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Sinusoidal shaped hollow fibers for enhanced mass transfer

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ABSTRACT

Geometrically structured flow channels induce secondary flows and vortices enhancing mass and heat transport rates. In particular, these vortices may reduce concentration polarization and subsequent fouling in membrane transport processes. In this work we present a new method of producing hollow fiber membranes with a sinusoidal change in diameter along the fiber length. We engineered a pulsation module that imposes a sinusoidally fluctuating bore liquid flow rate. Harmonic bore flow conditions can be varied over a wide range of operational settings. The fluctuating bore liquid flow rate translates into axial membrane properties varying with respect to inner bore diameter and wall thickness.

We suggest that the resulting narrowing and widening of the membrane lumen channel induces secondary vortices to the liquid feed inside the membrane lumen. In gas/liquid membrane absorption processes these secondary vortices reduce the diffusional resistance, also known as the Bellhouse effect. For the produced hydrophobic PVDF membranes, improved oxygen transport from shell-to-lumen side prove superiority over straight hollow fiber membranes in G/L absorption process by a factor of 2.5 at higher liquid flow rates. We anticipate the dynamic flow module to be easily integrated into currently existing hollow fiber membrane spinning processes.

1. Background

1.1. Importance of hollow fiber geometry

Hollow fiber membranes offer important advantages over other membrane configurations. They show well-defined flow conditions on the inside of the fiber. Packing densities are superior over flat sheet based membrane modules. In fact, applications requiring mass production of membranes mainly rely on hollow fibers as their production and assembly into modules is highly scalable. This is particularly true for medical applications such as hemodialysis and blood oxygenation [1]. While commonly assumed to be done only by spiral-wound modules [2], even seawater desalination is done with hollow fiber membranes [3] at a scale as important as spiral-wound modules. Parallelization and high degrees of production automation allows for scalable spinning processes [4].

1.2. Hollow fiber spinning

In industrial hollow fiber fabrication the fiber is extruded through a spinneret [5]. The extrusion of the inner lumen flow channel is done parallel to the main flow direction of the polymer solution by engineering parallel flow inside the spinneret. Although radial stress may occur due to die swell, the resulting geometry is a constant lumen channel cross-section along the main direction of the fiber. This undisturbed tubular geometry causes close to perfect laminar flow profiles on the fiber's lumen. In applications like hemodialysis, the fibers are slightly undulated to maintain a good dialysate flow on the fiber shell side [6], while lumen side flow is still assumed to remain undisturbed laminar.

The overall mass transfer resistance in hollow fiber membrane contacting application (G/G, G/L, L/L and dialysis) comprises resistances on the shell side, inside the fiber wall and on the lumen side of the fiber. Depending on the application either one of those resistances or the combinations of the three gets predominant. The rigorous deconvulotion is often intricate as we recently demonstrated for G/G membrane contactors [7]. In membrane contactor modules, shell side baffles and other means are integrated into the hollow fiber module to allow for fluid flow perpendicular to the main fiber direction [8]. This allows for increased mixing and mass transfer on the shell side of the fiber. This improves mass transfer in the broad range of contacting applications, where the chosen flow configuration locates the most dominant mass transfer resistance on the fiber outside. However, increased mixing on the fiber inside is still hampered leading to developed boundary layers and concentration polarization.

In a previous study we presented a way to produce curled fibers by

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using the liquid rope coiling effect during hollow fiber spinning [9]. Mixing in the lumen of the curved curly fibers is due to formation of Dean vortices, whereas shell mixing is induced by flow disruption. In the present study, we focus on the creation of mixing effects inside the hollow fiber lumen by variation in lumen diameter along the flow direction of the fiber.

1.3. Mass transport in furrowed and structured channels

The fluid flow in furrowed or grooved flow channels has been reported in literature since the work of Bellhouse [10] in 1973. In oscillatory flow patterns, vortices form at a certain critical Reynolds number. As the Reynolds numbers increase, vortices grow in the furrows and eject during the decrease of Reynolds number. Due to Bellhouse's fundamental work [11], this effect is frequently referred to as the Bellhouse effect. These early studies revealed that periodic geometrical flow disturbances can lead to increased mixing inside the flow channels. The increased mixing overcomes diffusional resistances and increases the transfer rate (either heat or mass transfer) across the flow channels surface [12,13]. Early numerical and experimental studies agreed well [14,11]. More intricate channel modifications such as staggered herringbones are also known to enhance mass transfer [15], however, they remain to be relevant for flat channel geometries only and cannot be transferred to hollow fiber geometries.

Recently, Kasiteropoulou [16] investigated the fluid flow in periodically grooved microchannels. Nishimura et al. investigated the fluid flow in wavy channel in numerous publications as early as 1991. They used both experimental [17–23] and numerical methods [17,19–21,23,24] to investigate the flow behavior in wavy flat channels [17–21,24] and wavy walled tubes [22,23]. In both cases the formation of vortices have been reported. When comparing both geometries they conclude, that the mass transfer increment in the studied flow regime ($50 < Re < 1000$) is larger for the wavy-walled tube than the wavy-walled flat channel [22]. Neusser and coworkers recently attempted to transfer the concept of furrowed flow channels to new biohybrid membranes. They developed a setup to transfer a flat sheet oxygenation membrane into a membrane having furrows and seeded them with endothelial cells [25,26].

Unfortunately, all these principles have not entered the fabrication process of hollow fibers yet. Some work was performed on structuring hollow fiber membranes to affect mass transport. Culfaz et al. investigated corrugated hollow fiber membranes in filtration applications [27,28]. They found that the corrugations in the main flow direction increase the potential for resistance increase by fouling related phenomena. On the other hand the corrugations increase the active surface area, overcompensating the negative effects of fouling and concentration polarization in the tested applications. In a recent simulation study, the Zydney group analyzed how the combination of twisted fiber and inner imposed geometry facilitate beneficial hydrodynamical effects and mass transport [29]. We therefore suggest that new geometrical features of hollow fibers can have the potential to increase the performance of a membrane module in fluid contacting applications. However, experimental evidence is scarce.

It is the aim of the work presented below to establish evidence that a continuous fabrication method of hollow fibers having furrowed lumen channels is feasible and offers the anticipated improvements in mass transport. Not all fundamental questions arising from this work can be completely addressed and answered, yet the work is meant to stimulate the membrane materials community to (a) consider diffusional resistances as important as the membrane resistance and (b) to realize that materials processing into new membrane geometries is important to reduce the negative influence of laminar diffusional boundary layers.

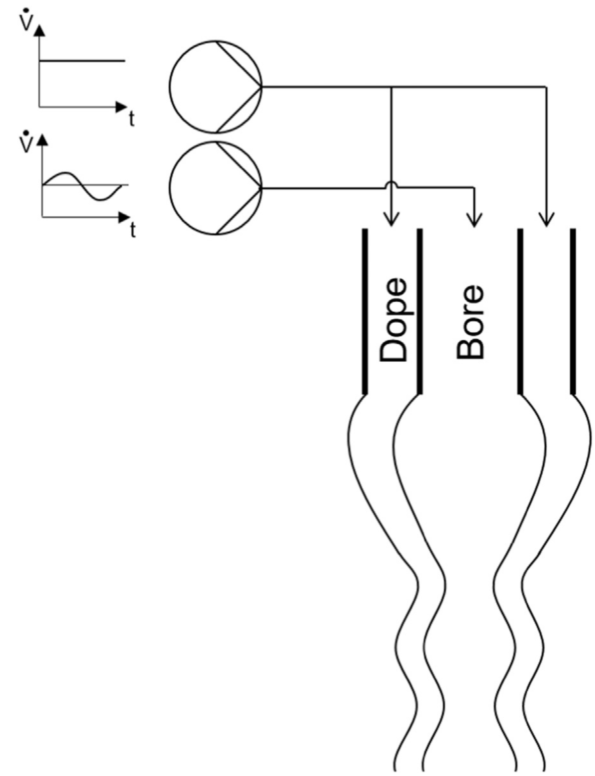

Fig. 1. Pulsation concept for the production of sinusoidal shaped hollow fibers. The flow rate of polymer solution is constant whereas bore liquid flow rate is a function of time, leading to variable axial fiber diameters.

2. Materials and methods

2.1. Transient flow conditions in membrane spinning

To allow for a membrane geometry that combines static mixing by furrowed channel geometry with a hollow fiber membrane fabrication process, we choose to design a sinusoidal variation in fiber lumen diameter along the fiber length. The variation is realized by adding a fluctuation in flow to a constant bore fluid flow rate as shown in Fig. 1. The constant flow of the polymer solution was induced by a HARVARD syringe pump. Pulsation was induced by a custom made pulsation module shown in Fig. 2: through a T-piece, liquid volume is pressed and withdrawn alternatingly into and from the lumen pipe to reach the desired pulsation. This volume was pumped using a microliter syringe incorporated into the pulsation module. Using the variable rotational

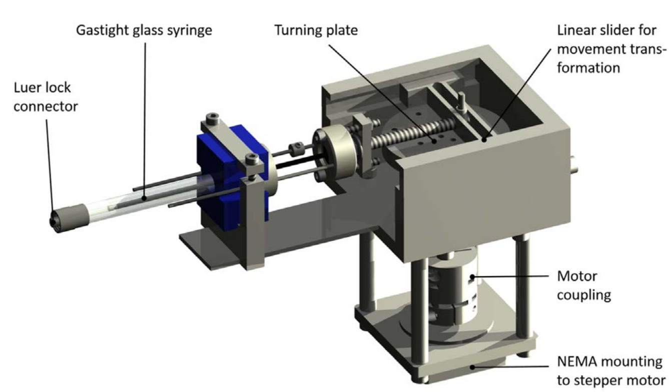

Fig. 2. Custom made pulsation module consisting of: 1: Luer Lock connector for plug and play use in state-of-the-art spinning lines, 2: HAMILTON gastight glass syringe, 3: turning plate with discrete eccentric drillings for amplitude manipulation, 4: linear slider for transformation to linear movement, 5: motor coupling, 6: mounting plate for NEMA connection to stepper motor. Stepper motor not shown.