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Biofouling in membrane devices treating water with different salinities: a modeling study

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ABSTRACT

The impact of biofilms on reverse osmosis (RO) membrane performance loss was studied using a two-dimensional mathematical model that couples fluid dynamics, salt and substrate mass transport and biofilm development. Decline in the permeate flux was simulated at different salt concentrations in the feed assuming: (i) the same feed pressure and (ii) pressures adjusted for constant initial flux. The pattern of biofilm development in the spacer-filled membrane channel was similar for all cases. Numerical results indicated that the detrimental effect of a biofilm is more pronounced for higher salinity of the feed, effect mainly due to the biofilm-enhanced concentration polarization. When pressure is increased to compensate for the osmotic pressure created by higher salt in feed, the local flux under the biofilm strongly deteriorates while a slight flux enhancement is observed in biofilm-free areas. Parametric variation within commonly measured range of biofilm permeability did not affect strongly the flux. Smaller effective diffusion coefficients of salt in the biofilm slightly decreased the permeate flux.

Keywords: Biofouling; Model; Reverse Osmosis; Brackish water; Salinity; Flux Decline

1. Introduction

Biofouling has been reported as a serious problem for reverse osmosis (RO) systems treating brackish water and seawater [1], drinking water [2] and wastewater [3]. Experimental studies have suggested several ways through which biofilms can impact the membrane device performance: by introducing an additional hydraulic resistance [4], by increasing the feed channel pressure drop [2], and by enhancing concentration polarization [3]. A numerical model including all these effects was recently developed by Radu et al. [5]. We aim in this work at evaluating the relative importance of feed salinity and biofilm formation on the membrane device performance, by using the computational approach from [5].

Although biofouling seems to be a general problem for all RO membrane plants, the impact of biofilms may not be the same for different water compositions (i.e., salt content). The effect of feed salinity on membrane performance in the absence of any fouling mechanism was addressed in previous modeling studies (numerical [6–8] and analytical [9]). A recent review on the impact of salinity on membrane bioreactor performance has summarized several aspects associated to high salinity [10]. In general, a significant flux decline is expected when increasing feed salinity (and maintaining a constant TMP) [11].

A systematic computational study for the effect of salinity in RO systems with biofouling is still lacking. Therefore, the objectives of this work are: (i) to investi-

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gate the impact of biofilms on membrane performance loss for different feed water salinities and (ii) to analyze the model sensitivity to biofilm hydraulic permeability and diffusion coefficient for salt inside the biofilm.

2. Model description

The numerical model couples liquid flow in laminar regime with mass transport of solutes plus biofilm development, in the feed spacer channel with two permeable membranes. We use the model described in detail in [5], thus only the main features will be summarized here. To evaluate the impact of biofouling as a function of feed water quality, simulations with variable salinities were carried out. Two possible operational scenarios were considered: (i) devices operated at the same feed pressure; (ii) devices operated at different pressures so that the same flux is obtained in the biofilm absence, for any feed salt content.

A two-dimensional geometry of the RO feed channel containing zigzag spacers is chosen for this study (Fig. 1), for reasons explained in [5]. Channel dimensions are set according to practice [12]. The stationary laminar incompressible Navier-Stokes equations are used to calculate flow in the bulk liquid domain, for an average inlet velocity of 0.1 m/s ($Re_{ch} \approx 160$ based on the hydraulic diameter of spacer filled flow channel [13]). The biofilm is assumed to be a porous medium, through which the flow is described by a Brinkman model. Mass transport is calculated for two soluble compounds: salt (NaCl) and substrate. The convection-diffusion equation is used to obtain the salt distribution in the liquid and biofilm. For the substrate, beside convection and diffusion, consumption inside the biofilm is also considered. The biofilm development is based on the discrete biofilm modeling framework previously developed [14]. Bacteria can (i) attach to the membrane, spacer and biofilm, (ii) grow as a function of available substrate and (iii) detach due to local shear stress determined by liquid flow. The boundary conditions used for the flow and mass transport equations are listed in Table 1.

Most model parameters are identical to those presented in [5]. For the constant initial flux study, the pressure was set to 13.1, 15 and 16.9 bar for feed salt concentrations of 10, 40 and 70 mM respectively. For the constant pressure study, the TMP was maintained at 15 bar

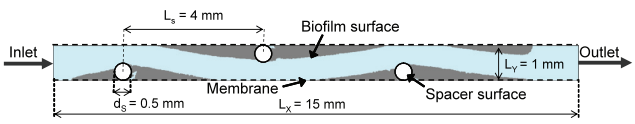

Fig. 1. Schematic description of model geometry used for simulations.

Table 1
Boundary conditions for flow and solutes mass transport (see also Fig. 1)

Location	Flow	Solute mass transport
Inlet	Laminar velocity profile	Prescribed concentration
Outlet	Prescribed pressure	No diffusion
Spacer surface	Impermeable wall	Impermeable wall
Biofilm surface	Flow continuity	Flux continuity
Membrane	Velocity (function of pressure and salt concentration)	Flux (function of flow velocity and concentration)

for all salt concentrations. In the sensitivity study, feed salt concentrations were varied between 0 and 300 mM, the biofilm permeability was 10^{-17} to 10^{-15} m^2 and the salt diffusion coefficient in the biofilm was from 50 to 100% of its value in water.

The biofilm framework is implemented in Matlab and Java codes, coupled with finite-element solution of hydrodynamics and mass transport using a commercial solver (COMSOL 3.5a, Comsol Inc, Burlington, MA, www.comsol.com).

3. Results and discussion

3.1. Biofilm development in time

The biofilm develops in the spacer filled channel following the generally described trend [5,15]: initially small colonies are present on the membrane and spacer (Fig. 2, 3 d), these expand laterally (Fig. 2, 5 d) and will eventually merge into a layer (Fig. 2, 7 d). There is only little or no biofilm in the regions opposite to the spacer elements because in these areas with high shear the cells will be detached. A quasi-steady state biofilm thickness is obtained when biomass growth is balanced by detachment due to shear stress (Fig. 2, 12–16 d; Fig. 3 A, B).

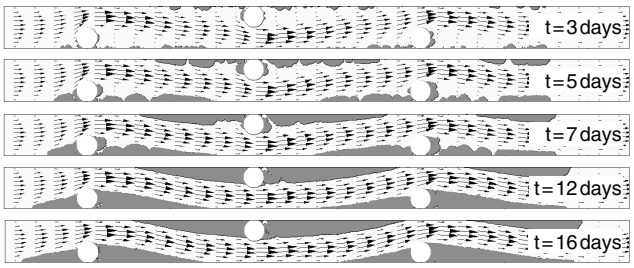

Fig. 2. Biofilm development in time (10 mM salt in inlet, 15 bar TMP). The arrows indicate the velocity vector field. The white circles represent the spacer and dark gray areas are the biofilm.

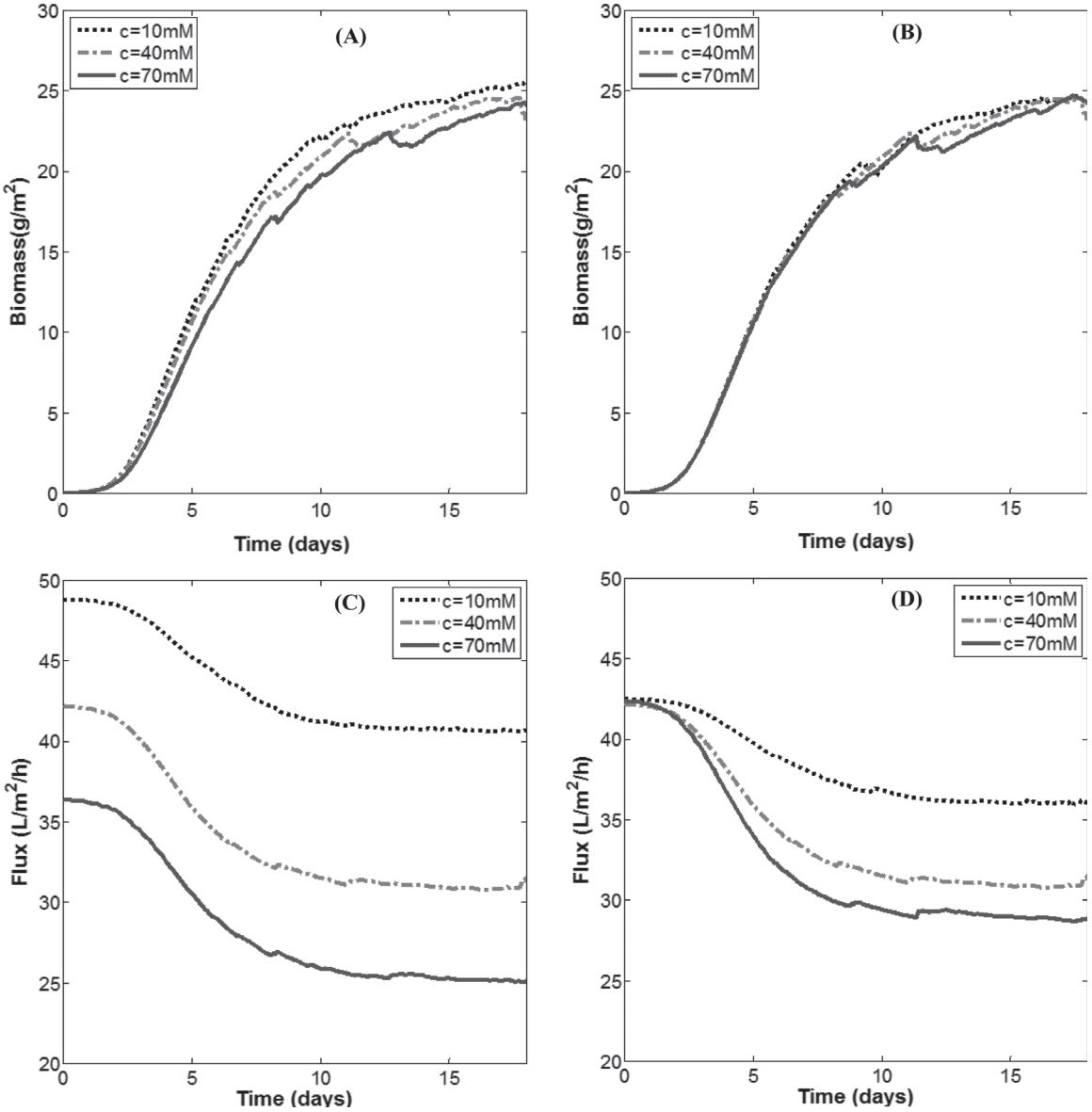

Fig. 3. Compared biomass amount (A, B) and permeate flux (C, D) developed in time at different salt content of the feed (10, 40 and 70 mM). Left: constant operating pressure (p = 15 bar); Right: constant initial flux (J = 42 l/m^2/h)

The shape of the biofilm growth curve, in this model, is not affected by the salt concentration (Fig. 3 A, B): exponential phase, linear substrate limited phase and quasi-steady state regime. We assumed the same growth parameters, independent of salt concentration, as if the microbial community forming the biofilm would be already adapted to certain salinity. When constant initial flux is set, the same amount of biomass develops in the channel independent of feed salt content (Fig. 3B). However, small differences in the amount of biomass in the system can be noticed in the substrate-limited phase when operating at constant pressure (TMP): there is slightly less biomass formed at higher salt concentrations (Fig. 3A). Two effects could contribute to these differences. First, higher salt concentration in feed determines higher osmotic pressure next to the membrane, which will reduce the permeate flow, and thus reduce substrate availability in the biofilm. Second, the reduced permeate flow decreases also the substrate concentration polarization, which could have boosted the biofilm growth rate in the initial phase (shown in [5]).

3.2. Detrimental effect of biofouling function of feed salinity

As expected, when the pressure is maintained constant, the initial flux (i.e., without biofilm) obtained for water with low salt content is 49 l/m^2/h, whereas for higher salt content it declines to 36 l/m^2/h (Fig. 3C) due to the high osmotic pressure at the membrane which reduces the effective driving force. The local permeate flux on the membrane for different salt concentration is shown in Fig. 4A (continuous line). Once the biofilm starts to develop, the flux will decline following the trend described experimentally [3] and theoretically [5,15]. Although there is only a small (~10%) difference in the total amount of biomass (Fig. 3A), the biofilm developed when the module is fed with 70 mM salt has a more pronounced effect on the global permeate flux compared with that fed with 10 mM salt (Fig. 3C). The local permeate flux is drastically reduced (Fig. 4A, dashed line) due to the biofilm enhanced concentration polarization effect. The importance of this effect has been emphasized in several previous experimental [3,16] and modeling studies [5].

When the feed pressure is adjusted so that the same initial flux can be obtained at higher salt concentration in feed, approximately the same amount of biomass in the channel causes 10% flux reduction in the module fed with low salinity water (10 mM) and 35% reduction when fed with the higher salinity water (70 mM) (Fig. 3D). In this case, in the biofilm absence, the local permeate flux is decreased in the spacer region when

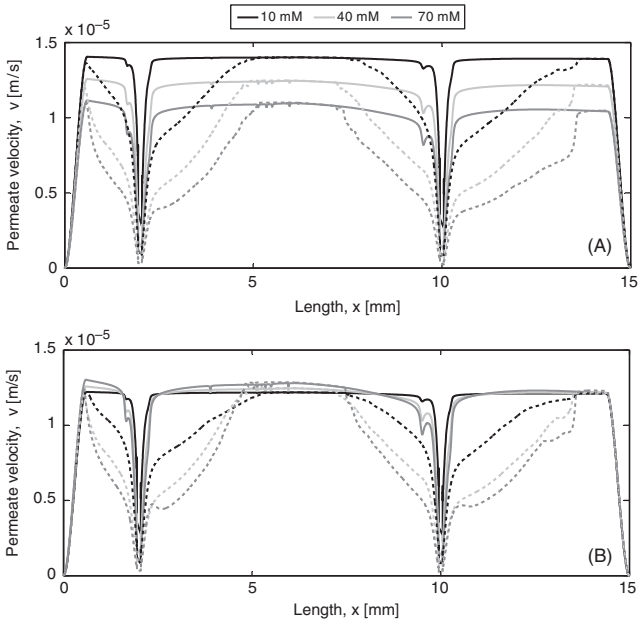

Fig. 4. Permeate velocity on the lower membrane. (A) constant pressure; (B) constant initial flux. Continuous lines: case without biofilm; dashed line: case with biofilm at day 14.

Fig. 5. Relative contribution of convective to total flux of salt in a channel (70 mM salt in inlet, biofilm at day 6). The gray scale represents the ratio of convective and total flux.

increasing feed salinity (Fig. 4B), but it increases in other regions in the channel, so that the average flux is identical for all studied cases (Fig. 3D). When a biofilm develops (mostly next to spacer filaments), the reduction of local permeate flux is more pronounced for higher salinity of the feed. Membrane areas not covered by biofilm will still benefit from the increased pressure. Our results therefore strongly indicate that the impact of biofilm may be different as a function of salt content in the feed stream. Between colonies (Fig. 5) salt convection is reduced compared to the bulk liquid. Interestingly, at the surface of certain colonies the salt transport is diffusion dominated due to the fact that the liquid flow (and thus convective flux) preferred the path of minimum resistance, i.e., by-passing the colony.

3.3. Influence of effective diffusion coefficient of salt

To analyze the importance of effective diffusion coefficient for salt in the biofilm on permeate flux, several simulations were performed for a given biofilm structure (day 14, grown at 40 mM salt, 15 bar, Fig. 1). The diffusion coefficients for low molecular mass solutes (such as NaCl) within the biofilm can be as low as 50% of those in bulk liquid [17]. Fig. 6A shows that the flux decline in the presence of the same biofilm in the channel is only slightly (max. 10%) decreased when assuming smaller diffusion coefficients for salt within the biofilm. The biofilm thickness,

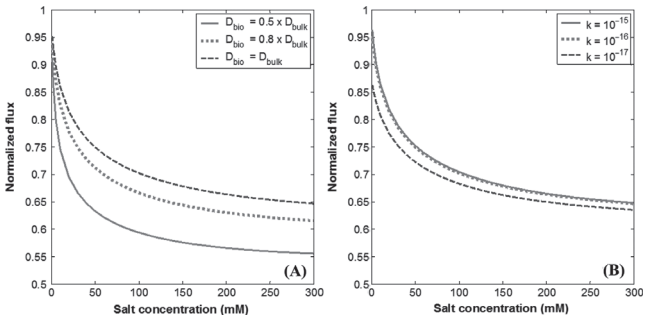

Fig. 6. Influence of (A) effective diffusion coefficient of salt in the biofilm and of (B) biofilm permeability, on the normalized permeate flux (flux in the presence of a 14 d old biofilm related to the flux in the biofilm absence).

as a transport barrier, is more important than the reduction on salt diffusion coefficient in the biofilm. A considerable flux reduction occurs compared to the case without biofilm (Fig. 6A) even at maximum diffusion coefficient in the biofilm. The biofilm simply enhances the CP by hindering the salt transport by convection in direction parallel to the membrane.

3.4. Influence of biofilm hydraulic permeability

The importance of biofilm permeability was evaluated for different salt contents of the feed stream, given the same biofilm structure (Fig. 1). Three values for biofilm permeability in the range reported in literature [4,18] are evaluated. The effect of biofilm permeability on flux decline can be estimated in the absence of salts, when there is no enhanced concentration polarization effect. Our model results show that there are no significant differences (<5%) in the permeate flux for biofilm permeability between 10^{-15} and 10^{-16} m^2 (Fig. 6B). An even lower permeability (10^{-17} m^2) produced more significant flux decline in the absence of salt (~15%). This could mean that the biofilm in this case had a hydraulic resistance comparable to that of the membrane itself.

In spite of the observed differences in the flux obtained at very low (or no) salinity, for salt concentrations above 10 mM the flux decline due to biofilms is approximately the same indifferent of biofilm permeability. This happens because the increase in salt polarization has a greater effect on the flux decline than the lower biofilm permeability. Moreover, a higher biofilm hydraulic resistance allows less convective flux salts towards the membrane, thus producing less CP. In conclusion, changing the biofilm permeability within the commonly measured range does not have a sensible effect on the flux, especially when compared with the effect produced by the salt concentration of the feed.

4. Conclusions

A two-dimensional numerical model including fluid flow, mass transport and biofilm development was used to evaluate the impact of biofilm upon plant performance for different salt contents of the feed. The pattern of biofilm development was not influenced by the salt concentration. The biomass amount is however slightly affected by the salt concentration when operating at the same pressure when changing the salt content in feed. When increasing the operational pressure to compensate for the salt increase (operation at the same initial flux), there are no differences in the amount of biomass developed in the channel. Model results indicate that, even when the biomass growth rate is not affected by salinity, the same biofilm can cause more severe flux decline at 70 mM compared to 10 mM salt content. Changing the biofilm permeability within the commonly measured range does not affect much the flux. A smaller effective diffusion coefficient of salt in the biofilm decreases the permeate flux. However, the existence of the biofilm itself, hindering the cross-flow next to the membrane, is more important. Biofouling causes performance loss for all RO systems, but the extent of this loss depends of feed salinity.

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References

[1] F.A.A. El Aleem, K.A. Al-Sugair and M.I. Alahmad, Biofouling problems in membrane processes for water desalination and reuse in Saudi Arabia, Int. Biodeterior. Biodegrad., 41 (1998) 19–23.
[2] J.S. Vrouwenvelder, D.A. von der Schulenburg, J.C. Kruithof, M.L. Johns and M.C.M. Van Loosdrecht, Biofouling of spiral wound nanofiltration and reverse osmosis membranes: A feed spacer problem, Water Res., 43 (2009) 583–594.
[3] M. Herzberg and M. Elimelech, Biofouling of reverse osmosis membranes: Role of biofilm-enhanced osmotic pressure, J. Membr. Sci., 295 (2007) 11–20.
[4] R. McDonogh, G. Schaule and H.C. Flemming, The permeability of biofouling layers on membranes, J. Membr. Sci., 87 (1994) 199–217.
[5] A.I. Radu, J.S. Vrouwenvelder, M.C.M. Van Loosdrecht and C. Picioreanu, Modeling the effect of biofilm formation on reverse osmosis performance: flux, feed channel pressure drop and solute passage, J. Membr. Sci., 365 (2010) 1–15.
[6] L. Song and S. Yu, Concentration polarization in cross-flow reverse osmosis, AIChE J., 45 (1999) 921–928.
[7] W. Zhou, L. Song and T.K. Guan, A numerical study on concentration polarization and system performance of spiral wound RO membrane modules, J. Membr. Sci., 271 (2006) 38–46.
[8] S. Wardeh and H.P. Morvan, Detailed numerical simulations of flow mechanics and membrane performance in spacer-filled channels flat and curved, Desalin. Water Treat., 1 (2009) 277–288.
[9] L.Y. Hung, S.J. Lue and J.H. You, Mass-transfer modeling of reverse-osmosis on 0.5–2% salty water, Desalination, article in press (2010).
[10] W.C.L. Lay, Y. Liu and A.G. Fane, Impacts of salinity on the performance of high retention membrane bioreactors for water reclamation: a review, Water Res., 44 (2010) 21–40.
[11] M.F.A. Goosen, S.S. Sablani, S.S. Al-Maskari, R.H. Al-Beshudi and M. Wilf, Effect of feed temperature on permeate flux and mass transfer coefficient in spiral wound reverse osmosis systems, Desalination, 144 (2002) 367–372.
[12] J. Schwinge, D.E. Wiley and D.F. Fletcher, Simulation of the flow around spacer Filaments between channel walls: 2. Mass-transfer enhancement, Ind. Eng. Chem. Res., 41 (2002) 4879–4888.
[13] J. Schwinge, D.E. Wiley and D.F. Fletcher, Simulation of the flow around spacer Filaments between channel walls: 1. Hydrodynamics, Ind. Eng. Chem. Res., 41 (2001) 2977–2987.

[14] C. Picioreanu, M.C.M. Van Loosdrecht and J. Heijnen, Two-dimensional model of biofilm detachment caused by internal stress from liquid flow, Biotechnol. Bioeng., 72 (2001) 205–218.
[15] A.I. Radu, J.S. Vrouwenvelder, M.C.M. van Loosdrecht and C. Picioreanu, Effect of Flow Velocity, Substrate Concentration and Hydraulic Cleaning on Biofouling of Reverse Osmosis Membranes, Water Research, (2010) submitted for publication.
[16] T.H. Chong, F.S. Wong and A.G. Fane, The effect of imposed flux on biofouling in reverse osmosis: Role of concentration polarization and biofilm enhanced osmotic pressure phenomena, J. Membr. Sci., 325 (2008) 840–850.
[17] H. Horn and E. Morgenroth, Transport of oxygen, sodium chloride and sodium nitrate in biofilms, Chem. Eng. Sci., 61 (2006) 1347–1356.
[18] E.M. Johnson and W.M. Deen, The permeability of agarose gels, AIChE J., 42 (1996) 1220–1224.