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Wall proximity effects on flow over a simple membrane spacer

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ABSTRACT

Spacer-filled channels are employed in membrane modules in many industrial applications where feed-flow spacers (employed to separate membrane sheets and create flow channels) tend to enhance mass transport characteristics (and possibly) mitigate fouling and concentration polarization phenomena. In this work direct numerical simulation was performed for the flow in spacer-filled channels to obtain a better understanding of fluid flow phenomena in these assemblies. Reynolds numbers of 300, 500 and 800 were considered. The effect of spacer location was also studied for three different configurations: spacer at the centre of the channel, off-centre, and attached to the wall. Instantaneous velocity fields and flow structures, such as boundary layer separation on the walls and on the cylinder, eddies on the walls, recirculation regions and vortex shedding were investigated. A Fourier analysis was carried out on the time series velocity data. Using this analysis the Strouhal number was calculated and the development of the flow towards a broader turbulent state at higher Reynolds number was captured. Other statistical characteristics such as time-averaged velocities and wall shear rates are obtained and discussed. The average pressure loss was calculated for the channels and found to be highest for spacer at the centre of the channel and lowest for spacer attached to the wall.

1. Introduction

Membrane technology is employed in separation, filtration and electricity production. The separation of species in a solution is accomplished by applying driving forces such as gradients in pressure, temperature and electrical potential. In pressure-driven membrane separation, solute passes across a semi-permeable wall and the feed flow is separated into permeate and retentate. Microfiltration (MF); ultrafiltration (UF); reverse osmosis (RO); gas separation; electrodialysis and pervaporation are different types of such processes. Also blood oxygenators, artificial kidneys, and controlled release of drugs are other examples of membrane processes [1].

Microfiltration, ultrafiltration, reverse osmosis, and conventional filtration differ in the average pore size of the membrane material. Microfiltration and ultrafiltration are similar in that the mode of separation is molecular. In reverse osmosis membranes, the membrane pores are so small that they are within the range of thermal motion of the polymer chains that form the membrane. The mechanism of transport through these membranes is explained using the solution–diffusion model. According to this model, solutes permeate the membrane by dissolving in the membrane material and diffusing along a concentration gradient. Separation occurs because of the difference in solubilities of different solutes in the membrane.

The three commonly used configurations in membrane modules are capillary-fibre, hollow-fine fibre and spiral-wound modules. Plate-and-frame and tubular types are also used, however due to the high manufacturing cost, their application is usually limited to small-scales. Spiral wound modules (SWM) and hollow fibre modules are the most common types in industry. SWMs are often preferred due to a good balance between permeation rate, ease of operation and packing density [2].

In membrane separation processes, a fluid mixture passes across the feed side of the membrane, and part of that is transferred to the permeate which is enriched in one of the components of the mixture. In this process, unless the solutions are well mixed, concentration gradients form in the fluids on both sides of the membrane because the feed mixture components permeate at different rates. This phenomenon is called concentration polarization. A layer of solution adjacent to the membrane wall becomes enriched in the permeating component on the permeate side and diluted in the permeating component on the feed side. Thus, the flux decreases because the concentration difference of the permeating component is reduced across the membrane. In addition, membrane fouling is a process by which solute or particles deposit onto a membrane surface or into membrane pores so that the performance is degraded by higher resistance to the solvent.

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In membrane modules, spacers are employed to prevent adjacent membrane walls from contacting and sticking together. The spacers may also promote mixing and instabilities by disrupting fluid flow in the module channels. This may decrease concentration polarization and fouling tendencies in SWMs. However, the existence of spacers in the modules also increases the pressure drop along the feed channel and therefore increases the unit operation costs. Some researchers and SWM producers try to optimize the performance of modules with new spacer designs. Such spacers for spiral-wound modules have the form of net-like arrangement of filaments aligned parallel with, transverse to or at an angle to the module axis.

The wide range of membrane module applications in industry has motivated researchers to study flow in spacer-filled channels using numerical analysis and/or experimental methods to study the hydrodynamics and heat and mass transfer processes so as to improve the performance of the modules, see for example [3].

Yuan et al. [4] indicated that for duct flow and heat transfer, entrance effects are shorter than for flows without the disturbances. Therefore the heat and fluid flow become fully developed after a few repetitions of the periodic section, depending on the Reynolds and Peclet numbers. A membrane module channel may consist of hundreds of repeating sections, the analysis of a single section can give a clear picture of the transport phenomena of the module. This is done by simulating a "unit cell" with periodic boundary conditions.

Patankar et al. [5] proposed a method for obtaining a periodic temperature and velocity field, this method performs an iterative solution of the flow field by decomposing the pressure into a linear and a periodic component and reapplying the outlet flow variables and their gradients at the inlet of the unit cell. In this method constant fluid properties must be assumed.

The proper choice of boundary condition for simulation of membrane walls was considered in some studies. Geraldes and Afonso [6] showed that the permeate velocity through the membrane walls is some orders of magnitude smaller than the velocity of the bulk fluid in the channel for nano-filtration and RO processes, therefore for simulations the velocity can be assumed to be zero on the membrane walls when chemical reactions are not involved.

To optimize spacer design, Schwinge et al. [7–9] performed two-dimensional numerical simulations of flow and mass transfer in narrow spacer-filled channels for SWMs. The simulations were carried out for laminar, steady and unsteady flow in the range Re = 90–2000 (based on the hydraulic diameter and the bulk velocity). They changed the distance between the spacers and the diameter of the spacers for three different configurations namely cavity, zigzag and submerged. The characteristics of the flow in terms of wall shear stress, mass transfer and pressure drop were investigated for each configuration.

Koutsou et al. [10] performed calculations for laminar unsteady flow around an array of cylindrical spacers in a channel, employing periodic boundary conditions. They performed two dimensional simulations for $174 \leqslant Re_h \leqslant 633$ and investigated the effect of Reynolds number on flow transition to chaotic states, pressure drop and wall shear stress.

While two-dimensional analyses have provided insight into the interactions between the fluid flow and mass transfer, SWMs in practical applications are 3D. To illustrate this, Iwatsu et al. [11,12] simulated and analyzed the flow in a 3D cavity with a moving top wall, this work demonstrated the differences that exist between 2D and 3D flows. It was found that at low Reynolds numbers the flow on the vertical symmetry plane is similar to the flow obtained from 2D simulation. However, for Reynolds numbers above 800 (based on the velocity of the moving wall and the cavity height), the 3D simulation cannot be extrapolated from the characteristics of the 2D flow and the differences are more important.

Kumar and Karode [13] performed the first 3D simulation of steady laminar flow for ($225 \leqslant Re \leqslant 2225$, based on bulk velocity and hydraulic diameter of the channel of fluid flow around commercial spacers in membrane modules. A unit cell was considered of 2.01 mm height, 25 mm wide and 35 mm long to evaluate the effectiveness of spacers. Pressure drop and shear stress on the membrane surfaces were used as measures of this effectiveness. The spatial resolution of the simulation was low and mass transfer was not considered in their study. It was determined that the bulk of the fluid followed a zig-zag path through spacers that possessed a large inter-spacer distance to spacer diameter ratios.

Ranade and Kumar [14] employed a periodic unit cell to simulate rectangular and curvilinear spacer-filled channels. It was noted that the curvature of the channels, unlike the shape of the spacer, did not affect the flow behaviour significantly. However, Li and Tung [15] found different performance on the inner and outer walls in a curvilinear spacer-filled channel and therefore recommended using spacer diameters along the inner walls that were larger than those on the outer walls so as to mitigate the unequal shear stress distribution on two membrane walls.

Koutsou et al. [16] employed direct numerical simulation with periodic boundary conditions to investigate three dimensional spacers in the steady and the unsteady flow regimes. The flow attack angle, thickness and spacing between spacers were equal for top and bottom spacer for all cases. Flows with Reynolds numbers between 35 and 300 (based on cylinder diameter and bulk velocity) were considered. Unlike two-dimensional flow, in three dimensions the flow does not move in closed streamlines but in spiral paths along the spacers. They found a central free vortex and the interaction of this vortex with the vortices adjacent to the spacers created some closed recirculation regions. Transition to unsteady flow at Reynolds number within the range from 35 to 45 were reported.

In addition to numerical work, researchers have employed experimental methods to investigate the flow in spacer-filled channels. Kang and Chang [17] reported that the critical Reynolds number at which flow becomes unsteady varies with the geometric characteristics of the system. As Re is increased the flow regime changes from steady laminar with recirculation to a vortex shedding regime.

Belfort and Guter [18] investigated the effects of spacers on fluid dynamics and mass transfer. They recommended that an efficient spacer must generate as few regions of stagnant flow as possible and must enhance mixing without significantly increasing the pressure drop.

While in the current work mass transfer is not considered, it is useful to review briefly the relevant literature that included this additional transport phenomena. Kim et al. [19] found that the use of spacers in a channel causes the flow to recirculate in regions close to the concentration boundary layer and therefore can increase the mass flux from the walls. Other researchers [20,21] concluded that the interaction of the wake behind the spacer with the boundary layer on the membrane surface with the concomitant increase in viscous friction on the walls improves the overall mass transfer in membrane modules. Da Costa et al. [22] found that by employing spacers, mass transfer may be enhanced between 3 and 5 times compared with an empty channel but that pressure losses also increased between 5 and 160 times. It was also found that by varying the characteristic angle of the spacer the mass transfer enhancement is improved significantly. Recently, Beale et al. [23] presented results for flow and mass transfer calculations for in-line spacer configuration at low Reynolds number. Gimmelshtein and Semiat [24] used two dimensional particle