Journal of Membrane Science 463 (2014) 41–48

Contents lists available at ScienceDirect

Journal of Membrane Science

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

Helically microstructured spacers improve mass transfer and fractionation selectivity in ultrafiltration

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ARTICLE INFO

Article history:
Received 8 November 2013
Received in revised form
19 March 2014
Accepted 21 March 2014
Available online 28 March 2014

Keywords:
Rapid prototyping
Spacer
Molecular weight cut off
Ultrafiltration
Hydrodynamics

ABSTRACT

The separation performance of ultrafiltration processes is strongly affected by the hydrodynamic flow conditions in the feed channel close to the membrane surface. In particular, spacer mats required to separate the membranes have a strong influence on the mass transport in the bulk liquid towards the membrane surface. Commercially available net-spacers have proven to influence mass transport advantageously depending on their geometrical structure: spacers improve mixing phenomena, diminish concentration polarization and increase mass transfer coefficients. Little is known about the effect of such spacers on the mass transfer in multi-component mixtures with respect to the separation between different solutes dissolved in a solvent.

This paper investigates new 3D-printed helically microstructured spacers in comparison to state-of-the-art net spacers. In particular, we report the influence of fluid hydrodynamics on mass transport enhancement and process selectivity. Ultrafiltration experiments with well-defined Dextran solutions focus on the molecular weight cut-off and the separation quality at various operating conditions. Compared to net-spacers, the application of the micro-structured spacers resulted in significant improvements of the overall mass transfer coefficient as well as process selectivity. A higher overall performance at equal cross flow power consumption is obtained as well.

1. Introduction

Membrane process performance in ultrafiltration (UF) depends on optimized flow conditions within the membrane module. Membrane spacers largely contribute to efficient operation since mass transfer rates are substantially increased by the spacer induced flow, while fouling is significantly reduced [1,2]. The increase in mass transfer is attributed to a boundary layer disruption and renewal being a direct result of the hydrodynamics imposed by the spacer. Forced flow towards the membrane surface, recirculation regions as well as moving vortices have been identified as the main mechanisms for mass transfer enhancement [3–5].

Although significant work has been performed regarding the understanding of mass transfer enhancement mechanisms and spacer optimization [1,2,6,7], the influence of membrane spacers on separation characteristics such as molecular weight cut-off (MWCO) or the fractionation selectivity of the membrane process is yet insufficiently understood. Separation characteristics are not only determined by the membrane selected, but are largely influenced by the operating conditions such as flux through the membrane and cross flow velocity in the feed channel. This has been worked out in detail for hollow fiber membranes [8], but spacer filled channels have been touched upon only very recently [9].

This paper aims to extend the current understanding of the influence of hydrodynamics, spacers and spacer geometry on the separation characteristic in ultrafiltration applications. Different state-of-the-art net-spacer geometries and new two-layer micro-structured membrane spacers are investigated here with respect to their filtration performance of well-defined dextran solutions. These microstructured spacers have their conceptual origin in the geometry of well-known Kenics mixers [10,11]. The latter show effective mixing of viscous fluids for instance, but also have very little contact – single point contacts – with the supporting surface. Kenics mixers also have very little dead zones where recirculating stagnant vortices could evolve.

For a broad range of operating conditions we report the influence of these spacer geometries on filtration characteristics and mass transfer. Molecular weight cut-off measurements are performed and retention curves are obtained using size-exclusion chromatography of feed and permeate phase. Special emphasis is directed to the evaluation of the influence of the microstructured

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http://dx.doi.org/10.1016/j.memsci.2014.03.059
0376-7388/

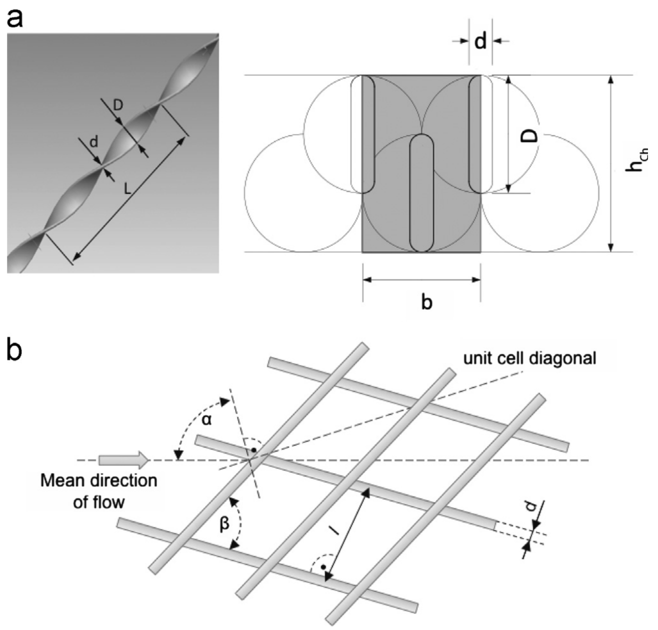

Fig. 1. (a) Double-helix form twisted filament with spacer cross section, shaded area displays one repeating spacer element and (b) net spacer with geometry parameters.

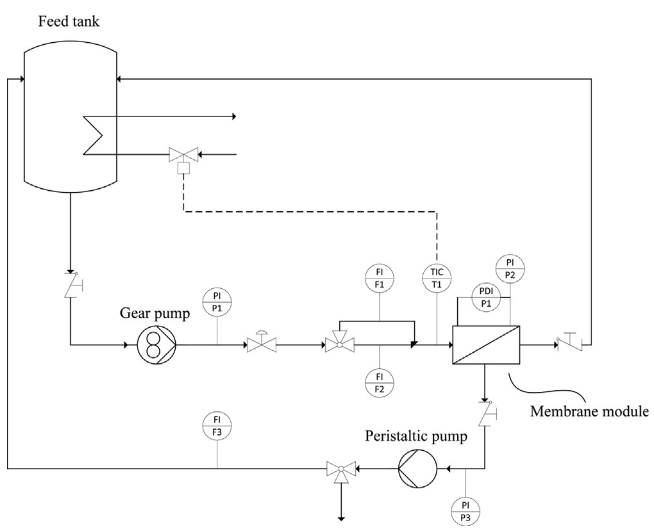

Fig. 2. Experimental set-up.

spacer on process selectivity and performance in comparison with standard net-spacers.

2. Materials and methods

2.1. Spacer properties

The geometry of the new spacer and the resulting improvements for applications in ultrafiltration are described in detail in [12,13]. The core element of the micro-structured spacer is the double helix form filament. Its geometric characterization and the alignment in mean flow direction is depicted in Fig. 1a (left). The overall geometry comprises two layers which partially fit into each other, thus offering a mechanically stable structure. The twist orientation of the filaments of the first layer is opposite to the filaments in the second layer. The geometry parameters shown in Fig. 1a (right) are required to quantify the spacers hydrodynamic properties, i.e. the hydraulic diameter d_h. On the bottom part of Fig. 1 the commercially available net-spacer and its characteristic geometry parameters are visualized.

In Tables 3 and 4, the parameters of the investigated spacers are listed. The spacer design targets in particular (a) an intensified mass transport by reducing the effect of concentration polarization, (b) low feed side pressure losses and (c) reduced contact area between the spacer and the membrane (single point contact). When Kenics mixers are used in pipe geometries their outer body touches the walls of the duct. In the geometries reported here, the helically twisted filaments are stacked in two layers between two planar membranes and spacer and membrane contact exist only in a single point. This, we hypothesize, is beneficial for fouling and concentration polarization reduction.

Table 1
Membranes applied in the experiments.

	UH050	UP020
Nominal cut-off (kDa)	50	20
Membrane material	PES	PES
Water flux @3 bar, 20 °C (LMH)	250	200

2.2. Materials and methods

2.2.1. Experimental setup

Lab scale filtration tests have been performed in flat channel test cell experiments. The set-up of the laboratory plant is schematically shown in Fig. 2. The feed tank has a volume of 15 l, the temperature of the feed is automatically controlled. The feed is pressurized with a gear pump and fed to the membrane test cell. Flow meters F1 and F2 are implemented for low and high volumetric flow rates. Pressure and differential pressure are measured within the test cell in the spacer filled channel. For the low pressure range, pressure was measured with a U-tube manometer, while pressure indicators have been used for higher cross flow velocities. The pressure on the feed side is controlled manually with a throttle valve located behind the membrane module. To ensure constant feed concentrations, permeate is directly recycled to the feed tank.

Permeate samples for determination of permeate composition are extracted at the valve behind the peristaltic pump. The small volume samples of about 5 ml each ensure that only minor changes are observed in the feed composition over the full run time of the experiments.

The active membrane area of the test cell is $80 \times 200\ mm^2$. The test cell inlet and outlet design ensures equal distribution of flow in the free cross sectional area of the feed channel to minimize any entrance effects. The feed channel height can be adjusted to the individual spacer height.

2.2.2. Membrane

For the experiments performed in this investigation only commercially available UF membranes have been used. The membranes purchased from Microdyn Nadir are flat sheet membranes, from which membrane samples were cut to fit the test cell. Table 1 shows the nominal membrane properties as supplied by the manufacturer. The UH050 membrane has been implemented if not otherwise stated.

2.2.3. Macromolecular solution

The filtration tests have been performed with dextran solutions. To be able to measure the molecular weight cut-off (MWCO) as well as filtration selectivity an aqueous solution of a mix of