Chemical Engineering Science 163 (2017) 215–222

Contents lists available at ScienceDirect

Chemical Engineering Science

journal homepage: www.elsevier.com/locate/ces

The role of fouling in optimizing direct-flow filtration module design

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HIGHLIGHTS

- A direct-flow filter comprises a series of hollow fibers packed into a single device.
- The transmembrane pressure distribution in each fiber affects the filter performance.
- The pressure evolves with time due to pore clogging by contaminants.
- We evaluate the optimum inter-fiber spacing that maximizes the fluid processed.
- Significant improvements can be made through careful choice in the fiber spacing.

ARTICLE INFO

Article history:
Received 6 October 2016
Received in revised form 20 December 2016
Accepted 19 January 2017
Available online 31 January 2017

Keywords:
Membrane
Filtration
Fouling
Hollow fiber
Module design

ABSTRACT

The local transmembrane pressure (TMP) distribution plays a crucial role in the performance of hollow-fiber microfiltration and ultrafiltration membrane devices. A direct-flow filter comprises an array of hollow fibers encased within a single module. The TMP in each hollow fiber is dependent on the spacing between neighboring fibers, and evolves with time due to pore clogging by contaminants (fouling). We consider an idealized set-up in which the fibers are undeformable and equally spaced within the device, and study the impact of the pore-blocking phenomena on the TMP during the filtration process. The model is used to evaluate the optimum inter-fiber spacing that maximizes the fluid processed either after a prescribed time or before the filter blocks and its dependence on the membrane permeability and the fouling rate. We show that significant improvements can be made on the operating efficiency of a direct-flow device through careful choice in the fiber spacing during fabrication.

1. Introduction

The design of filtration modules is key to membrane technology: the performance and economics of a membrane process is dependent on the art and sophistication of the device manufacture (Ho and Sirkar, 2012). As a result, exploring the scope of module design optimization for commercial exploitation of membrane systems has become increasingly important (Sutherland, 2003; Belfort, 2012). The filtration technique may be classified by a series of methods. In classical dead-end filtration, the flow and filtration direction both occur normal to the membrane surface. However, in cross-flow filtration the feed flows parallel to the surface of the membrane with fluid filtration occurring normal to the flow (Noble and Stern, 1995). Each filtration technique has its merits and downfalls. Cross-flow filtration is the *de facto* method when processing high volumes of fluid. However, it is complex in operation and capital intensive. On the other hand, dead-end filtration is straightforward to implement but cannot compete when it comes to processing high volumes of fluid or high contaminant concentrations. Direct-flow filtration offers an efficient combination of the benefits of both dead-end and cross-flow filtration. This is achieved by capping the end of a crossflow device so that all the fluid is forced to pass through the walls. Direct-flow filtration offers superior performance in situations where low contaminant concentrations as well as moderate fluid volumes are processed and the product quality as well as simplicity is preferred, such as in applications related to bio-pharmaceuticals, virus separation and sterile filtration.

The main quantity of interest in any filtration scenario is the rate at which fluid is processed, or the *throughput*. This increases with transmembrane pressure (TMP) and filtration area. In a typical industrial application, the filtration area in a direct-flow device is increased by bundling together many hollow fibers with porous walls, or *lumen*, into a single cartridge whose end is blocked, so the inlet is through the hollow-fiber core and the outlet is across the porous wall (Fig. 1a). However, if the fibers are packed too closely

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http://dx.doi.org/10.1016/j.ces.2017.01.043

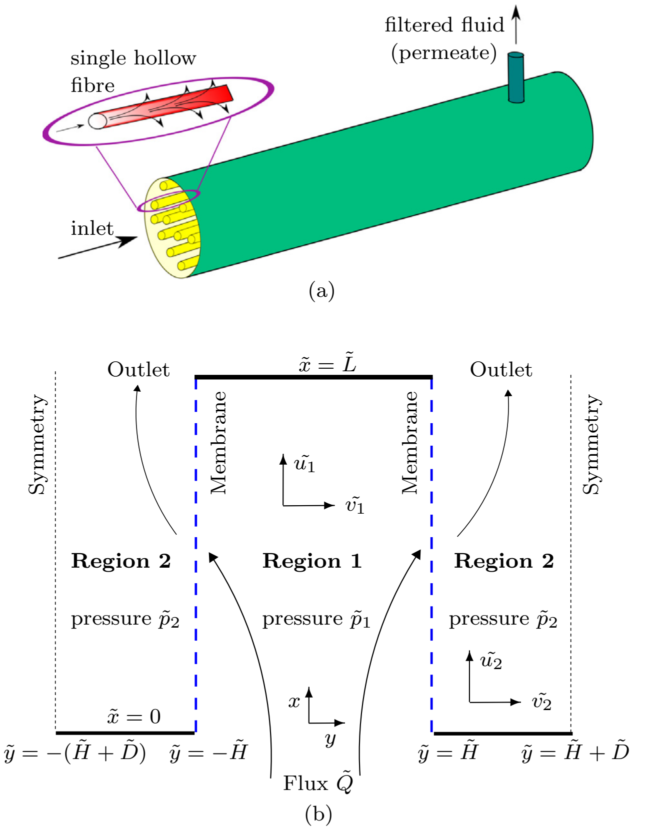

Fig. 1. (a) Schematic of a hollow-fiber direct-flow filtration device. Multiple permeable fibers are encased within a single unit. (b) Schematic of the flow within a single hollow fiber. The solid lines denote impermeable walls, the blue dashed lines are permeable membrane walls, and the dotted lines indicate symmetry in the flow. Flow enters from the bottom and passes through the permeable walls. Beyond the capped end the fluid continues to an outlet following the black arrows. The inside of the membrane-walled channel is denoted by Region 1 and outside is Region 2. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the TMP across significant proportions of the fiber walls is reduced. As a result, despite the increased membrane area, continuing to pack in more fibers causes the overall rate of fluid processed by the device to fall (Karode, 2001; Herterich et al., 2016). A key question to ask is thus how many fibers should we pack into a single cartridge to maximize the overall fluid processing rate (Pearce, 2011)?

A mathematical model of the direct-flow process has been proposed by Hurwitz (1989) by considering the fluid transport inside a single porous tube with a capped end. The flow was determined in the asymptotic limits of low permeability and low Reynolds number. The effect of deposition of the particles on the surface in a single hollow-fiber dead-end filtration set-up has been examined (see, for example, Chang et al., 2006; Serra et al., 1998), while the blocking behavior in a membrane when channels are packed adjacent to one another has also been investigated (Sanaei et al., 2016). While emphasis has been placed on the spatio-temporal distribution of the local pressure as a function of the length and diameter of the fibers, the effect of the proximity of the neighboring tubes was not considered.

Herterich et al. (2016) focus specifically on the variations in TMP in a direct-flow device by accounting for neighboring fibers, and show that a packing fraction that maximizes the processed fluid exists. Here the membrane permeability is assumed to be uniform and unchanged as the fluid is filtered. In practice, however, as time progresses the membrane will become blocked due to the particles that become trapped within. This reduces the wall permeability and thus the ease with which subsequent fluid may be processed. Furthermore, since the flow across the membrane varies with axial position this will lead to spatial inhomogeneities in the wall permeability. When operating at a fixed pressure difference across the device the effect of this membrane blocking, or *fouling*, presents itself through a continual decline in the rate at which the filtered fluid is generated. Such fouling behavior poses significant additional complications when addressing the question of how best to arrange the hollow fibers within a direct-flow device.

In this paper we develop a mathematical model to determine the optimum fiber packing criteria taking into account the membrane fouling due to particle clogging with filtration time. We discuss what is meant by efficiency in a direct-flow device and show that this is not necessarily determined by a single measurable outcome. We identify a family of metrics that are able to classify system optimization for a given filtration challenge, and show how the results are affected by the blocking behavior.

2. Model development

2.1. Set-up

A direct-flow device is composed of a series of fibers packed within a larger vessel (Fig. 1a). For simplicity we consider a slice through such a device, analyzing an analogous two-dimensional problem. (Such an assumption has been justified in Herterich et al. (2016).) We consider fluid entering a single 2D channel, of length $\widetilde{L}$ and width $\widetilde{H}$, with porous walls of permeability $\tilde{\kappa}$, and a capped end (Fig. 1b). We use a Cartesian coordinate system $(\tilde{x}, \tilde{y})$ to represent the system, where $\tilde{x}$ denotes the distance along the channel and $\tilde{y}$ the direction perpendicular to the permeable channel walls.

Fluid enters the channel (Region 1) and passes through the membrane side walls into the permeate region (Region 2). The flow in Region 2 is influenced by the proximity of the surrounding channels in the direct-flow device. (For a single channel Region 2 would be a quiescent bath.) Since the end of the channel is blocked, all of the fluid must eventually flow from Region 1, through the permeable walls, into Region 2. We consider an array of channels with a center–center separation $2(\widetilde{H} + \widetilde{D})$ and so impose a symmetry condition at $\tilde{x} = \pm(\widetilde{H} + \widetilde{D})$. This symmetry means that we only need to solve the system for $(\tilde{x}, \tilde{y}) \in ([0, \widetilde{L}], [0, \widetilde{H} + \widetilde{D}])$. We denote the membrane thickness by $\tilde{h}$ so that Region 1 occupies $(\tilde{x}, \tilde{y}) \in ([0, \widetilde{L}], [0, \widetilde{H}])$ and Region 2 occupies $(\tilde{x}, \tilde{y}) \in ([0, \widetilde{L}], [\widetilde{H} + \tilde{h}, \widetilde{H} + \widetilde{D}])$. The fluid velocity field in the $(\tilde{x}, \tilde{y})$ directions in Region i $(= 1, 2)$ is $\boldsymbol{u}_i = (\tilde{u}_i(\tilde{x}, \tilde{y}), \tilde{v}_i(\tilde{x}, \tilde{y}))$, while the pressure is $\tilde{p}_i$.

We consider an idealized set-up in which the membrane is composed of uniformly spaced pores of initially constant radius $\tilde{r}_0$. In practice it is inevitable that there will be some randomness in the inter-fiber spacing, but we expect that the results of the analysis we present will provide the averaged behavior over a series of such devices. In addition, the model we present here may be generalized to describe a system that is characterized by a mean inter-fiber spacing and standard deviation about this mean. We assume that the fluid in Region 1 is uniformly laden with particles of radius $\tilde{a} < \tilde{r}_0$. As the fluid passes through the membrane the particles are filtered out by adhering to the pore walls with a finite probability. We assume, for simplicity, that these particles are neutrally buoyant, so that the density of the fluid is unchanged when the particles are removed, and that the viscosity is unaffected by the presence of the particles (though our analysis readily generalizes to account for such variations).