Shape Effects on Microorganism Removal by Microfiltration and Ultrafiltration Membranes

Microfiltration (MF) and ultrafiltration (UF) membranes are increasingly employed in the food processing, biotechnology, and pharmaceutical industries, for municipal water and wastewater treatment, etc. Preventing microbial contamination of the filtered water (physical disinfection and sterile filtration) is integral to these applications. Improved design of MF and UF membranes can reduce microbial risk by physically removing pathogens as well as the dosage and contact time for chemical disinfectants, reducing cancer risk from disinfection by-products. Even though MF/UF membranes achieve only fractional virus and bacteria removal, the factors governing microorganism transport across them are not quantitatively understood. This lack of understanding, especially for non-spherical viruses and bacteria, necessitates conservative membrane design and implementation, increasing capital and operating costs.

This work is a collaborative effort between Ruth Baltus at Clarkson University and Shankar Chellam from the University of Houston. In our recent submission to *Industrial & Engineering Chemistry Research* [1] we describe results from short-term MF experiments that were performed to measure the removal of two Gram-negative bacteria (*Brevundimonas diminuta* and *Serratia marcescens*), two bacteriophages (PRD1 and T4), and several highly spherical silica particles in a stirred-cell under high axial Peclet number conditions before the onset of fouling. These (bio)colloids ranged from being highly spherical to rod shaped, with aspect ratio in the range 1–9. Track etch membranes with well defined capillary pores with a tight pore size distribution were used. Membrane rejection was characterized using the reflection coefficient, $\sigma$, which was determined from feed and permeate reservoir concentrations:

$$\sigma = 1 - \frac{C_{\text{permeate}}}{C_{\text{feed}}}$$

Experimental measurements for the removal of the silica particles and PRD1 viruses were in good agreement with theoretical predictions developed for spherical particles. This provides validation for the assumptions that permeate samples were collected prior to any membrane fouling and that concentration polarization was not significant in our experimental system. A comparison of our laboratory measurements for the non-spherical particles to predictions from a hindered transport model for rod-shaped particles developed by Anderson [2] is shown in Figure 1a.
Figure 1. Comparison of experimental results for rod-shaped microorganisms with theoretical predictions using the approach presented in ref. [2]. The aspect ratio of B. diminuta is 4, of S. marcescens is 3.4 and of B. diminuta long is 8.9 and that of T4 virus, based on the head diameter and the head plus tail length, is 2.7. In 2a, results are presented using the volume equivalent sphere diameter to characterize particle size. In 1b, results are presented using the rod diameter to characterize particle size. Pore sizes determined by porometry were used to non-dimensionalize microorganism size.

Anderson’s model considers the configurational restrictions experienced by a rod shaped particle within a pore of comparable dimensions. Hydrodynamic interactions between particle and pore wall are neglected. As shown in Figure 1a, theory predicts an increase in the reflection coefficient (better removals) as particle aspect ratio increases for fixed particle volume. Our experimental results are in contradiction to those predictions, with similar measured reflection coefficients for particles with a range of aspect ratios. Inherent in the model development is the assumption that particles sample all sterically allowed radial positions and are not carried through the pore along a limited number of streamlines. Typical radial diffusion times were considerably shorter than particle residence times in the pore, supporting the validity of this assumption. Another important model assumption is that all sterically allowed particle orientations are equally probable, an assumption that requires short times for rotational relaxation of the particles relative to axial transport times. Under the conditions of these experiments, rotational relaxation times were quite long, indicating that particles may become aligned with the flow rather than sampling all sterically allowed orientations at each radial position. In Figure 1b, the same experimental results are presented with the rod diameter as the characteristic particle size. Results are compared to theoretical predictions for a sphere. If the particles travel through the pore with an ‘end on’ configuration only, one would expect them to behave as spheres with the same diameter. The fact that the theory for spheres underpredicts the experimental observations indicates that the particles may be only biased towards an end on configuration. These results indicate that microorganism removal by membranes can be conservatively estimated using the rod diameter as the size parameter in hindered convection.
predictions, conclusions that are consistent with reports from other investigators [3-5]. However, the discrepancy between theory and experiment may also be due to the fact that hydrodynamic particle-pore wall interactions are neglected in Anderson’s model. Alignment of particles along streamlines as they enter the pore is also neglected in Anderson’s model.

Our future efforts with this project will focus on systematically and rigorously determining the influence of microorganism aspect ratio (=length/diameter) and the importance of axial and rotational Peclet numbers on transport. We will examine both purely diffusive transport as well as the filtration of numerous approximately rod-shaped viruses and bacteria across a range of pore sizes and transmembrane pressures using both track-etched and phase inversion membranes. A comprehensive model that incorporates Brownian diffusion and particle alignment with the flow will be developed.