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Generation of Dean vortices and enhancement of oxygen transfer rates in membrane contactors for different hollow fiber geometries

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ABSTRACT

This work aimed to study the enhancement of oxygen transfer rates in hollow fiber membrane contactors by applying Dean vortices. Systematic investigations of how the geometric parameters, like curve diameter, helical pitch or geometric shape, and flow rates affect the mass transport were done to assess the potential for membrane contactors. The membrane was a hydrophobic microfiltration hollow fiber (polypropylene). Helical, meander and twisted formed hollow fibers with fiber lengths from 5 to 30 cm and curvature diameters between 5 and 19 mm were constructed. The oxygen transfer rates per membrane area were investigated. The curved hollow fibers show a linear dependence between Dean number and enhancement factor and an increase of transfer rates up to an enhancement factor of 2.4. For the meander shaped fibers a critical Dean number/range between 10–20 was found, where the mass transport enhancement is adjusted rapidly to those of helical hollow fibers. Also the mass transfer in packed membrane modules was investigated, taking into account the theoretical packing densities of the different fiber geometries. It was found that a volumetric enhancement of gas transfer rates for helical and meander formed fibers can only be improved applying very small curvature diameters less than 4 mm.

1. Introduction

Hollow fiber membrane contactors already have been applied in a wide range of gas-transfer processes such as the absorption of SO_2 [1], CO_2 capturing [2,3] or the bubble free oxygen supply for blood oxygenators [4], wastewater treatment [5] and membrane aerated bioreactors [6–9]. Due to their large surface to volume ratio higher mass transfer coefficients can be achieved compared to conventional equipment like packed towers [10] or bubble column reactors [11].

Nevertheless, the overall mass transport in conventional modules with parallel packed straight hollow fibers is limited. Because of the small hollow fiber diameters at usual cross flow velocities only low Reynolds numbers can be realized, which leads to a laminar flow regime and a diffusion controlled mixing inside the hollow fiber. One possibility to enhance the mixing performance and overcome this limitation is to generate secondary flows like Dean vortices. In several membrane applications this enhancement has already been demonstrated [12–14]. Moulin et al. [15] compared a conventional membrane module equipped with parallel straight hollow fiber membranes and a module with helically wound hollow fibers for oxygenation and showed that the presence of Dean vortices leads to higher oxygen transfer rates with improvement factors in the range of 2–4. The same coiled module was used by Schnabel et al. [16] to improve the removal of volatile organic compounds from water with an improvement factor of 2.3. Recently, Jani et al. [17] investigated oxygen transfer rates of single microporous helically wound hollow fibers. A flux enhancement of more than 80% compared to straight fibers was observed. In addition to helically wound hollow fiber membranes, other curved geometries for generation of Dean vortices are possible [18]. Ghogomu et al. [19] compared flux performances of linear, helically coiled, twisted and meander shaped modules for the ultrafiltration of bentonite suspensions.

However, till date for gas–liquid membrane contactors no major attempt has been made to investigate systematically oxygen transfer rates for single hollow fibers of different curved geometries. In addition, the improvement factors have always been related to the membrane surface area and not to the volume of the membrane module. For lab scale applications with small dimensions, so called micro-, midi- or minimodules, this is not a limitation. For an industrial application on the other hand, the mass transfer per unit volume ratio probably represents the critical value. For this reason, in this study we investigated oxygen transfer rates for single hydrophobic microporous hollow fiber membranes. The mass transport enhancement for various helical geometries as well as meander shaped forms was compared.

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Within this study we took also into account the theoretically possible packing density in a membrane module for the investigated hollow fiber geometries in order to determine the highest oxygen transfer rates per volume.

2. Theory

2.1. Dean vortices in curved pipes

The generation of Dean vortices in curved pipes and their influence on the mixing behavior are well described in literature [19–23]. Dean vortices develop in curved pipes due to the continuity. The outer curve is longer than the inner curve, but the velocity maximum is located in the center of the flow. Therefore, fluid moves radially towards the outer curve and tangentially towards the inner curve [24]. The intensity of the formation of this secondary flow is described by the dimensionless Dean number De, which is a function of Reynolds number Re, curvature of the pipe d_c and the internal diameter d_i

$$De = Re\sqrt{\frac{d_i}{d_c}} \tag{1}$$

For helically wound tubes this Dean number is modified to

$$De' = Re\sqrt{\frac{d_i}{d_c\left[1+\left(\frac{h}{\pi d_c}\right)^2\right]}} \tag{2}$$

where h is the pitch of the helix. The enhancement factor E, which is used to describe the effect of Dean vortices on the overall oxygen mass transport, is defined as

$$E_{area} = \frac{OTR_{helical\ fiber}}{OTR_{straight\ fiber}} \tag{3}$$

2.2. Theoretical mass transport in packed membrane modules

The theoretically achievable aeration rate per membrane module volume is calculated from the mass transport per membrane area N [mol/(m^2 s)] and the maximum packing density P [m^2/m^3] of the hollow fibers.

2.2.1. Straight geometry

The densest packing of straight fibers in a hollow fiber module is the hexagonal lattice with a packing density P of 90.7% (see Fig. 1a). For helically wound fibers the theoretically achievable area per module volume two border cases can be differentiated: helical and twisted.

2.2.2. Helical geometry

Helical fibers with a low pitch cannot be packed closely, so that the packing density is reduced by the internal free volume of the helix, which is a function of the curvature diameter d_c and the hollow fiber outer diameter d_m (see Fig. 1b). The packing density can approximately be determined by the following equation:

$$P = 0.907\left(\frac{(d_c-\frac{d_m}{2})^2}{(d_c+\frac{d_m}{2})^2}\right)\frac{\pi(\frac{d_m}{2})^2}{{d_m}^2} \tag{4}$$

2.2.3. Twisted geometry

For increasing helical pitch the fibers can be arranged as a multi helix, see Fig. 1c. Depending on the number of membranes twisted into each other, the packing densities approaches for infinite number also to the hexagonal lattice of 90.7%. But for small numbers, e.g. two, three or four fibers only low packing densities of 45, 58 and 62% are obtainable.

2.2.4. Meander shaped geometry

For meander shaped fibers the packing density is a function of the ratio between the curvature of the pipe and the membrane thickness d_m expressed by

$$P = \frac{\pi(\frac{d_m}{2})^2\pi\frac{d_c}{2}}{2d_c\sqrt{\left(\frac{d_c}{2}+\frac{d_m}{2}\right)^2-(\frac{d_c}{2})^2}} \tag{5}$$

The mass transport enhancement per membrane module volume E_{volume} for the different hollow fiber geometries can be calculated using the enhancement factor per membrane area and the ratio between the packing densities

$$E_{volume} = \frac{OTR_{helical\ fiber}}{OTR_{straight\ fiber}}\frac{P_{helical\ fiber}}{P_{straight\ fiber}} \tag{6}$$

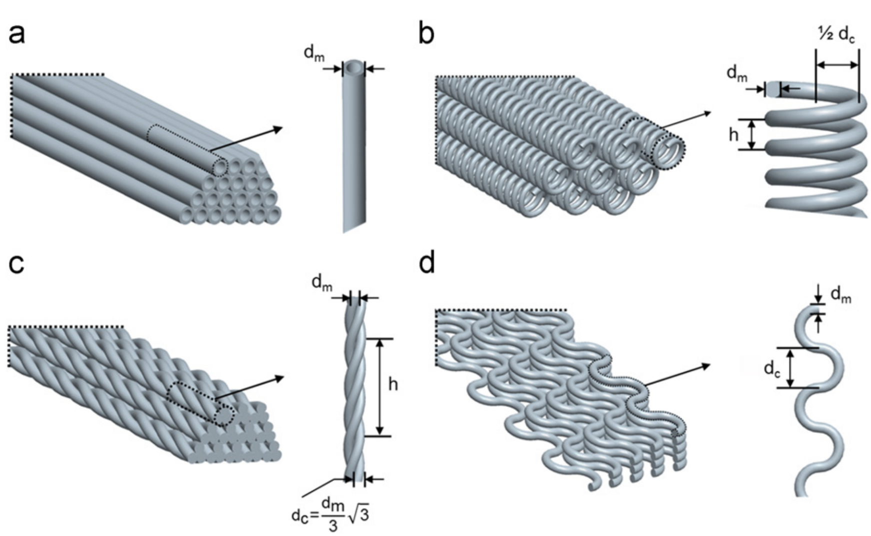

Fig. 1. Schematic depiction of different hollow fiber geometries for the generation of Dean vortices: (a) straight; (b) helically wound; (c) twisted; and (d) meander formed.