Incorporating membrane deformation into the boundary layer equation to model water and reverse salt flux in osmotic processes

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Osmotic processes (OP) involve the contact of two solutions with different chemical potentials of water across a membrane interface to generate a water flux. This difference in chemical potential commonly is obtained by a difference in concentration or/and hydrostatic pressure. OP utilize spacers with large openings to reduce detrimental concentration polarization. When hydrostatic pressure is applied in processes such as osmotically-assisted reverse osmosis, pressure-assisted osmosis, and pressure-retarded osmosis (PRO), membranes undergo a mechanical deformation as they are compressed against the spacer. This deformation causes an increased reverse salt flux as the hydrostatic pressure increases.

We developed a model that incorporates membrane deformation into modern boundary layer equations to describe water and reverse salt flux in OP. Initially, we deformed three commercial thin-film composite membranes using an Instron machine in creep test mode with the goal of correlating deformation (defined as linear membrane strain) with water permeance and salt reverse flux obtained via direct-flow permeation. Then, we performed cross-flow PRO water flux measurements and used similar literature data to train the mathematical model for predicting changes in salt reverse flux with increased hydrostatic pressure. Using laser measuring microscopy we were able to pinpoint the area on the membrane with increased deformation, and confirmed that the deformation profile follows a parabolic trajectory. With this information, we refined our model and correlated our PRO data with the opening size and relative open area of feed spacer used in each experiment.

Results confirmed that membrane deformation increases with feed spacer opening size at constant pressure. Moreover, the linear membrane strain reaches values above 15%, which are greater than the reported strain-to-fracture values for these membranes. Water and salt flux were not statistically different when measured using increasing and decreasing pressure profiles, suggesting that active layer deformation is partially reversible. Best fits were obtained using a model that incorporated diffusion through a film comprising intact polymer, deformed polymer, and occasional fracture sites. These results indicate that deformations in more than 2% of the membrane area lead to exponential increments in the reverse salt flux as pressure increases. This work introduces membrane deformation as a factor to consider in the design of membranes and modules for osmotic processes.

Keywords: thin-film composite membrane, osmotic processes, membrane deformation