A mini-module with embedded spacers for high-throughput ultrafiltration

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Abstract

Ultrafiltration membrane modules suffer from performance losses that arise during filtration from concentration polarization and fouling. Such performance losses are frequently mitigated by controlling the hydrodynamic conditions at the membrane/fluid interface. For instance, the hydrodynamic conditions are manipulated using mesh spacers that act as a static mixer. The design of such spacers is rarely optimized to effectively maintain mass transport through the membrane. Also, the spacer is an additional part added to the feed channel of the membrane module, improving mass transport in general, yet accepting less transport in dead zones.

Here, we present a mini module with spacers embedded in the module housing of a flat-sheet ultrafiltration membrane to attain high permeation rates. The performance of two new embedded spacer geometries – staggered herringbone and sinusoidal corrugation – prove experimentally that indeed a CFD-simulated flux increase can be realized during bovine serum albumin (BSA) filtration. The flow characteristics inside the mini module are further investigated using magnetic resonance velocity imaging. The new embedded sinusoidal corrugation spacers outperform conventional mesh spacer inlays. The fabrication of such module-embedded spacers has been conceptually implemented through an in-silico design and a 3D-printing production process. The latter can be easily realized using injection molding processes, as is now done for the Sartorius ambr[®] crossflow product line.

Keywords: Ultrafiltration membrane module, embedded static mixers, fouling mitigation, CFD, Magnetic Resonance Imaging

1. Introduction

Ultrafiltration membrane modules play an important role in the biotechnological and pharmaceutical industries [1–3]. Ultrafiltration membranes remove harmful matter such as bacteria and viruses, concentrate a desired product such as proteins and enzymes or separate other valuable products from one another to increase purity [4].

Particulate and colloidal matter is omnipresent in biotechnological processes and tends to accumulate at the membrane surface, forming a complex deposit film on top of the membrane [5]. This leads to a decrease in the permeation performance of membrane modules

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[6]. Matthiasson and Sivik have already stated in the 1980s that concentration polarization occurring in ultrafiltration processes leads to mass transfer inhibition [7]. To address this issue, various measures are taken, one of which are static mixers inserted into membrane modules to increase mixing and subsequently mass transfer [8]. Static mixers increase the shear rate and thus reduce fouling [9] induced by biological or colloidal matter. The mixers function as obstacles disrupting the laminar flow profiles and causing vortices in the flow field normal and away from the membrane surface. This induced mixing also leads to higher velocities at the membrane surface. Computational fluid dynamics (CFD) simulations of mesh type spacers show better mixing (high shear rate, low drag coefficient), but also an increase in pressure drop [10]. This leads to a constant trade-off between flux increase and the correlated rise in energy input due to higher pressure loss [11, 12].

The downside of mesh type spacers is that they require several assembling steps in line production. A single-step production such as injection molding could accelerate the production process and reduce operating costs. Removing such mesh spacers from a module architecture has been addressed by incorporating spacers as turbulence promoters into the membrane as so-called membrane-con-spacer geometries [13–15].

Studies on net- or diamond-shaped spacers and meshes are available in large numbers and are discussed in several reviews [12, 16, 17]. The literature on experimental and simulation-based investigations of mesh spacers proves reduced biofouling and prolonged stable membrane-module performance [11, 18–20]. To describe such mesh spacers or static mixers, conventional literature uses simple 2D structures like triangles, squares or circles and focuses on their position and dimensions [21, 22]. As those static mixers are not suitable for injection molding, they are not further discussed here.

Only few studies focus on module-embedded instead of inlay static mixers. A patterned membrane surface acts as spacer structure and induces vortices [23]. An implementation of commercial mesh spacers used as embedded spacer structure exists only for simple geometries such as squares [24]. A ladder-type spacer within a frame fabricated by 3D printing was studied in ultrafiltration experiments [25]. Here, the spacer elements direct the fluid flow to the upper and lower parts of the membrane module but contain undercuts, which is not

suitable for injection molding. Other experiments show positive effects only in the entrance region for mesh type spacers and embedded ribbon-type spacers [26]. Another spacer type suitable for ultrafiltration is a zigzag spacer without any obstacles, which outperforms mesh-type spacers in terms of pressure drop [27]. Staggered herringbone structures are a good example for embedded spacer structures, but are suitable primarily for microfluidic applications [28]. Shrivastava et al. [29] examined asymmetric herringbone, helix and ladder-type structures intending to provide a guide for developing reasonable spacers. Positive effects in mass transfer were found to be highest for helices, followed by herringbones and ladder-type spacers [29].

While much work deals with flow distribution only, some studies also address the corresponding simultaneous mass transfer phenomena quantitatively [11, 30, 31]. Mass transfer enhancement is accompanied by an increase in axial pressure drop [31]. This results in an increase in mass transfer coefficients with increasing shear rates [30]. Mass transfer investigations were considered for simple geometries only [30, 31], but recently our group has addressed membranes with spacers [13, 32, 33] and 3D printed novel spacer and mixer geometries [34–36]. A general overview is given by the Virtual Issue of the Journal [37].

Only few studies investigate 3D printing-aided membrane modules, despite the great potential of 3D printing for fast and cheap module improvement [38]. Module design and material selection must be considered in 3D printing, but research on 3D printing of membrane process-related questions progresses rather slow [17].

Most of the research has so far focused on fluid flow simulations, simple 2D structures or inlay mesh-type spacers, which are not suitable for single-step production. 3D simulations are preferable to 2D simulations because the latter underestimate the parameters examined [18]. In this study, we therefore tackle 3D simulations including mass transfer, implement an obstacle-free spacer structure for a high-throughput membrane module and use 3D printing for fast prototyping. For the first time, we complement CFD simulations with both experimental validation and flow-MRI measurements.

Figure 1: 3D printed membrane module with embedded sinusoidal spacers.

2. Materials and methods

2.1. Additive manufactured membrane modules

The mass transport properties for different embedded spacer geometries were evaluated in an additively manufactured membrane module that was fabricated using polyjet 3D printing (Stratasys, Objet Eden 260V). The membrane module shown in Figure 1 was printed layer by layer with a transparent photo-polymer (Stratasys, RGD810). During printing, the internal fluid channels need supporting structures (Stratasys, SUP705), which were later removed using a high-pressure washer (Krumm-tec, RK Top 5). Any remaining material was subsequently dissolved in a stirred bath of 1 mol L^{-1} sodium hydroxide for approximately 24 hours.

2.2. Design of the embedded spacer

The challenge is to design the membrane module for injection molding. The module investigated in this work is a small-scale cross flow module consisting of two parts. The first part contains the feed inlet and a retentate outlet. The feed inlet leads to a rectangular channel upon which the membrane is placed. The corners of the feed channel are rounded off in order to minimize material deposition in dead zones. The second part of the module contains a permeate outlet.

The advantage of replacing mesh spacers with embedded spacers is the possibility of single-step production that requires less time, e.g. injection molding without the need for a

spacer placement step. During injection molding, polymer granulate is molten and transferred into a metal shape where it is injected into a mold cavity via a nozzle. For the design of the spacer embedded in the membrane module, any ramifications or undercuts need to be avoided in order to facilitate removing the molded part. Simple superficial cavities ensure a uniform distribution of the mold mass in the tool and a smooth surface of the module resulting in consistent quality of the product [39]. Embedded spacer structures were designed following injection molding restrictions, thus avoiding ramifications or undercuts and too detailed structures.

To find a suitable novel spacer design, the literature was studied and new approaches were implemented. In the literature, results from 2D and 3D simulations as well as from experiments were compared. On the basis of these studies, ten structures were investigated in CFD simulations, from which two final structures were selected (see supporting information). The selection process based on a good agreement between shear rate at the membrane, shear rate distribution, and pressure drop between inlet and outlet. The selected structures, a staggered herringbone and a sinusoidal corrugation, were compared to the empty channel in simulations and additionally to an inlay net spacer in experiments.

Empty channel. The feed channel measures a width of 13.5 mm and a length of 76 mm. Channel heights on the feed and permeate sides are chosen in accordance with the used spacers. The investigated feed side channel was set to a height of 250 μm .

Herringbones. Staggered herringbone structures improve mixing in microfluidics and are adapted to this work for different element distances and the element height. To form herringbones, rods of 0.22 mm radius and 32 μm membrane distance are arranged in an angle of 60° and 3 mm of distance. The dimensions result in 22 rods along the feed channel.

Sinusoidal corrugation. To create the sinusoidal surface, a basic element with four perpendicular sides is constructed. The adjacent sides of the basic element display sinus functions, which differ by half a period. As the sinus functions are orthogonal, they form a cross-shaped pattern. A complete sinus wave measures 4 mm and, like the herringbone structure, has

a membrane distance of 32 μm . These dimensions result in 19 peaks for the feed channel length. As a variation of the sinusoidal corrugation, the number of peaks is doubled.

2.3. Fluid dynamics simulation

To perform the experiments under well-defined flow conditions, the design process of the membrane module was assisted with CFD simulations using COMSOL Multiphysics. In particular, the flow conditions at the membrane fluid interface were optimized with the geometry of the embedded spacers. The three different spacer configurations were simulated with laminar inflow conditions and zero pressure at the outlet. The simulation used pure water from the COMSOL material library for the fluid properties. Geometrical adjustments (e.g. symmetry) and periodic boundary conditions were applied to the simulations to reduce the calculation effort. The mesh was refined, leading to a stable pressure loss probed between the inlet and outlet. Based on the CFD simulation results, the spacer geometry was altered using computer-aided design (CAD) to influence and adapt the desired homogeneous flow field inside the membrane module.

The inlet velocity was set to 0.152 m s^{-1} , which equals a flux of 6.7 mL min^{-1} passing the inlet cross-section of 1 mm diameter. These flow condition results in a Reynolds number of 18 for the empty feed channel. In accordance with Baker [40], simulations can be done for the case of laminar flow.

Navier-Stokes equations for an infinitesimal control volume serve as the basis for evaluating the fluid flow [41]. The conservation of momentum is described by the correlation:

$$\rho (\mathbf{u} \cdot \nabla \mathbf{u}) = \nabla \cdot \left[-p \mathbf{I} + \mu \left(\nabla \mathbf{u} + (\nabla \mathbf{u})^T \right) - \frac{2}{3} \mu (\nabla \cdot \mathbf{u}) \mathbf{I} \right] + \mathbf{F}, \quad (1)$$

where ρ stands for the density, $\mathbf{u}$ describes the velocity vector, p is the pressure, μ is the dynamic viscosity, $\mathbf{I}$ is the identity matrix, ∇ is the Nabla operator and $\mathbf{F}$ are external forces. In this case, no external forces are applied so $\mathbf{F}$ is not accounted. The fluid is assumed to be Newtonian, incompressible and continuous. Thus, the viscous force term $-\frac{2}{3} \mu (\nabla \cdot \mathbf{u}) \mathbf{I}$ is also neglected. The Navier-Stokes equations are solved together with the continuity equation:

$$\nabla \cdot (\rho \mathbf{u}) = 0, \quad (2)$$

describing the conservation of mass.

Shear stress is a tangential force generated through distortion of a fluid element and reduces the formation of fouling layers on membrane and module surfaces. Thus, high shear rates are considered to increase the permeation rate of a membrane [22, 23, 30]. Since the presented module structures are to be compared on the basis of their permeate flow as proof of performance, the shear rates at the surface are examined. This study compares shear rates averaged over the membrane surface for mentioned embedded spacer structures. The shear rate is a tensor of the strain-rate:

$$\dot{\gamma} = \left(\nabla \mathbf{u} (\nabla \mathbf{u})^T \right). \quad (3)$$

Laminar flow indicates further assumptions for this case including settings regarding the time, temperature, solver and initial fluid properties. As no change in time is desired, the flow is investigated under steady-state condition. The model sets the temperature to 293.15 K and neglects change in temperature. All simulations assume a full developed and constant feed flux. Default selection results in the stationary solver with fully coupled conditions and direct iterations using the PARDISO solver. The mesh system consists of a refinement of boundary layers at the membrane and a total of 10^5 mesh elements for the empty channels.

Concentration polarization plays a significant role in ultrafiltration processes. This work implements *transport of diluted species* to the model to describe mass transport and thus concentration polarization at the membrane/ fluid interface. To model concentration polarization, fluid-like conditions of dissolved salt in water are introduced.

Extending laminar flow by transport of diluted species merges convective with diffusive flow. This study bases their combination on the following assumptions:

- membrane rejection of 100 % for salt;
- constant ambient pressure and pure water on permeate side;
- constant feed composition with a fixed salt concentration;

- and density, viscosity and diffusion coefficients independent from concentration.

178 The system conditions taken from [42] are summarized in Table 1, where c_0 stands for the entry concentration, c_p for the permeate concentration and A_w for the membrane permeability.

Table 1: System conditions for simulation with concentration polarization using material properties according to [43]

Parameter	Value	Unit
Laminar flow		
v_{in}	0.152	$m\ s^{-1}$
p_{out}	0	bar
Transport of diluted species		
c_0	6.23	$mol\ m^{-3}$
c_p	0	$mol\ m^{-3}$
D	1.5×10^{-9}	$m^2\ s^{-1}$
General		
A_w	9.3943×10^{-12}	$m^2\ s\ kg^{-1}$
Diluted component	Chlorophenol	

180

Transport of diluted species calculates the convective and diffusive movement of a species
 182 diluted in water according to equation:

$$\nabla \cdot (-D_i \nabla c_i) + \mathbf{u} \cdot \nabla c_i = R_i. \quad (4)$$

184 D denotes the diffusion coefficient and i describes the component. As no reaction takes place, the reaction term R_i is not assigned. Convective flow characterizes flow through the bulk;
 186 diffusive flow describes the laminar boundary layer in the vicinity of the module walls. At

walls – including the membrane – fluid slows down to $v = 0$ and diffusion predominates over
 188 convection.

Calculations are complemented by the conservation of mass equation:

$$\mathbf{N}_i = -D_i \nabla c_i + \mathbf{u} c_i, \quad (5)$$

190 where $\mathbf{N}_i$ is the amount of total moles. Boundary conditions remain the same compared to
 laminar flow, supplemented by additional inflow and outflow for the concentrated species. The
 192 extension by transport of diluted species demands a further characterization of the transport
 at the membrane. The model provides a permeate flux as a second outlet condition as function
 194 of the local pressure and concentration at the membrane. The membrane flux increases
 with higher pressure and decreases with increasing osmotic pressure due to higher local
 196 concentration (see equation (6)). In this case, the additional membrane flux is described as
 the orthogonal outlet velocity U_p , where the characteristics of the membrane are summarized
 198 in the permeability or solvent transport coefficient A_w :

$$U_p = A_w \cdot (p - (R \cdot T \cdot c)). \quad (6)$$

All other boundaries are set to no-flux condition. According to equation (6), the permeate
 200 volume flow depends on pressure p at the membrane. To enable permeate volume flow,
 trans-membrane pressures (TMPs) from 2.5 bar to 12.5 bar were applied in the laminar flow
 202 node according to

$$\text{TMP} = \frac{p_{\text{Outlet}} + p_{\text{Inlet}}}{2} - p_{\text{Permeate}}. \quad (7)$$

To compare the different structures, the permeate volume flow was determined by integrating
 204 the orthogonal outlet velocity across the membrane surface for the TMPs.

2.4. Filtration setup and (flow-) MRI measurements

206 The technique of magnetic resonance imaging (MRI) allows the visualization of structures
 and fluid flow inside membrane modules in situ and non-invasively. It utilizes the property
 208 of nuclear spins reacting to a magnetic field.

In this study, the measurements were performed on a Magritek low-field NMR tomography system. It operates at a Larmor frequency of 23.8 MHz with a field strength of 0.56 T. A 2D spin-echo pulse sequence was used in all measurements. MRI parameters are provided in Table 2. The signal-to-noise ratio in all measurements was larger than 10. The measuring and post-processing technique was done with MATLAB combined with PROSPA (Magritek) and is explained in more detail in our previous studies. [33, 44–47].

Filtration experiments were conducted in a commercially available 30 kDa ambr[®] crossflow module modified as a screening filter for a broad range of concentrations and molecules. A constant feed flow of 10 mL min⁻¹ of a buffer solution consisting of de-ionized water and 1.48 g L⁻¹ copper(II) sulfate pentahydrate (CuSO₄ · 5 H₂O, CAS: 7758-99-8, Carl Roth, Germany) was set using two continuous neMESYS syringe pumps by CETONI GmbH, Germany. A bubble trap was used to prevent air from entering the module. The pressure in the retentate channel was set to 1.5 bar over-pressure using a back-pressure valve.

Table 2: MRI parameter settings for the flow measurement of the ambr[®] crossflow module.

	Value	Unit
Repetition time	400	ms
Echo time	32	ms
Spatial resolution [x · y · z]	30 · 8 · 10	mm · mm · mm
Number of pixels [x · y]	256 · 128	—
Number of scans	12	—

2.5. Experimental characterization of mass transport

Simulation results determined the most promising spacer structures and motivated those to be 3D-printed and tested in experiments with protein filtration. The proposed embedded spacer structures were supplemented by and compared with commercial net spacers.

The tested ultrafiltration membrane was a Hydrosart[®] 30 kD by Sartorius Stedim GmbH. It was placed either in an empty 3D-printed prototype or in 3D-printed modules with

Figure 2: a) CFD simulations show (top) even but low shear rate distribution for the empty channel, (middle) shear rate peaks above the herringbone structures, and (bottom) various peaks and valleys for the sinusoidal corrugation. b) (top) In the empty channel, the concentration increases fast due to concentration polarization. (middle) The herringbone structure delays the concentration increase. (bottom) The Sinus proposes the slowest concentration increase and an even distribution.

embedded structures. In the empty module, a Clearedge 230 μm acted as a benchmark
 230 mesh-type spacer, which was placed on top of the membrane. Six screws then fixed the
 module housing at a torque of 1 N m with a torque wrench (DremoMeter DBGM Rahsol
 232 10-100 cm kp).

Due to the pre-wetting of the membrane with glycerin, each module was first flushed with
 234 100 mL ultrapure water. All modules were tested for integrity and water flux beforehand.
 The water flux test included flushing of 100 mL solution while tracking the permeate. Only
 236 modules with a specific, membrane-related permeate quantity according to the datasheet were
 used for the experiments. Water flux test and experiments were performed at a back-pressure
 238 of 1.5 bar in the retentate while the permeate channel remained open to ambient pressure
 (retentate outlet was closed for water flux test). The inlet feed volume flow was set to
 240 10 mL min^{-1} . The module operated vertically from bottom to top to prevent gas bubble
 formation. During the experiments, the retentate and feed pressure, the volume flow, and
 242 the amount of permeate were recorded. Permeate volume flow was measured simply by using
 a stopwatch and a measuring cylinder. The syringe pump (PHD Ultra, Harvard Apparatus)
 244 ran a 50 ml plastic syringe (Terumo). Pressure sensors (High-Tech EL-PRESS FLOW-BUS,

Bronkhorst) tracked inlet and outlet pressure. BSA (CAS 9048-46-8, Carl Roth) was used to
 246 prepare a 10 g L^{-1} and a 50 g L^{-1} solution in 10 mmol phosphate buffer of pH 7, pre-filtered
 with $0.2 \mu\text{m}$ filter.

248 3. Results and discussion

3.1. Laminar flow simulations visualize hydrodynamics

250 Several studies have shown that high shear rates improve mixing and thus mass transfer
 [9, 30]. Therefore, this study compares spacer designs to one another in order to find high
 252 shear rate distributions averaged over the membrane. CFD results show that the highest
 shear rates (shown in white in Figure 2 a)) are achieved for small distances between membrane
 254 and module wall.

The empty channel (Figure 2 a) (top)) shows an even shear rate distribution with low
 256 shear rates around $0.5 \times 10^3 \text{ s}^{-1}$. For spacer designs, where the shape runs over the whole
 module width, shear rate peaks appear above the top area of the spacer shape. This is the
 258 case for the herringbone structure (Figure 2 a) (middle)), where high shear rates are observed
 over the diagonal bars with $45 \mu\text{m}$ distance compared to low shear rates (in red) in between
 260 those bars ($50 \mu\text{m}$ distance to the membrane).

In the case of the sinusoidal corrugation, the filaments do not form a continuous barrier over
 262 the whole width; instead, alternating peaks and valleys appear. The varying structure results
 in an even distribution and high shear rates (around $2 \times 10^3 \text{ s}^{-1}$, see Figure 2 a) (bottom)),
 264 simultaneously.

3.2. Salt retention simulations

266 Solutes in ultrafiltration processes have sizes of about $0.01 - 0.5 \mu\text{m}$ and demand particle
 representations and hydrodynamics to be described by CFD simulations combined with
 268 discrete elements representing the particle [48]. However, this emerging simulation technology
 goes far beyond the questions to be answered here and is too microscopic and hence too
 270 simulation-intensive. Instead, we use salt retentions to investigate and represent the effect of
 flow conditions on solute retention for the different geometries.

Figure 3: a) Simulations show the highest permeate flux enhancement for the sinusoidal corrugation, followed by herringbone structure and the sinusoidal corrugation with half the frequency. All results are better than those for the empty channel. b) sinusoidal corrugation achieves the highest permeate flux in BSA experiments, followed by the commercial net spacer, herringbone structure, and the empty channel.

A fluid can be described by continuous movement under tangential or shear force [41]. This is the case for dissolved salts in a diluted solution of water. In section 2.3, fluid-like conditions were introduced to model concentration polarization. To use fluid-like conditions and enable simulation time of few days only, the ultrafiltration system was replaced by a reverse osmosis process. Ultrafiltration and reverse osmosis can be considered similar regarding mechanisms creating concentration polarization [7]. This study uses specifications for a reverse osmosis membrane and its permeability for the concentration of chlorophenol studied by Al-Obaidi and Mujtaba [42]. The calculated results of Al-Obaidi and Mujtaba were validated by experiments [43].

To investigate the correlation between shear rate and concentration, 2D plots for the concentration at the membrane surface are compared. Low concentrations at the membrane are desired as they result in a small osmotic pressure increasing the permeate flux (see the function for the permeate flux in equation (6)). In the legend in Figure 2 b), light colors indicate low concentrations. Figure 2 b) shows a concentration increase from left to right, which correlates with the feed-flow direction. The concentration trend implies an increase in the number of retained components. The empty channel (Figure 2 b) (top)) shows rapid growth in concentration at an early position within the first eighth. The herringbone and the sinusoidal corrugations (Figure 2 b)(middle) and (bottom)) show that high concentrations are reached at a later point: the herringbone structure reaches the same concentration level as the empty channel at halfway, whereas the sinusoidal corrugation delays the concentration increase up to the last third. As in the case of shear rates, peaks (indicated by light colors) are observed on top of obstacles: above bars for the herringbone structure and above sinus peaks for the sinusoidal corrugation. Where there were high shear rates above the filaments of the herringbone structure in Figure 2 a) (middle), there are now low concentrations in the same regions (lighter colors compared to the space between filaments). The sinusoidal corrugation represents a more even concentration distribution compared to the herringbone structure.

The volume flow of the empty spacer J_{empty} is compared to the permeate volume flow of the structures J_P for different TMPs according to $J_{compare} = J_P - J_{empty}$ (see Figure 3 a)).

The permeate volume flow rises for increasing TMP according to equation (6). Figure 3 a) also shows a higher permeate volume flow for the sinusoidal corrugation compared to the herringbone structure. A second sinusoidal corrugation with half the frequency, and thus half the number of sinus peaks, loses performance and shows lower permeate volume flows.

3.3. Flow-MRI shows mixed fluid flow distribution

Flow-MRI measurements under constant flow were conducted for the sinusoidal corrugation. Figure 4 a) depicts a magnetic resonance image of the cross-section of the membrane module. The image reveals the inner structure of the membrane module consisting of sixteen permeate channels with a membrane on top and the feed channel with the embedded sinusoidal corrugation. The brighter the color in the magnetic resonance image, the higher the density in the respective pixel in the image. The reason for the fifth permeate channel from the left not being visible is the absence of water in the measuring area. Figure 4 b) depicts a flow magnetic resonance measurement of radial velocities inside the membrane module with magnifications in Figure 4 c). The color bar identifies the velocity magnitude, whereas the arrows represent the direction of flow. Higher velocities of up to 8 mm s^{-1} (dark red) are located at the top of the cross-section at the same position as the sinusoidal corrugation. Thus, the sinusoidal corrugation can be directly correlated with the local velocity increase in radial direction. Furthermore, arrows show a vortex formation in the cross-section and support the assumption of mixed flow in the sinusoidal corrugation. Slow fluid-flow velocities down to 0 mm/s are indicated in dark blue. In the lower part of the module corresponding to the permeate channels, no significant radial velocities could be measured.

3.4. Experimental validation from BSA experiments

Figure 3 b) shows the permeate volume flow J_P for the empty channel, the herringbone structure, the sinusoidal corrugation (all 3D printed prototypes), and the commercial net spacer, which was placed in the empty membrane module. Permeate volume flows were conducted for BSA concentrations of 10 g L^{-1} and 50 g L^{-1} . Permeate volume flow is higher for low BSA concentrations (see equation (6)). The sinusoidal corrugation shows the best

Figure 4: (Flow-)Magnetic resonance imaging on ambr[®] crossflow module (a) reveals the inner structure of the module, (b) shows high radial velocities, and (c) vortex formation in the sinusoidal structured feed channel.

performance with the highest permeate flow rate, followed by the commercial net spacer, the herringbone structure, and the empty channel. BSA experiments demonstrate that all three spacer structures outperform the empty channel, which is in accordance with literature. Sinusoidal corrugations outperform all others in agreement with the simulations.

4. Conclusion

The comprehensive methodology to design fluid compartments with minimized concentration polarization resulted in a novel high-throughput membrane module optimized for flexible use in ultrafiltration screenings.

The chosen structure, the sinusoidal corrugation, shows 10 % to 30 % better results compared to the traditionally used net-shaped spacers. Simulations with a focus on mass transfer and permeate flux visualize that geometrical shape influences velocity gradients and thus shear rate distribution. Simulations show good agreement between shear rate peaks and concentration valleys on the membrane surface and explain the observed permeate flux enhancement. The embedded sinusoidal corrugation outperforms the conventional net-shaped

342 spacer in experiments with BSA, which is followed by the herringbone structure and, finally,
the empty channel. Both simulations and experiments prove the good performance of the
344 sinusoidal corrugation. An extensive parameter study could further optimize the sinusoidal
geometry.

346 The proposed CFD simulation can detect concentration accumulation and dead zones in
membrane modules in advance and supports module design. The proposed salt retention
348 model is an acceptable first-order approach and elucidates the interaction of hydrodynam-
ics and membrane transport during membrane filtration affected by local hydrodynamic
350 conditions. For a more representative ultrafiltration model, the concentration-dependent
properties such as diffusion coefficient, viscosity, and density should be implemented.

352 The new module design with embedded structures improves the filtration process due
to mass transfer enhancement and makes conventional net-shaped inlays obsolete. Spacer
354 structures could also be modified according to specific applications (e.g., high or low viscous
concentration profiles, shear sensitive products like cells).

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