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A conceptual design of spacers with hairy structures for membrane processes

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ABSTRACT

The development of membrane technology requires spacers that can significantly enhance the mass-transfer rate while avoiding a severe pressure drop across the membrane module. A potential solution to this challenge is to introduce some flexible and dynamic structures into the spacer mesh. The current work was motivated to explore a conceptual design of spacers with hairy structures. The hairy structures were simulated using highly flexible nylon fibers that were fixed on a well-designed framework. The effects of fiber asymmetry and spacing on the vibrations were discussed in terms of the observations via a high speed camera. A variety of spacer prototypes were employed in a forward osmosis process to examine the performance of the hairy structures. The experimental results indicate that fiber vibrations could have a great impact on the mass transfer in the vicinity of the membrane surface and enhance the filtration flux (up to ~20%). This fundamental study not only provides insight into the mechanisms underlying the complex fiber-flow interactions but also charts the direction for future hairy spacer design.

1. Introduction

The filtration performance of a spiral wound module (SWM) can be significantly affected by the spacers. They not only define the space between the membrane leaves, but also play a role as a turbulence promoter (some studies refer to them as an eddy promoter since the flow may not be fully developed [1,2]). Schwinge et al. indicate that the spacer in a fluid channel can intensify the mass transfer, thereby mitigating the negative effects caused by the concentration polarization (CP) and membrane fouling [2]. It is of primary importance to optimize conventional spacers and design novel structures for better filtration performance. Indeed, if potential improvements in membrane permeability are to be translated into higher fluxes, it will be necessary to develop spacers with better mass-transfer performance.

Early studies of spacer-filled modules concentrated on investigating the effects of the basic geometrical characteristics (e.g., mesh size, filament thickness, spacer orientation, etc.) of conventional spacers on the pressure drop and mass transfer [3–5]. These studies were further refined by advanced approaches based on computational fluid dynamics (CFD) [1,6–14] owing to the development of computational technologies. With the aid of CFD-based simulations, deeper insight was obtained to reveal the complex hydrodynamic environment in spacer-filled channels and to optimize the basic geometrical characteristics for better performance. Some novel experimental approaches were also developed to visualize the secondary flows caused by the spacers. For example, Willems et al. [15] employed particle-imaging velocimetry (PIV) to investigate the planar velocity distribution in spacer-filled channels; Gao et al. [16] developed a characterization technique based on optical coherence tomography (OCT) that is able to obtain the depth profiles of the fluid field in a unit spacer cell. As more knowledge about conventional spacers was obtained, researchers began to design novel spacers with modified structures for further enhancing filtration performance.

The modifications were initially made by changing the geometry of the filaments. Most of these ideas were borrowed from the spacer designs for heat exchangers, such as twisted tapes [17,18]. Several novel designs specific for the spacers used in a membrane module were also reported in the past decade. For example, Schwinge et al. [19] added an additional layer of filaments into the conventional spacer mesh that consists of filaments

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crossing each other in two directions. The idea of this design is to reduce the void space in the fluid channel without increasing the membrane area covered by the spacer. Spacers with multilayer structures were studied by researchers from the University of Twente [20,21]. In contrast to the designs for generating more vortices in the fluid channel, these designs were aimed at optimizing the distribution of the vortices. This is realized by sandwiching a spacer with normal or modified filaments between two thinner spacers that contact the membrane surface in a more intimate manner; the middle layer diverts the bulk flow to the channel walls while the outer layers generate eddies in close proximity to the membrane surface.

Although these modified spacers are able to markedly enhance the mass transfer, they inevitably increase the pressure drop through the membrane module, thereby resulting in higher energy consumption. Studies of spacer design [22] have rarely reported a higher mass-transfer coefficient while avoiding a significant increase in the pressure drop. Xie et al. [23] recently employed sinusoidal spacers in reverse osmosis (RO) processes, which were originally designed for heat exchangers [24]. It was expected that the sinusoidally shaped channels could reduce the hydrodynamic resistance owing to the smoother paths. However, a marked increase in the pressure drop was observed when the amplitude of the sinusoidal curve was increased and the wavelength was shortened to some critical values.

An interesting phenomenon in nature is that some organisms growing in flowing water usually develop flexible bodies that help them minimize hydrodynamic drag forces by deforming into a more streamlined shape. This is like a tree that bends itself in a strong wind. The underlying mechanisms of these phenomena that are related to the drag reduction through self-similar bending of a flexible body were experimentally and theoretically studied by Alben et al. [25] (a summary of their work is given by Steinberg [26]). Flexible structures usually undergo severe vibration (or flapping) due to the complex fluid–structure interactions as shown by several studies [27–30]. Taherzadeh et al. [31,32] studied the behavior of the streamers in a biofilm and demonstrated that the oscillatory movement of the streamers is beneficial to the mass

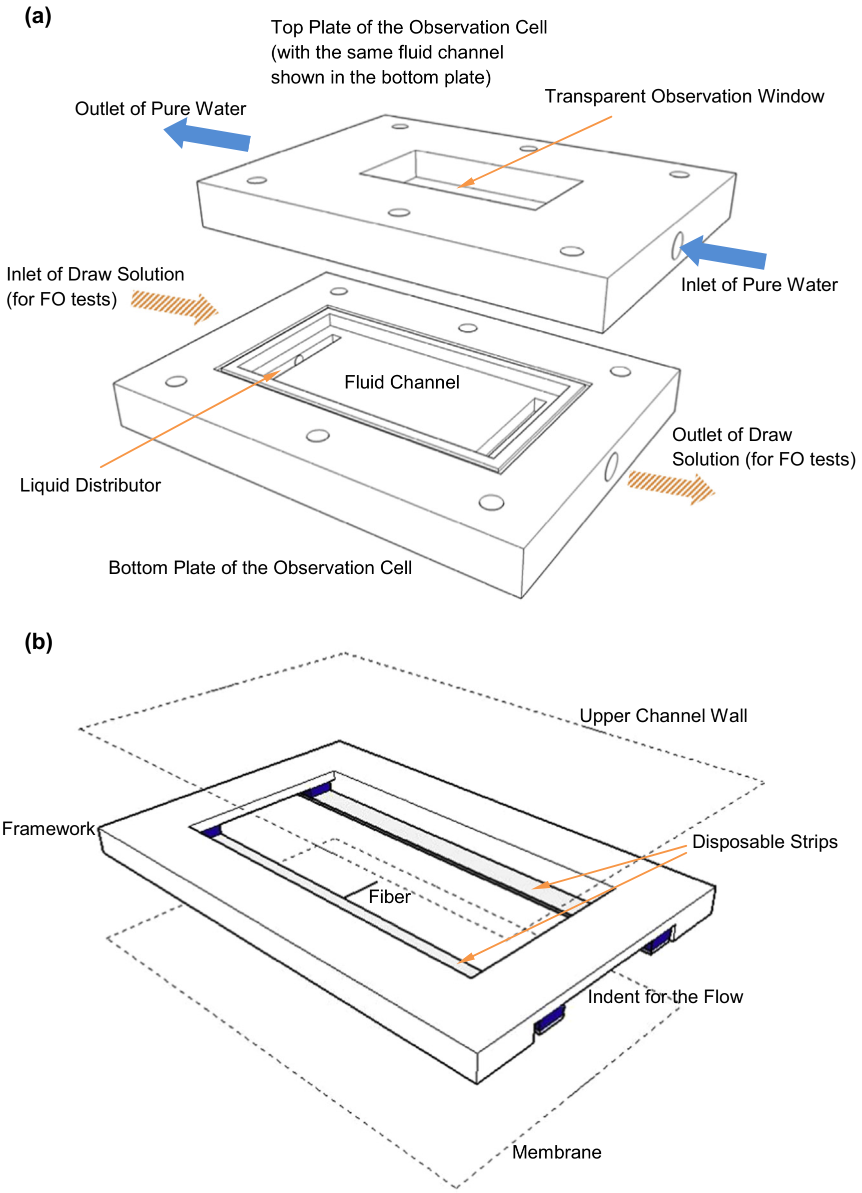

Fig. 1. Schematic of the dual function cell for the vibration characterization and FO filtration: (a) the structure of the top plate (with the observation window) and the bottom plate; (b) the framework for fixing the fibers. Both plates have a fluid channel with the same geometry.