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Rotating disk-like membrane cell for pressure-driven measurements with equally-accessible membrane surface: Numerical simulation and experimental validation

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ABSTRACT

This work presents a new approach to correcting for concentration polarization (CP) in pressure-driven membrane measurements. In the existing test cells (both cross-flow and stirred-batch) there are distributions of extent of CP over membrane surface. This complicates the interpretation of experimental data.

A novel design of test cell with equally-accessible membrane surface has been developed based on the classical configuration of rotating disk combined with the possibility of applying trans-membrane hydrostatic pressure differences of up to 20 bar. Due to the equal accessibility, corrections for CP can easily be made even in multi-ionic systems, which would be much more difficult with other membrane test cells.

Since the membrane has to be sealed at the edge the geometry somewhat deviates from the ideal case of infinite disk. The impact of these deviations has been quantified via CFD simulations. A major part of the membrane surface is shown to be equally accessible while there are some expectable deviations close to the sealed membrane edge. This zone could be "screened" in the experiments. The approach could also be validated experimentally via studying the dependence of observed rejection on the rotation speed and demonstrating that intrinsic rejection was practically independent of it.

Finally, to demonstrate the cell utility, we performed and interpreted a number of experiments using commercial NF270 membrane and various feed solutions (single salts and electrolyte mixtures). We conclude that this cell can be employed for systematic transport characterization of membranes and the obtained information can be used as input in the CFD modelling of membrane modules.

1. Introduction

In test cells for pressure-driven membrane processes (both cross-flow and batch [1]) there is some distribution of extent of concentration polarization (CP) over membrane surface. A number of CFD studies have demonstrated this inhomogeneity of CP, which is especially pronounced in test cells with spacer-filled feed channels [2–7], and revealed up to one order of magnitude variation in the local mass-transfer coefficient depending on the position along the membrane surface [6,8–10]. However, this fact has been usually ignored and average values of mass transfer coefficient were reported [3–6,9–12].

A previous theoretical study [13] illustrated the implications of inhomogeneous CP distribution for the interpretation of membrane-transport measurements. It was demonstrated that disregarding the CP distribution can under-estimate the CP of strongly positively-rejected solutes and over-estimate the CP for negatively-rejected ones, leading to a several-times difference in the effective unstirred-layer thicknesses estimated for such solutes by using standard Nernst model. Therefore, the CP inhomogeneity makes difficult obtaining accurate information on the membrane transport properties from experimental data especially in the case of multi-ion solutions. Given the complexity of mechanisms of nanofiltration (NF) [14,15], this makes highly desirable decoupling of internal and external mass-transfer problems because coupled models involve too many adjustable parameters and uncertainties. Such a decoupling can easily be performed provided that the extent of CP is the same over the whole membrane surface. In this study, we achieve this experimentally in a novel test cell using rotating disk-like membrane (RDM).

Feron et at [16] developed a test cell for the characterization of high flux flat sheet gas separation membranes with uniform mass-transfer and constant permeate concentration over the whole membrane surface. Other publications also investigated experimental systems using

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Nomenclature

c_i	ionic concentration
	bulk concentration
c_m	surface membrane concentration
c_{ip}	ionic permeate concentration
D	diffusion coefficient of the salt
D_i	ionic diffusion coefficient
F	Faraday constant
J	solute flux
J_V	trans-membrane flux
k	mass-transfer coefficient
p	hydrostatic pressure
N	rotation speed (rpm)
Pe_i	ionic Péclet number
Pe_s	Péclet number of the salt
R	ideal gas constant
$R_s^{(obs)}$	observed rejection of the salt
$R_s^{(int)}$	intrinsic rejection of the salt
T	temperature
u	radial component of the fluid velocity
$\vec{u}$	velocity vector
v	angular component of the fluid velocity
V	velocity magnitude
w	axial component of the fluid velocity
x	coordinate across the unstirred layer
Z_i	charge of ion

Greek letters

δ	thickness of concentration polarization layer
ξ	coordinate normalized by the local unstirred layer thickness
μ	dynamic viscosity
ν	kinematic viscosity
ρ	density
φ	electrostatic potential
ω	angular velocity

rotating elements, in particular, rotating disk-like bodies with membranes fixed to them [17–27]. However, the principal purpose of those studies was the enhancement of shear rate at the membrane surface in view of applications with high-viscosity fluids. The geometry of these systems was quite different from infinite rotating disk and didn´t give rise to homogeneous distribution of CP. At the same time, the hydrodynamic and convection-diffusion equations for the system of interest have been extensively studied in electrochemistry in the context of rotating disk electrodes [28–30]. Those are experimental systems of choice for a quantitative control of mass-transfer limitations in the studies of electrode kinetics.

Besides, a previous study employed electrochemical techniques to characterize shear stress and mass transfer coefficient at the membrane surface in a high-pressure stirred filtration cell [1]. The authors observed a considerable variation of local values of shear stress at relatively low rotation speeds, with its time-averaged standard deviation decreasing with increasing Reynolds number. As for the mass-transfer coefficient, the radial distribution is qualitatively similar but more uniform than that of shear stress, although there is still a variation around 50% in the time averaged Sherwood number. Thus, the equal accessibility could not be achieved.

This study presents a novel design of membrane test cell with

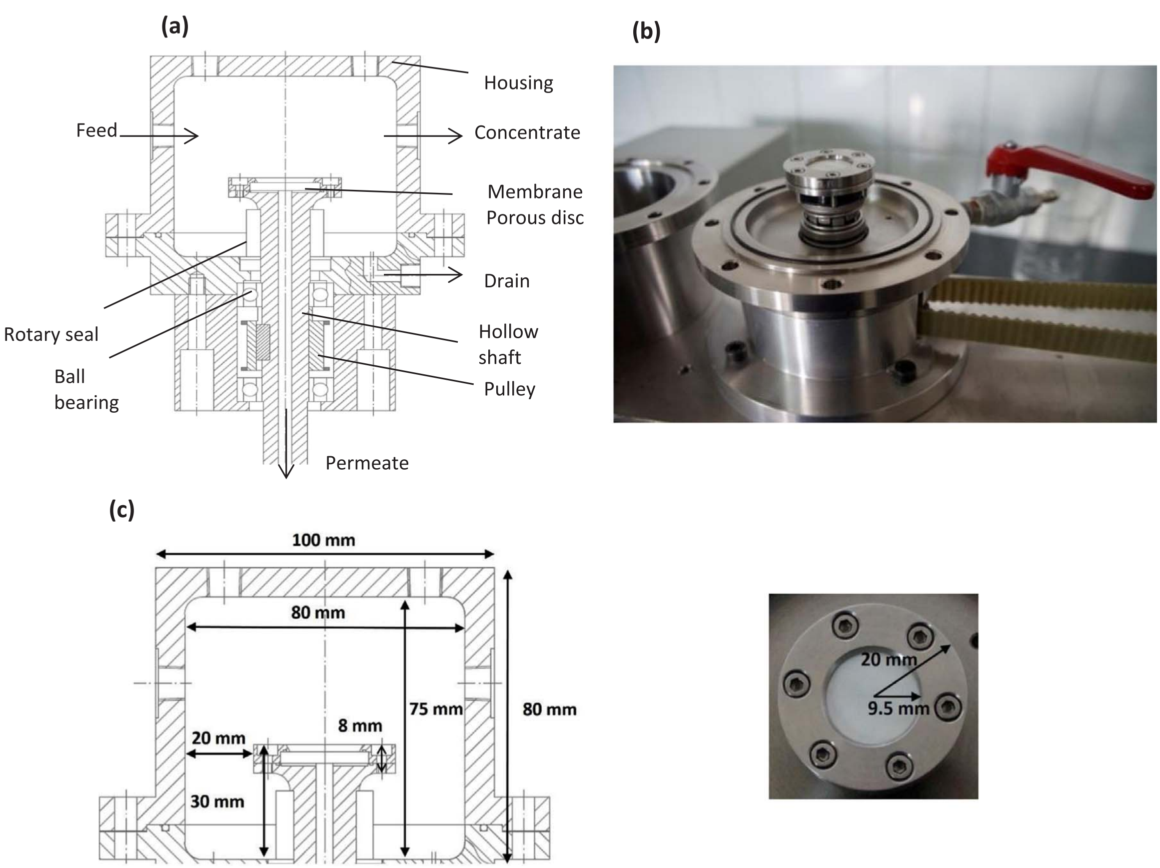

Fig. 1. (a) Schematic diagram, (b) photo of RDM cell and (c) cell dimensions.