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Mitigating the curvature effect of the spacer-filled channel in a spiral-wound membrane module

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ABSTRACT

This study optimizes the design of a spiral-wound membrane module by considering the curvature of the spacer-filled channel. A three-dimensional computational fluid dynamic (3D CFD) technique and an experimental set up with a curved channel filled with a two-layer-filament spacer were used to analyze fluid flow in the channel and the shear stress on the permeable membrane surfaces. Emphasis was placed on the relative size of the filaments between the inner and outer layers, as compared to previous studies that emphasized the characteristic angle toward the feed direction of the spacer, the diameter, the shape and spacing of filaments in the spacer, and the multi-layer arrangement of the spacer. Numerical results and experimental data show that there are inherent changes in the hydrodynamic behavior of the curved spacer-filled channel between the inner and outer permeable walls due to curvature variations. A spacer with unequal filament diameters between the inner and outer layers could be adopted to reduce the imbalance of shear stress between the inner and outer walls so as to extend the service time of the membrane module.

1. Introduction

Spiral-wound membrane modules have been widely adopted in water and wastewater treatment membrane processes due to the advantages of higher packing density achieved by wrapping the membrane assembly into a spiral roll and the higher shear rate induced by the spacer as compared to other modules using flat sheet membranes. The spacer acts both as a mechanical stabilizer for the channel geometry and as a turbulence promoter for the reduction of polarization phenomena near the membrane surface. The spacer was first introduced in the spiral-wound module at Gulf General Atomics with funding from the Office of Saline Research for desalination applications in the mid-1960s [1]. Although a spacer can suppress concentration polarization in the membrane module, it inevitably increases pressure loss along the feed channel. Several experimental and theoretical studies have focused on optimizing spacer configuration in order to extend the service time of the membrane module. Methods of optimizing spacer configurations reported in the literature include varying the characteristic angle toward the feed direction of the spacer, the diameter, shape and spacing of filaments in a spacer, and the multi-layer arrangement of a spacer.

Da Costa et al. [2] showed that a spacer with a characteristic angle of 80° had the minimum cost for the range of conditions studied, and they also showed a minimal cost under the specified feed concentration and flow rate. In addition, they found that the optimal net-type spacer configurations had a characteristic angle between 50° and 120° at low crossflow velocities and between 70° and 90° at high crossflow velocities [3]. Karode and Kumar [4] showed that asymmetric spacers resulted in a smaller pressure drop, and they also demonstrated an unequal shear rate on the top and bottom walls. The periodic boundary conditions of 3D-CFD have been widely used to observe flow and mass transfer in spacer-filled channels. Li and Tung [5] analyzed different cell types for periodic boundary conditions (PBCs) and suggested an appropriate cell type for three-dimensional CFD analysis of spacer-filled membrane module designs with various spacer arrangements. Li et al. [6,7] noted that the optimal spacer geometry was the configuration where the ratio of the distance between parallel filaments to the channel spacing equaled 4, the flow attack angle equaled 30°, and the angle between crossing filaments equaled 120°. Their CFD simulation results agreed well with experiments using an electrochemical limiting current measurement method.

Schwinge et al. [8,9] investigated the effect of three different spacer arrangements, namely, cavity, zigzag and submerged spacer arrangements, on hydrodynamics and mass transfer. Their results showed that the zigzag spacer was the most efficient spacer type for a spiral-wound membrane module. Li et al. [10] also discovered this phenomenon by particulate deposition on the membrane surface

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when using the CFD technique. In addition, Ahmad et al. [11] studied the effect of three different spacer shapes (circular, square and triangular) on mass transfer and concentration polarization. Based on their results, the square and circular filaments illustrated the highest degree of concentration minimization for low flow rates, while the circular filament was recommended for energy minimization at high flow rates. Dendukuri et al. [12] also found that new designs of spacers would be able to maintain strain rates near the wall surface and reduce the pressure drop across spacer-filled channels.

The conventional spacer was usually made of two layers of filaments. Schwinge et al. [13] suggested that an advanced three-layer spacer (A3LS) could support more than 20% higher flux when compared with the two-layer spacer under fouling conditions. In addition, the outer layers with optimal non-woven nets and twisted tapes in the middle-layer were designed to form a novel optimal multi-layer spacer. At the same power consumption, the average Sherwood number was found to be greater than that of the optimal non-woven spacer [14,15]. However, these optimal conditions were studied based on flat channels. As illustrated in Fig. 1(a), the flow behavior in the spacer-filled feed channel is similar to that in an annulus tube. Optimization of a spiral-wound membrane module has never considered the effect of the curvature of the spacer-filled channel.

Recently, Li and Tung [16] noted that although the outward appearance is similar to that of a spiral channel, a spiral-wound membrane module has three types of flow paths: the axis flow (along the feed spacer-filled channel, *i.e.*, the z-direction), the spiral flow (parallel to the permeate flow path, *i.e.*, *the* θ-direction) and the radial flow (toward the membranes, *i.e.*, the r-direction), as shown in Fig. 1(b). Their results indicated that the curvature of a spacer-filled channel affected the flow field in spiral-wound membrane modules. Their study further showed that the shear-stress of the inner-wall was more than that of the outer-wall in a curved spacer-filled channel with a two-dimensional numerical scheme.

In this study, the spiral-wound membrane module has been optimized by considering the curvature of the spacer-filled channel. A three-dimensional CFD technique and an experimental set up with a curved channel filled with two-layer filament spacer were used to analyze the fluid flow in the channel and the shear stress on the permeable membrane surfaces. The relative size of the inner and outer layer filaments was emphasized to achieve maximum extension of the service time of the membrane module.

2. Theoretical analysis

2.1. The simulation system

The flow field in the channels was calculated using the commercially available CFD software FLUENT. The appropriate cell type for periodic boundary conditions (PBCs) [5] in CFD analysis was used

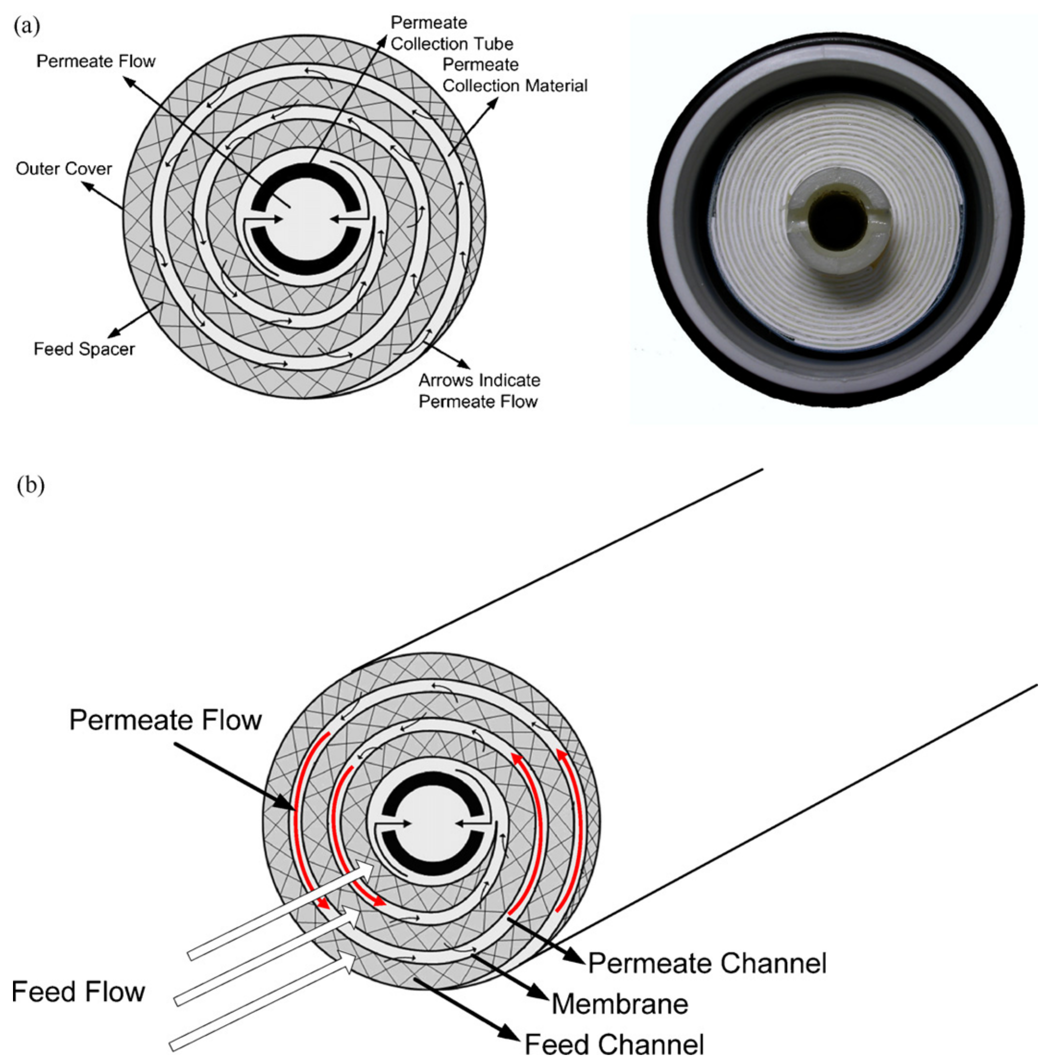

Fig. 1. (a) Cross-sectional view of a spiral-wound membrane module. (b) Types of flow paths in the spiral-wound membrane module.