average axial velocity and h is the channel half-height. The relevant boundary conditions for Eq. (1) are:

$$\text{at } x = 0; \quad c = c_0 \quad (4a)$$

$$\text{at } y = 0; \quad v_w (c_m - c_p) = D \frac{\partial c}{\partial y} \Big|_{y=0} + \rho_m (1 - \varepsilon_m) \tau_m \frac{\partial q}{\partial t} \Big|_{y=0} \quad (4b)$$

$$\text{at } y = \delta(x); \quad c = c_0 \quad (4c)$$

where, c_m is the solute concentration at the membrane surface ($y = 0$).

It may be noted here, that in mass-transfer analysis, the diffusive flux D

$\frac{\partial c}{\partial y} \Big|_{y=0}$, accounting for concentration polarization is always away from the membrane (in the form of back diffusion) as the solute concentration over the membrane surface is higher than the bulk concentration. However, this may not be true in the case of adsorption occurring on the membrane surface as in the case of MMM. The solutes polarized over membrane surface get adsorbed by the membrane and in the process, the surface concentration decreases. Hence, more solutes are diffused from the bulk toward the membrane surface, due to the positive concentration gradient [13].

The permeate flux of the membrane at any point of time is given by [15],

$$v_w = \frac{\Delta P - \Delta \pi}{\mu (R_m + R_{ad})} \quad (5)$$

where, R_{ad} is the adsorption resistance and $\Delta \pi$ is the osmotic pressure difference across the membrane feed and permeate side. For low molecular weight solutes and salts, the osmotic pressure is quantified using the Vant-Hoff's relation for ideal solution [16],

$$\pi = (|\gamma^+| + |\gamma^-|) \frac{R_g T}{M_w} c \quad (6)$$

where, M_w is the molecular weight of the salt. Thus, the osmotic pressure difference ($\Delta \pi$) is represented as,

$$\Delta \pi = \pi|_m - \pi|_p = (|\gamma^+| + |\gamma^-|) \frac{R_g T}{M_w} (c_m - c_p) \quad (7)$$

The kinetics of adsorption process is considered a first order rate process, represented by the Lagergren model as [17],

$$q = q_e [1 - \exp(-k_p t)] \quad (8)$$

Download English Version:

<https://daneshyari.com/en/article/7008370>

Download Persian Version:

<https://daneshyari.com/article/7008370>

[Daneshyari.com](https://daneshyari.com)