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CFD analysis of the initial stages of particle deposition in spiral-wound membrane modules

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ABSTRACT

Particle deposition in a spiral-wound membrane module was simulated using computational fluid dynamics (CFD). A scheme similar to the Eulerian–Lagrangian numerical method was adopted for the two-phase flow simulation. The effect of curvature on particle transport in four spacer-filled channel configurations with permeable membrane surfaces was analyzed by considering the fluid drag, body force and lift force exerted on the particles. The numerical results showed that there are inherent changes in the particle deposition profile in the spacer-filled channel due to variations in curvature. Comparing the particle deposition profiles and deposition ratios for submerged, zigzag, i-cavity and o-cavity spacer-filled channels showed that, for a given feed velocity and permeation rate, the zigzag-type spacer is best at decreasing the influence of curvature and preventing particle fouling on the membrane. A microscopic understanding derived from the CFD analysis could improve module design and enhance membrane module performance.

1. Introduction

Computational fluid dynamics (CFD) has been widely used to simulate the hydrodynamic behavior of membrane separation processes using membrane modules [1–5]. A substantial body of literature exists for the spiral-wound membrane module because of its complex structure, which includes a feed spacer, membrane, permeable spacer and collection-tube. A spiral-wound membrane module has three types of flow paths: axial flow (along the feed spacer-filled channel, i.e., the z-direction), spiral flow (parallel to the permeate flow path, i.e., the θ-direction) and radial flow (toward the membranes, i.e., the r-direction).

A two-dimensional model has been used to analyze transport phenomena in the spiral-wound membrane module owing to simplify the simulation system. Cao et al. [6] used CFD to qualitatively observe the local wall shear stresses associated with different spacer configurations that have filaments adjacent to the wall. Schwinge et al. [7, 8] revealed the effect of three different spacer arrangements, including cavity, zigzag and submerged spacers, on the hydrodynamics and mass transfer. Their results showed that the zigzag spacer was the most efficient spacer type for the spacer-filled channel. Later, several theoretical studies used CFD to examine mass transfer and concentration polarization [8–12], particulate deposition on a flat channel with a permeable membrane surface [13] and unsteady flow phenomena [12,14-15] in a spiral-wound membrane module.

A three-dimensional CFD study of spacer geometries in spiral-wound membrane modules was performed by Karode and Kumar [16]. They used a laminar model to calculate the flow field in the spacer-filled channel, and the flow pattern and shear stress they obtained was used to qualitatively compare the performance of different spacers. To enhance the performance of spiral-wound membrane modules, new spacer designs have been studied [17–25]. Additionally, the appropriate cell types and periodic boundary conditions have been suggested based on a three-dimensional CFD analysis of spacer-filled membrane module designs with various spacer arrangements [26]. A new three-dimensional computational model that couples fluid dynamics, solute transport and biofouling via biofilm formation in spacer-filled membrane modules has also been described [27–28]. The numerical simulations showed that the biomass accumulation was due to attachment and biofilm growth over time. Biomass accumulation strongly affected the feed channel pressure drop, liquid velocity distribution and residence time distribution.

Fluid flow in a spacer-filled, curved channel has recently been investigated [29–30]. However, the authors focused on the flow path in the spiral-direction. Li and Tung [31] pointed out that although the outward appearance was similar to that of a spiral channel, the fluid in the spacer-filled channel displayed the axial flow. Their results showed that the curvature of spacer-filled channels affects the flow field in spiral-wound membrane modules. Using a two-dimensional numerical scheme, they also found that in a curved, spacer-filled channel, the shear stress on the inner wall is greater than that on the outer wall. In addition, three-dimensional CFD and an experimental set-up with a curved channel filled with a two-layer filament spacer were used to analyze the fluid flow in the channel [32]. Efforts to

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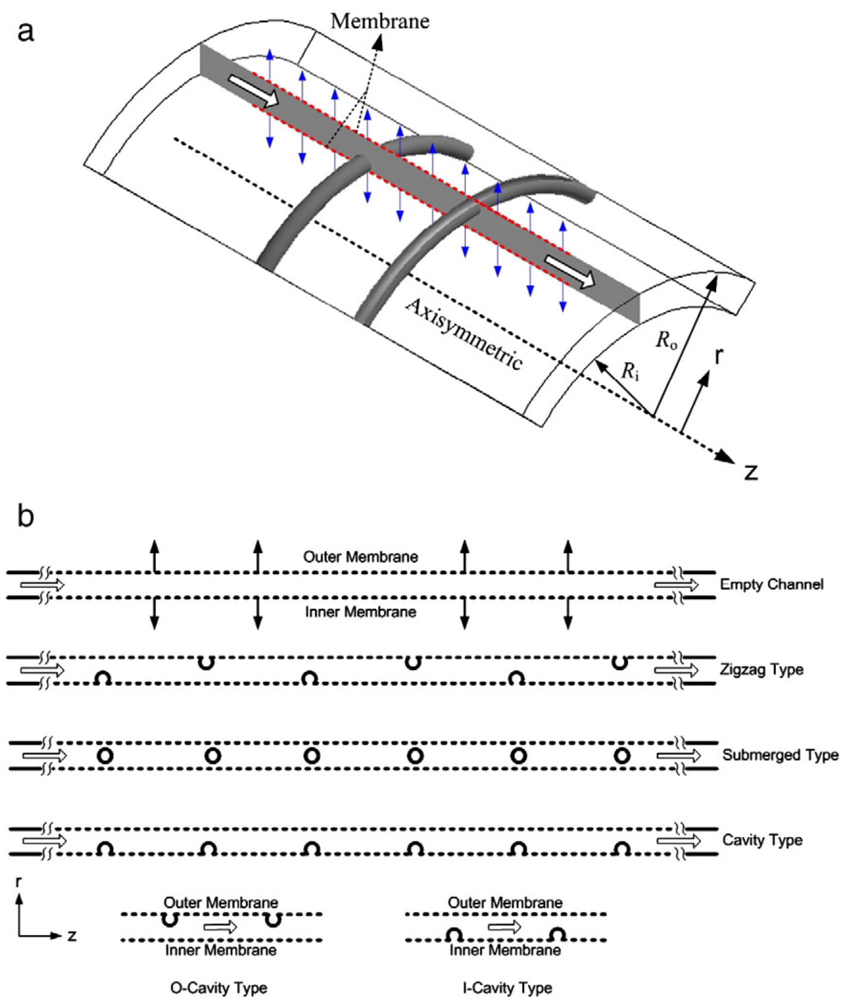

Fig. 1. The simulation systems: (a) the flow channel with permeable membrane surfaces, (b) the transverse filament configurations for the zigzag, submerged and cavity (o-cavity and i-cavity types) spacers.

mitigate the curvature effect in the spacer-filled channel of a spiral-wound membrane module have used a spacer with unequal filament diameters between the inner and outer layers. This type of spacer can be used to reduce the shear stress imbalance between the inner and outer walls and extend the service life of the membrane module.

In this work, the effect of curvature on particle transport in four spacer-filled channel configurations with permeable membrane surfaces was investigated using CFD. A scheme similar to the Eulerian–Lagrangian numerical method was used to model the fluid drag, body force and lift force exerted on the particles in a two-phase flow simulation of a spiral-wound membrane module.

2. Theoretical study

2.1. The simulated system

The simulation system for the spiral-wound membrane module is illustrated in Fig. 1(a). The feed channel with permeable membrane surfaces and various spacers, modeled by a flexible cylindrical fiber of circular cross-section, was assembled with two coaxial cylindrical tubes. Four different spacer configurations, submerged, zigzag, i-cavity and o-cavity, were used in this study, as shown in Fig. 1(b). The i-cavity and o-cavity types in the curved channel were named

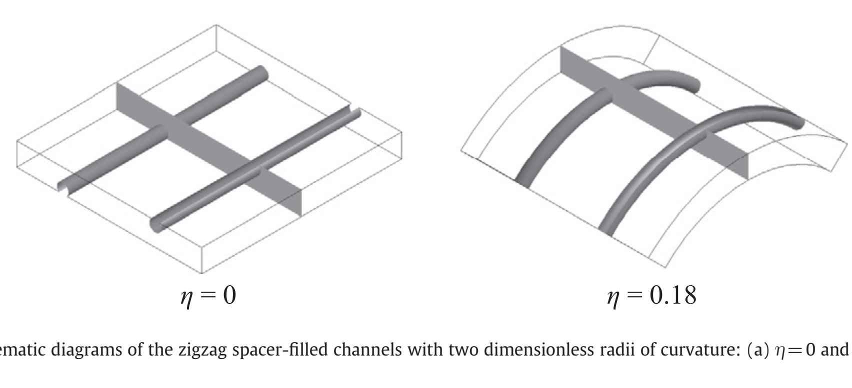

Fig. 2. Schematic diagrams of the zigzag spacer-filled channels with two dimensionless radii of curvature: (a) $\eta = 0$ and (b) $\eta = 0.18$.