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Mass transfer in 1812 spiral wound modules: Experimental study in dextrose-water nanofiltration

Serena Bandini*, Valentina Morelli

Department of Civil, Chemical, Environmental and Materials Engineering, Alma Mater Studiorum, University of Bologna, School of Engineering and Architecture, Via U. Terracini, 28, I-40131 Bologna, Italy

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ABSTRACT

Biotech 1812 spiral-wound elements manufactured by GE Powe&Water have been characterized, operating in NF with aqueous solutions containing 50 g/dm^3 dextrose at 50 °C and pH = 4. Operative conditions were selected in order to get experimental results of flux and observed rejections highly dependent on feed flow rate, so that a confident mass transfer correlation in the feed side has been obtained.

The mass transfer correlation accounts of the feed spacer geometrical characteristics included in the description of the hydraulic diameter. It matches in a surprising manner with the well-known correlation derived from heat and mass transfer analogies in turbulent flow regime, it is in a good agreement with a recently published correlation derived from OSN in 1812 modules, whereas it is heavily in contrast with the widely used Shock and Miquel equation. In addition, the elaboration of the experimental data according to the velocity variation method does not lead to confident results.

The correlation here presented can be extended to the simulation of industrial modules operating at feed flow conditions corresponding to Reynolds number in the range from 100 to 700, since it is rather independent of the way in which it was calculated.

A critical discussion is also presented about the differences between the values of membrane permeability and of the module permeability and about the role of the "module length to membrane width" ratio in data elaboration.

A sensitivity analysis concludes the work, in which authors discuss how the results of module characterization depend on the quality of the mass transfer correlation in the feed side and give some recommendations for a proper elaboration of experimental results.

1. Introduction

Potentialities of Nanofiltration (NF) are well-known for separation and/or fractionation in very different fields [1] as well as the main drawbacks of its applications [2].

One of the main problems regards the interpretation of experimental results. In the past two decades, scientific world has been very proficient of papers and patents in which new applications were introduced and new membranes were developed. At the same time, a wide investigation was carried out on modelling of transport phenomena involved in the process which led to the explanation of membrane behavior with neutral solutes, or with electrolyte solutions, as well as with complex mixtures of them; some representative references are [3–10].

However, the availability of these models does not allow to perform a process scale-up yet, only basing on few experiments of membrane characterization on small samples in bench-scale apparatuses, with the exception of the conventional Reverse osmosis applications as desalination of sea or brackish water.

Typically, big modules (40 in. long) are used in an industrial equipment, selected with a proper diameter, depending on the plant potentiality. For design purposes, module performances are obtained from an experimental characterization with actual solutions, by testing a single module of the same dimensions of the final plant, in order to optimize process parameters [11–14]. No simple confident models are available to describe transport phenomena in a spiral wound module, above all in those cases in which the role of concentration polarization as well as of the pressure drops in the permeate side should be quantified. Owing to the relatively higher transmembrane fluxes with respect to a corresponding reverse osmosis process, those phenomena can be expected to be remarkable in a NF process.

Operation of a spiral wound modules has been modelled in

* Corresponding author.
E-mail address: serena.bandini@unibo.it (S. Bandini).

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Nomenclature

Symbols

0^-	feed/membrane interface, feed side
0^+	feed/membrane interface, membrane side
A	nominal membrane area (m^2)
A_{eff}	actual membrane area excluding glue areas (m^2)
c	concentration (g m^{-3})
d_h	hydraulic diameter defined in Eq. (3.2)-Table 3 (m)
d_F	fiber diameter defined in Eq. (3.3)-Table 3 (m)
D_{iw}^0	unconfined diffusivity in water (m^2 s^{-1})
h_{fs}	feed spacer height (m)
h_{ps}	permeate spacer height (m)
J_V	total volume flux (m s^{-1})
k_{Li}	mass transfer coefficient of i component in the feed side (m s^{-1})
k_p	permeate spacer permeability (m)
l_M	mesh length (m)
L	module length (m)
$\langle L_p \rangle$	module permeability (m s^{-1} Pa^{-1})
$\langle L_{pw} \rangle$	hydraulic module permeability (m s^{-1} Pa^{-1})
N_e	number of envelopes in a module
Q_F	volume flow rate in the feed side (m^3 s^{-1})
Q_P	volume flow rate in the permeate side (m^3 s^{-1})
R_{real}	real rejection defined in Eq. (6.12)-Table 6
R_{obs}	observed rejection defined in Eq. (6.1)-Table 6
S_{eff}	feed side effective flow section defined in Eq. (3.5)-Table 3 (m^2)
v	effective velocity in the feed side defined in Eq. (3.6)-Table 3 (m s^{-1})
v_P	effective velocity in the permeate side defined in Eq. (2) (m s^{-1})
W	spiral length (m)
ΔP	average driving force defined in Eq. (1) (Pa)
ΔP_{av}	average driving force in the feed side defined in Eq. (1) (Pa)
$\Delta P_{drop,P}$	pressure drops in the permeate side defined in Eq. (2) (Pa)
ΔP_{eff}	effective pressure difference defined in Eq. (6.3)-Table 6 (Pa)
$\Delta \pi$	average osmotic pressure difference (Pa)
ε	feed spacer porosity
η_w^0	unconfined dynamic viscosity of water (Pa s^{-1})
η^0	unconfined dynamic viscosity of the solution (Pa s^{-1})
λ_i	hydrodynamic coefficient of the solute
ρ_w^0	unconfined density of water (kg dm^{-3})
ρ^0	unconfined density of the solution (kg dm^{-3})
ϕ_i	steric partitioning coefficient
σ_{vi}	Staverman reflection coefficient of i component

Subscripts/superscripts

bulk	bulk side
exp	experimental value
i	solute
inside	inside the pore
tot	total
IN	inlet section of the module
OUT	outlet section of the module
F	feed stream
P	permeate stream

literature for a long time [11,15–39]. Integration of mass and momentum balances equations is required along a two-dimension spacer filled channel, both for the retentate and for the permeate side. Definition of local equations typically requires the mass transfer coefficient in the retentate as well as the friction coefficients in the retentate and in the permeate side, which are greatly influenced by the geometry of the spacers.

Unfortunately, no direct measurement can be performed in a wound module actually operating; various devices have been properly designed to simulate transport performances of the unwound module [15,16,19,28].

First 2-D simulations [11] were performed by using correlations for flat channels with smooth walls mainly derived from heat and mass transfer analogies [16,40] or improved correlations [17,18].

Later, different methods to get mass transfer correlations were developed and critically analyzed, based on the osmotic pressure method and/or the velocity variation method [41].

Finally, CFD methods have been used to investigate the effect of retentate spacer geometry on the fluid-dynamics and mass transfer coefficients [20–23,27,29–37,39]; conversely, only few authors [19,20,31,38] investigated the role of permeate spacer geometry on determining the permeate side pressure drops.

So far, many correlations have been developed in literature to describe mass transfer characteristics in spacer filled channels of spiral wound membrane modules; a summary of the most representative correlations (to the best of our knowledge) is reported in Table 1.

Most of authors agree with the conclusion that the well known correlation by Shock and Miquel [19] is not adequate to describe mass transfer in the feed side, leading sometimes to overestimations [27] or to underestimation [22,23].

Very recently, Shi et al. [27] developed a correlation for mass transfer in small 1812 spiral wound modules, derived from experimental tests of organic solvent nanofiltration (OSN); the correlation was tested successfully with industrial modules. That correlation was obtained from a semiempirical regression on experimental data by a 2-D integration of the local balances equations; all the geometrical parameters were fitted, including the hydraulic diameter of the feed and permeate side, the geometric characteristics of the spacers, such as porosity and height.

Although the validity of the derived correlation has been demonstrated in 4″x40″ modules, its applicability to different spacer geometries is possible only if the fitting procedure is repeated, every each case.

At the same time, Roy et al. [26] documented that modelling of seawater NF in spiral wound modules could be performed simply by a unidimensional plug flow model of the retentate side co-currently with the permeate side, instead of computationally expensive and complex 2-D models, as it had been suggested by Rautenbach thirty years before [11].

Recently, the interest for 1812 modules is increasing; 1812 modules are small short lab-scale spiral wound modules which can be useful for preliminary experimentation, since they do not require high reagent volumes; at the same time, they offer the same configuration of an industrial module. In addition, since the spiral length is short, they offer a ratio "module length to membrane width" close to the values typical of the modern modules in which a high number of envelopes is used to achieve the maximum module productivities [13,19,25,31]. Experimental results can be then considered rather representative and might be useful for scale-up purposes.

A small short module presents also the advantage of a very simple experimental data management, since properties can averaged along the module, avoiding the use of computationally expensive and complex 2-D models, which are necessary in case of very long spirals.

Finally, 1812 modules might be interesting also to perform a