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Simplified CFD approach of a hollow fiber ultrafiltration system

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Abstract

Pressure driven membrane filtration processes have emerged as cost effective and confirmed technologies. Ultrafiltration is used to produce drinking water. Hollow fiber membranes are used in industrial processes but there is still a need of predicting pressure drops for design and optimization purposes: to control the production of water, to anticipate problems such as the clogging of the hollow fibers and/or the module position and to consider energy consumption. This prediction could also enhance current models that calculate pressure drop using the Hagen–Poiseuille law. In this work, the flow characteristics controlling the performance of a hollow fiber membrane module are investigated numerically. The aim of this study is to determine the pressure drop in a module depending on the operating conditions and membrane characteristics: a simplified model equation is proposed. We use a commercial CFD package (FLUENT). Numerical simulation can provide a better understanding of module performance, especially for permeable wall and/or complex multi-component systems. CFD can be used to better apprehend fluid flows in complex geometries and to test the influence of process parameters. The results are compared to experimental data obtained with an industrial pilot plant: a good agreement with our relation is obtained.

Keywords: Computational fluid dynamics; Hollow fiber; Pressure drop; Model; Ultrafiltration

1. Introduction

Ultrafiltration is a pressure driven membrane process that can be applied to a wide variety of fields: chemical industry, food technology, pharmaceutical industry and water treatment. One of the most important ultrafiltration design is the hollow fiber configuration. Some advantages of this geometry are the low cost of investment and the high specific area unit per volume. A high number of applications have proved that membrane processes are economically attractive and useful [1]. However, problems such as membrane fouling and concentration polarization phenomena limit the use of these membrane processes, because they reduce permeate fluxes, membrane life and efficiency and they have economic repercussions [2]. The membrane can be plugged or broken, which creates disturbances in the process. These problems also impose major limitations on the application and development of membrane processes. In this paper, we present a detailed model that describes ultrafiltration membranes. Numerical simulations were run to represent the phenomenon. Various simulations were run to show the flexibility of the relation developed in this work for a wide range of inlet velocities, inlet pressures, internal diameters, permeabilities and Reynolds numbers. This simplified relation represents the flow mechanism in the module and allows the calculation of the pressure drop for all the configurations. These results were compared to experimental results.

2. Previous study

The modelling of flow with permeable walls is not recent. Several diversely complex studies started emerging a long time ago. Berman [3,4] and Yuan and Finkelstein [5] were the first to solve the Navier–Stokes equations for a laminar flow in a porous slit and in a porous tube, respectively. They assumed that the axial flow was fully developed and that the shape of the non-dimensional velocity profile was invariant with the axial distance. In order to better understand the problems of membrane processes, it is necessary to describe laminar flows in porous tubes. One of the common ultrafiltration membrane designs is the hollow fibber module in which the membrane is formed on the inside of small polymer cylinders that are then ranged in a carter as shown in Fig. 1. For example, ultrafiltration

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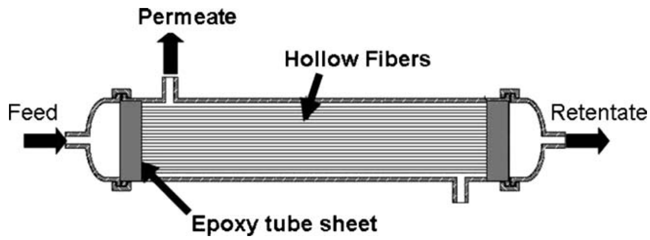

Fig. 1. Hollow fiber module.

permeates fluxes are mostly analysed using different models: the gel polarization model [6–8], the mass transfer model [9], the osmotic-pressure model [10,11] or the resistance-in-series model [12,13]. The main problem with these models is that they calculate the pressure drop along the membrane using the Hagen–Poiseuille law. This method results in a considerable approximation that could be an important error because the walls are considered as impermeable. There is a significant difference between the results obtained with the Hagen–Poiseuille equation and our results, more particularly for high permeability coefficients. The pressure drop in the membrane could be more than three times higher than the values calculated considering the wall as impermeable. This consideration affects the results of these models. Numerous efforts have been made to model membranes using the CFD approach. Commercial packages are frequently used and the method often consists in resolving the Navier–Stokes and continuity equations for a 2D or 3D steady, laminar flow of an incompressible homogeneous and Newtonian fluid. That is why many recent works have associated membrane processes and computational fluid dynamics [14]. Using CFD, Caroll studied the effect of the properties of the cake and of the fibers on flux declines in hollow fiber microfiltration membranes [15]. The author developed a model for hollow fiber membranes incorporating cake compressibility and demonstrated that the properties of the cake and of the fibers had an effect on the flux decline. Agashichev and Falalejev [16] developed a model giving a quantitative correlation for longitudinal pressure profiles. Their model allows the analysis of the influence of the tangential velocity, transmembrane flux and intrinsic rheological properties of the fluid and channel geometry on the configuration of the pressure profile. Their model, combined with auxiliary sub-models, was segmented and built in algorithm for the longitudinal calculation of the driving force and transmembrane flux. This model is not easy to use, many dimensionless parameters and approximations are involved. On the other hand, Chatterjee et al. [17] developed a numerical solution to model the performance of a radial flow hollow fiber reverse osmosis module. They clearly showed that the two-parameter models used by Sekino [18] may not be adequate for precise design and analysis of many solute–membrane systems. Damak et al. [19] showed that both high axial Reynolds numbers and high Schmidt numbers lead to a decrease in the thickness of the local concentration boundary layer:

$$Re = \frac{\rho v d}{\mu} \tag{1}$$

with ρ the density (kg m^{-3}), v the velocity (m s^{-1}), d the internal diameter (m) and μ is the dynamic viscosity (Pa s):

$$Sc = \frac{\upsilon}{D} \tag{2}$$

with υ the kinematic viscosity (m^2 s^{-1}) and D is the mass diffusivity (m^2 s^{-1}).

In addition, the evolution of the thickness of the local concentration boundary layer for a given wall Reynolds number depends on the values of the Schmidt number and of the axial Reynolds number near the wall:

$$Re_{\mathrm{w}} = \frac{\rho v_{\mathrm{w}} d}{\mu} \tag{3}$$

with v_{w} the wall velocity (m s^{-1}).

Many authors have tried these processes to model with the maximum of accuracy. Nassehi [20] proposed a general technique for linking the free flow modelled using the Navier–Stokes equations to the flow that passes through the membrane described by the Darcy equation. It can be regarded as the first step towards creating a complete model for cross-flow filtration. Damak et al. [21–23] also worked on this subject and they succeeded in modelling the concentration-polarization phenomena along the membrane under a wide range of operating conditions. Furthermore, numerical simulation can also be used to develop the mass transfer correlation in radial flow hollow fiber modules. In our work, the flow characteristics that control the performance of a hollow fiber membrane module are investigated numerically. The aim of this work is three-fold: determining the pressure drop in a hollow fiber ultrafiltration module under several operating conditions and investigating the effect of various physical parameters on the pressure and velocity profiles along the membrane surface. We propose a simple relation that can estimate the pressure drop as a function of operating and design parameters (permeability, inlet velocity, inlet pressure, channel diameter, etc.). Using the relation, we can deduce the number of clogged fibers and thus control the process. Our work should help to improve the design of the hollow fibers, to anticipate problems such as the clogging of the hollow fibers and/or the module position and to control water production. As a consequence, our work can be used to improve the previous mass transfer models that used the Hagen–Poiseuille law. A good agreement was achieved between the results obtained with our numerical simulation and experimental results.

3. Numerical simulation

In this study, we worked with a commercial CFD package called FLUENT, which is used to simulate the fluid flow in current geometries and to test the influence of the process parameters. The mathematical model consists in solving the Navier–Stokes and continuity equations for a steady, laminar flow of an incompressible homogeneous and Newtonian fluid. In our case, a laminar, incompressible, viscous and isothermal flow in a cylindrical tube with various permeable walls was considered. The geometry considered was axisymmetric (Fig. 2). The simulated domain was 1.3 m in length and up to 2 mm height.