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Investigation of nano-colloid transport in UF membranes using flow field–flow fractionation (flow FFF) and an irreversible thermodynamic transport model

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Abstract

Membrane fouling has been associated with the size of solutes, i.e., macromolecules and colloids in membrane filtration. Colloidal fouling propensity was investigated in terms of transport characteristics by the thermodynamic transport model combined with concentration polarization and flow field–flow fractionation (flow FFF). Transport characteristics in membranes were focused on, especially nano-colloid fouling in UF membranes. Whey protein and 30 nm of latex microsphere suspensions were used as test solutions. Transport parameters were determined in terms of mass transfer coefficient (k), solute permeability (P_m), and reflection coefficient (σ) by non-linear estimation. The flow FFF provided a consistent explanation for the nano-colloid transport, depending on the physicochemical interactions between membrane and solute through the transport parameters determined from filtration tests. The second and third moments, variance and skewness were expected to be very useful quantitative information on the membrane fouling propensity of a certain solute.

Keywords: Nano-colloids; Concentration polarization coupled thermodynamic transport model (CPCT); Flow field–flow fractionation; Moment analyses

1. Introduction

In aquatic systems macromolecules and colloids, including microorganisms, are ambiguous and complex components associated with toxic compounds and natural organic matter (NOM). However, macromolecules and colloids are different from small molecules such as NOM in terms of reactivity and transport, and the sizes of both NOM and aquatic colloids have been associated

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with all environmental topics: disinfection by-products (DBPs) formation, coagulation efficiency, membrane fouling in drinking water treatment, adsorption kinetics, metal speciation, and many others. Porous membranes such as both microfiltration (MF) and ultrafiltration (UF) could be widely used in the separation of these macromolecules and colloids in both drinking and wastewater treatments. However, the major obstacle to these membrane filtrations is flux decline, which results from pore blocking, adsorption, concentration polarization, and cake/gel layer formation. For the filtration of a colloidal suspension, surface interactions, such as attractive and electrostatic interactions, may play a very important role in colloidal fouling, providing different behaviors of the deposition and adsorption of colloids on the membrane surface [1].

Flow FFF has been traditionally used to determine the size distribution and diffusion coefficient of various solutes (i.e., colloids, particles, and microorganisms) with the separation channel equipped with regenerated cellulose membranes. In this study, flow FFF was used to evaluate the surface interactions between tested nano-colloids and membranes, using electrostatic interactions and colloidal transport by diffusion, along with solute properties such as size and shape.

Two different types of experimental methods were used to evaluate the transport characteristics of nano-colloids of interest: (1) flow FFF and (2) cross-flow UF tests using membranes with the same material. The first and second approaches were accompanied by moment analyses calculated from fractograms [especially the second and the third moments (i.e., variance and skewness)] obtained from the flow FFF under different conditions and the thermodynamic transport models, respectively.

2. Related theories

Transport of nano-colloids in the membrane was evaluated using membrane filtration tests with the thermodynamic transport model as well as the flow FFF analyses. The thermodynamic model was especially adapted in the concentration polarization relationship and coupled with irreversible thermodynamics [2].

From the concentration polarization, the relationship between the observed removal ratio and solvent flux can be defined as

$$\ln\left(\frac{T_{obs}}{R_{obs}}\right) = \ln\left(\frac{1-R_{obs}}{R_{obs}}\right) = \ln\left(\frac{1-R}{R}\right) + \frac{J_v}{k} \quad (1)$$

where R_{obs} and R are the observed and true removal ratios of a membrane, respectively. T_{obs} is the observed transmission percentage of a membrane, and T_{obs} can be defined in terms of R_{obs} (i.e., $R_{obs} = 1 - T_{obs}$). J_v is the solvent flux through the membrane, and k is the mass transfer coefficient that represents the mass transfer away from the membrane surface into a bulk phase.

Spiegler and Kedem (as in [2]) assumed the local equilibrium, and Eq. (2) can be obtained by integration of solute flux over the membrane:

$$\frac{1}{R} = \frac{\exp\left[J_v(1-\sigma)/P_m\right] - \sigma}{\sigma\left\{\exp\left[J_v(1-\sigma)/P_m\right] - 1\right\}} \quad (2)$$

Here, P_m and σ are the solute permeability and reflection coefficient, respectively. The Speigler–Kedem model can be applied for UF membranes more effectively than the Kedem–Katchalsky model. Combining Eqs. (1) and (2), Eq. (3) can be obtained.

$$\ln\left(\frac{1-R_{obs}}{R_{obs}}\right) = \ln\left(\frac{1}{R} - 1\right) + \frac{J_v}{k} = \ln\left(\frac{\exp\left[J_v(1-\sigma)/P_m\right] - \sigma}{\sigma\left\{\left[J_v(1-\sigma)/P_m\right] - 1\right\}} - 1\right) + \frac{J_v}{k} \quad (3)$$

From the Spiegler–Kedem model, i.e., Eq. (3),